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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April 15, 2014

Project ID #
ACE086

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Overview

Timeline

- Start Date: July, 2012
- End Date: July, 2015
- Percent Complete: 60%

Budget

- Total funding: $2,804,400
  - DOE share: $1,402,200
  - Contractor share: $1,402,200
- DOE 2012: $282,390
- DOE 2013: $831,422
- DOE 2014: $27,793 (through 1/2014)

Barriers

- Combustion performance
- Boosting system performance and durability with EGR dilution.
- Spark plug & ignition system durability with required high energy output.
- Transient control of boosting system and EGR dilution.

Partners

- Southwest Research Institute®
  Dedicated EGR System, Engine Testing

Project Lead

- GM

RELEVENCE – Solicitation Criteria

Subtopic 6B: Enabling Technologies for Engine and Powertrain Systems

The objective of this subtopic is to develop advances in enabling technologies for engine and powertrain systems for heavy-duty and light-duty vehicles, from vehicle and engine suppliers to support the achievement of breakthrough thermal efficiencies while meeting U.S. EPA emissions standards for the representative vehicle class technology. These novel approaches and ideas shall address existing barriers and limitations relating to the proposed technology which inhibit using advanced technologies on a mass market basis to address national energy concerns.

Applications shall include a clear path to commercialization

RELEVENCE - Objectives

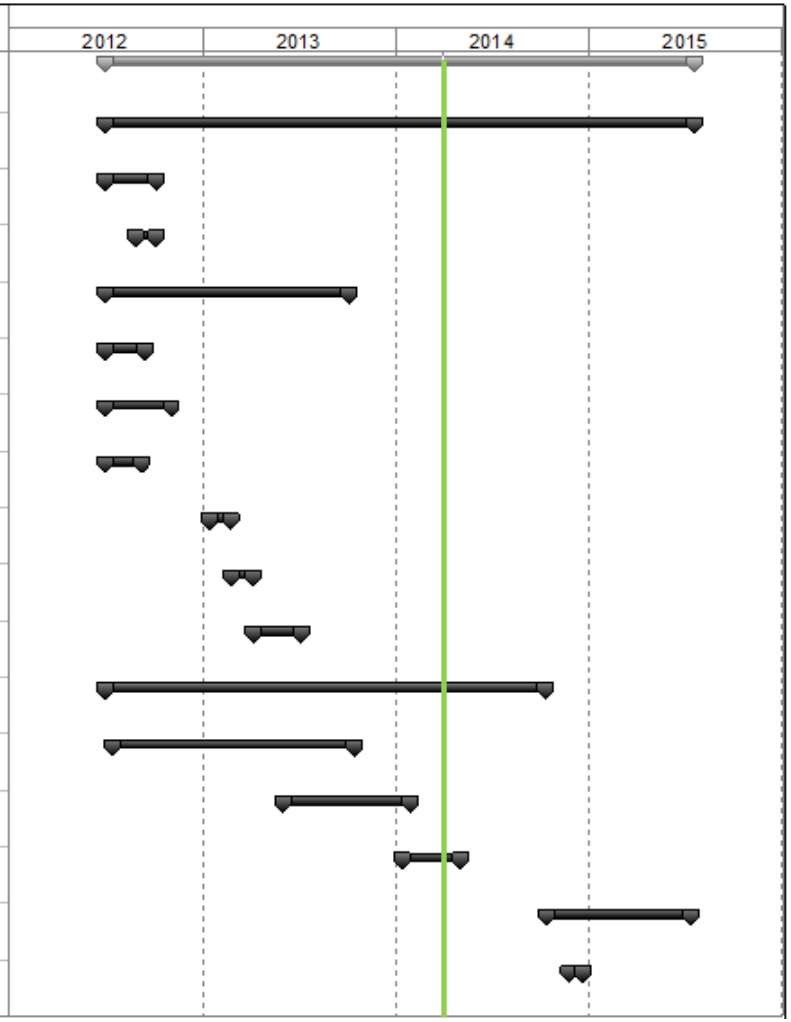
- Develop and demonstrate enabling technologies to achieve **12%** fuel consumption improvement while meeting U.S. EPA emission standards cost effectively.
- The selected enabling technologies accomplish this by enabling increased efficiency benefits from significant EGR dilution of a spark ignition gasoline engine during steady state and transient operation prior to exceeding customer acceptance limits regarding combustion stability and engine transient response.
- The enabling technologies identified offer the potential additional benefit of using increased quantity and quality of cooled EGR for knock suppression at high load enabling the specification of a higher compression ratio while reducing or eliminating the requirement for fuel enrichment.
- The ability to utilize current, stoichiometric mixture based emission aftertreatment devices is maintained.
- The final solution has been designed and developed to package within the engine compartment of a current GM mid-size vehicle.

APPROACH – Milestones

Milestone	Completion Date
Results of initial 1-dimensional engine and vehicle simulation (**Phase 2**) (**Phase 2**)	**COMPLETE**
Results of design, testing, development, and analysis of DCO™ ignition ignition system applied to initial GM 4-cylinder engine configured with with baseline low pressure loop EGR dilution and mixing solution (**Phase 3**) (**Phase 3**)	**COMPLETE**
Results of design, testing, development, and analysis of selected enabling enabling technologies applied to GM 4-cylinder engine updated with an an advanced dilution system (**Phase 4**)	**4Q14**
Results of design, testing, development, and analysis of the Phase 4 engine 4 engine converted to a single spark plug combustion system (**Phase 5**) **5**)	**2Q15**

APPROACH – Timing (high level)

ID	Task Name
0	**High Energy Ignition and Boosting/Mixing Technology**
1	**Phase 1 - Project Management and Planning**
25	**Phase 2 - Initial Simulation**
28	**Vehicle Simulation**
32	**Phase 3 - DCO Ignition System Development**
33	**Install and Test GM 2.4L LAF Ecotec Engine**
37	**Base Engine Hardware Design Update**
40	**Updated Base Engine Hardware Acquisition**
46	**Define EGR System and Control on Engine Installation**
49	**Implement DCO Ignition System on Engine Installation**
53	**Engine, EGR, and DCO Performance, Testing and Evaluation**
60	**Phase 4 - Initial Boost System and Mixer Development (D-EGR)**
62	**Base Engine Hardware Design Update**
74	**Updated Base Engine Hardware Acquisition**
90	**Boost, Mixing, D-EGR, and Ignition Testing and Evaluation**
99	**Phase 5 - Engine System Development**
102	**Integration of Optimum EGR Engine System Control and Hardware**



APPROACH - Technical Overview

Key enabling technologies specified that have been demonstrated to increase efficiency and mitigate issues with EGR dilution:

- Combustion burn duration and dilution tolerance improvement through hydrogen augmentation of the charge.
- Combustion burn duration and dilution tolerance improvement through the use of multiple spark plugs per cylinder.
- Thermal efficiency improvement through the use of increased compression ratio while specifying a low surface area to volume ratio combustion chamber.
- Combustion burn duration and dilution tolerance improvement through the use of increased charge motion (tumble and/or swirl)
- Combustion efficiency benefits via a dual GDI/PFI fuel system.
- Transient response and pumping work improvement through the installation of a variable geometry turbocharger system.

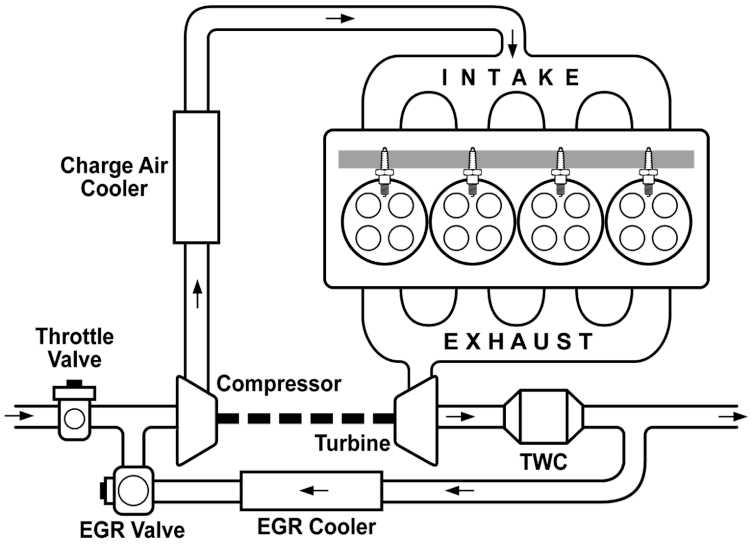
APPROACH - Technical Overview

Combustion burn duration, dilution tolerance and transient dilution control improvement through hydrogen augmentation of the charge via a dedicated cylinder …

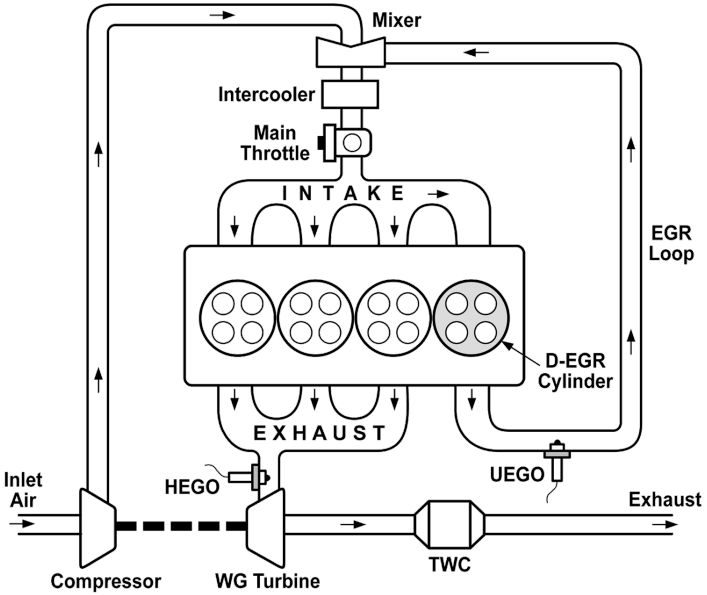
- Higher quality EGR may be generated through the use of dedicated EGR (D-EGR™) concepts developed at Southwest Research Institute® in recent years through multiple HEDGE® consortiums.
- The concept realizes benefits that have been well documented in the literature regarding hydrogen augmentation of the charge for SI combustion, but is capable of producing the hydrogen without the losses associated with external fuel reformers.
- The hydrogen augmentation is achieved by using the output from a “dedicated” cylinder for EGR that has been produced by combusting a rich mixture.

APPROACH - Technical Overview

- D-EGR™ has sufficient energy to eliminate the requirement to “pump” EGR with the charging system.
- Constant quantity Dedicated EGR eliminates the need for proportional EGR valves / sensors, minimizes control complexity



Conventional LPL EGR



D-EGR™

Diagram courtesy SwRI

APPROACH - Technical Overview

Combustion burn duration and dilution tolerance improvement through enhanced ignition …

- A solution to employ 2 spark plugs per cylinder has been implemented.

Thermal efficiency improvement through the use of increased compression ratio while achieving a low surface area to volume ratio combustion chamber.

- A redesigned combustion system has been implemented to achieve 12.0:1 compression ratio while minimizing surface area to volume ratio.

Combustion burn duration and dilution tolerance improvement through the use of increased charge motion (tumble and/or swirl) …

- A “tumble” inlet port has been implemented in order to produce in-cylinder tumble motion.
- A “swirl control valve” has been implemented to partially block one inlet valve in order to generate in-cylinder swirl motion as required.

APPROACH - Technical Overview

Combustion efficiency and friction benefits of dual GDI/PFI fuel system.

- A single GDI fuel injector along with dual PFI fuel injectors per cylinder have been implemented to allow optimal fuel injection strategy in conjunction with “swirl control valve”.

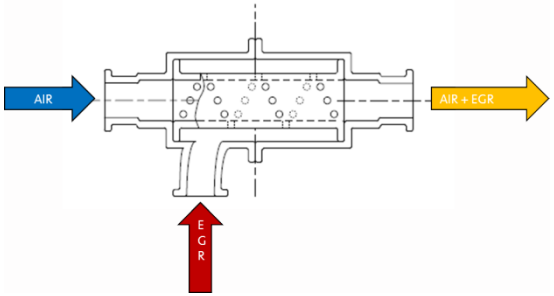
Transient response and pumping work improvement through the installation of a variable geometry turbocharger system

- A modified “Diesel” specification variable geometry turbocharger system has been selected enabled by low turbine inlet temperatures realized with high EGR dilution.

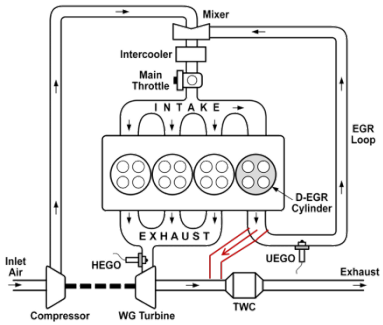
APPROACH - Technical Overview

Challenges to dedicated EGR implementation …

- Possible poor EGR distribution due to EGR pulse from single dedicated EGR cylinder
  - *An enhanced air-EGR mixer has been developed.*



- Inadequate engine EGR Tolerance at low engine speeds/loads
- Requirement to eliminate dedicated EGR during engine cold start
  - *A dilution bypass system is implemented.*



TECHNICAL ACCOMPLISHMENTS and PROGRESS

Phase 2 Vehicle Simulation (baseline engine in mid-size GM vehicle) Complete

- 11 engine speed – load points identified that represent ~95% of the fuel energy used during FTP City/Hwy/US06 cycles
- *These points are being used during engine dynamometer testing to represent "weighted" vehicle fuel economy*

Phase 2 Initial engine simulation complete at 11 engine speed-load points

- Baseline Engine
- Phase 3 "Conventional" LPL EGR dilution with high energy ignition
- Phase 4 Advanced dilution with key enabling technologies

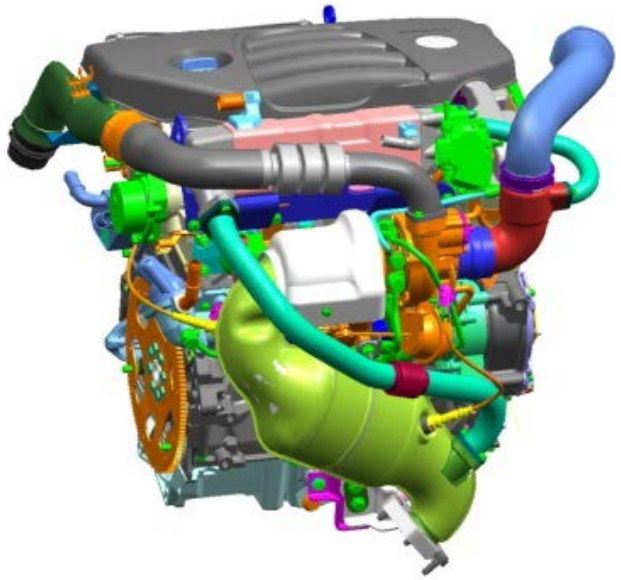
Phase 3 Baseline 2.4L NA engine dynamometer testing completed and fuel efficiency baseline established at 11 engine speed – load test points

- *Weighted average simulation results were within 1.5% of actual engine test results*

TECHNICAL ACCOMPLISHMENTS and PROGRESS

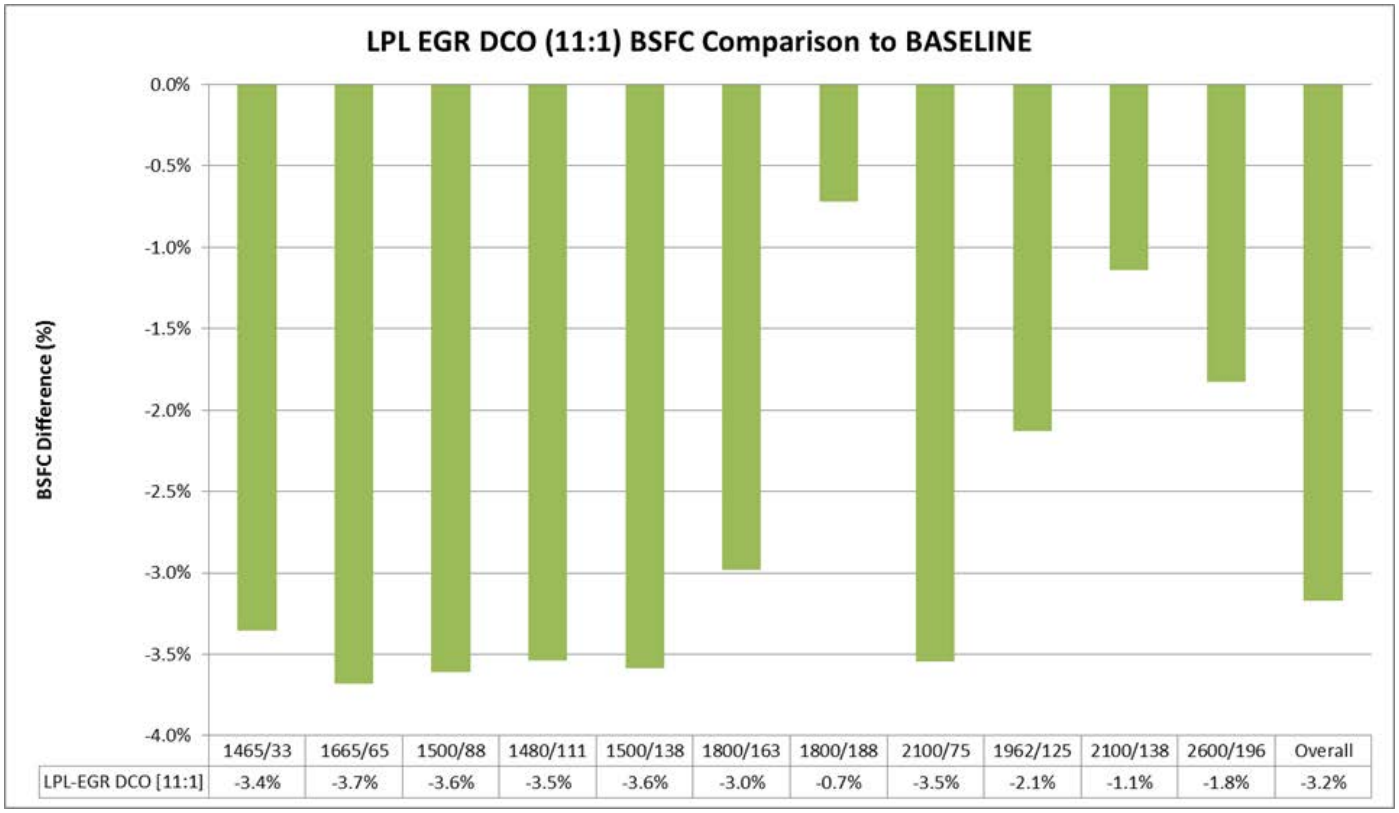
Phase 3 "Conventional" Low Pressure Loop (LPL) EGR System/DCO$_{TM}$ engine dynamometer testing completed and fuel efficiency established at 11 engine speed – load test points …

- Design, Engine Build, and Testing has been completed applying 11:1 Compression Ratio, DCO$_{TM}$ Ignition system and conventional LPL EGR system to current production GM turbocharged engine packaged in a current mid-size vehicle



TECHNICAL ACCOMPLISHMENTS and PROGRESS

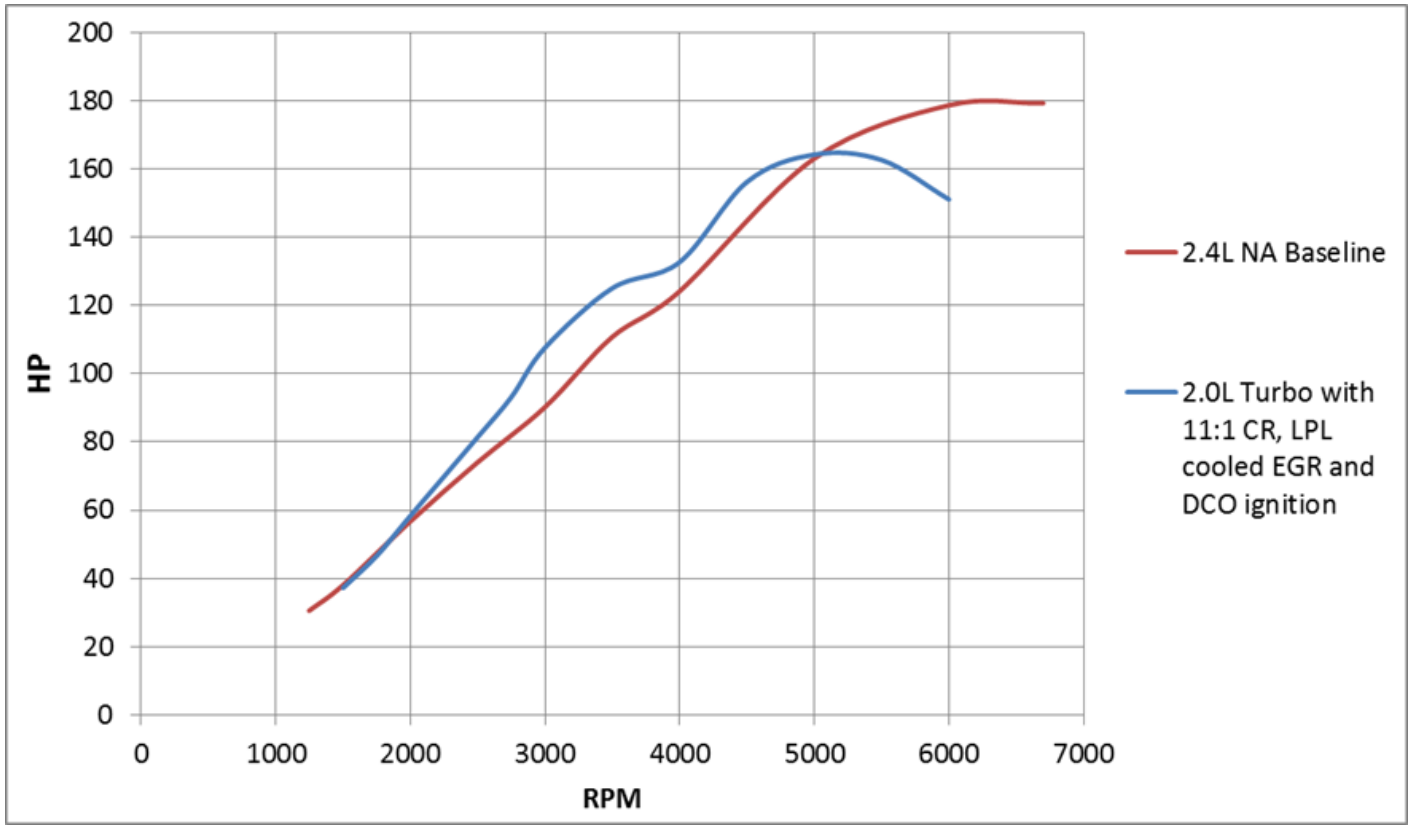
The fuel consumption results are shown graphically below:



	1465/33	1665/65	1500/88	1480/111	1500/138	1800/163	1800/188	2100/75	1962/125	2100/138	2600/196	Overall
LPL-EGR DCO [11:1]	-3.4%	-3.7%	-3.6%	-3.5%	-3.6%	-3.0%	-0.7%	-3.5%	-2.1%	-1.1%	-1.8%	-3.2%

TECHNICAL ACCOMPLISHMENTS and PROGRESS

The power results with 20%+ EGR dilution are shown graphically below:



TECHNICAL ACCOMPLISHMENTS and PROGRESS

Phase 4 Dedicated EGR & Enabling Technology System Status …

- Design and build of a turbocharged GM 4-cylinder engine has been completed incorporating:
  - ✓ 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
  - ✓ D-EGR™ bypass valve

TECHNICAL ACCOMPLISHMENTS and PROGRESS

Phase 4 Dedicated EGR & Enabling Technology System Status …

- *Testing of the updated Phase 4 2.0L turbocharged engine has begun. Testing is scheduled to be completed by the end of the 4th quarter 2014.*

COLLABORATION and COORDINATION

Southwest Research Institute® – Sole Subcontractor

- Primary Responsibility
  - Ignition and EGR system Expertise
  - Engine Testing

FUTURE WORK

Milestone	Completion Date
Results of design, testing, development, and analysis of novel enabling technologies applied to GM 4-cylinder engine designed to optimize the application of dedicated EGR (**Phase 4**)	4Q14

FY 2014 …

Complete testing of turbocharged GM 4-cylinder engine designed for optimization with dedicated EGR, dilution bypass valve, 12.0:1 CR, low S/V ratio, **2 spark plug/cylinder combustion system**, enhanced charge motion, GDI + PFI fuel system and a variable geometry turbocharger.

- *Compare performance and fuel consumption to baseline naturally aspirated 4-cylinder engine.*
- *Update simulation models as required to improve predictions for future work.*

Complete design and acquisition of hardware to update a Phase 4 turbocharged GM 4-cylinder engine with an alternate combustion system (**Phase 5**).

FUTURE WORK

Milestone	Completion Date
Final results of design, testing, development, and analysis of selected novel enabling technologies applied to GM 4-cylinder engine (**Phase 5**)	2Q15

FY 2015 …

Complete testing of turbocharged GM 4-cylinder engine designed for optimization with dedicated EGR, dilution bypass valve, 12.0:1 CR, low S/V ratio, **1 spark plug/cylinder combustion system**, enhanced charge motion, GDI + PFI fuel system and a variable geometry turbocharger.

- *Compare performance and fuel consumption to baseline naturally aspirated 4-cylinder engine.*

SUMMARY

- **The project defines enabling technologies that enable the use of advanced EGR dilution on a mass market basis to address national energy concerns**
  - *The technologies defined have a clear path to commercialization*
- **Vehicle Simulation (baseline engine in mid-size GM vehicle) is complete**
  - *11 engine speed – load points identified that represent ~95% of the fuel energy used during FTP City/Hwy/US06 cycles*
- **Initial engine simulation complete at 11 engine speed-load points**
  - Baseline Engine
  - Phase 3 “Conventional” LPL EGR dilution with high energy ignition
  - Phase 4 Advanced dilution with key enabling technologies
- **Baseline 2.4L NA engine dynamometer testing is complete and fuel efficiency baseline has been established at 11 engine speed – load test points**

SUMMARY

- **The Phase 3 GM 2.0L turbocharged engine updated to 11.0:1 compression ratio, high energy ignition system, and cooled LPL EGR hardware has been tested for fuel efficiency and power.**
  - *Fuel efficiency was improved by a weighted average of 3.2% over the baseline*
  - *Peak power was reduced from 180 to 165*
  - *Torque was improved at low engine speeds*
- **The Phase 4 2.0L turbocharged engine design and build was completed by the end of the 4th quarter 2013.**
- **Testing of the updated Phase 4 2.0L turbocharged engine has begun. Testing is scheduled to be completed by the end of the 4th quarter 2014.**