

Development of the Combustion System for General Motors' High-Efficiency Range Extender Ecotec Small Gas Engine

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ABSTRACT

General Motors has developed an all-new Ecotec 1.5 L range extender engine for use in the 2016 next generation Voltec propulsion system. This engine is part of a new Ecotec family of small displacement gasoline engines introduced in the 2015 model year. Major enhancements over the range extender engine in the current generation Voltec propulsion system include the adoption of direct injection (DI), cooled external exhaust gas recirculation (EGR), and a high 12.5:1 geometric compression ratio (CR). Additional enhancements include the adoption of high-authority phasers on both the intake and exhaust camshafts, and an integrated exhaust manifold (IEM).

The combination of DI with cooled EGR has enabled significant thermal efficiency gains over the 1.4 L range extender engine in the current generation Voltec propulsion system at high engine loads. The addition of a high geometric CR and high-authority camshaft phasers for extended late intake valve closing (LIVC) operation has enabled improved low- and mid-load engine efficiency. The combination of DI and high-authority camshaft phasers has minimized the full-load engine torque loss inherent with traditional high CR and LIVC implementations.

The combustion system was developed with extensive use of computational fluid dynamics (CFD) simulation for optimization of in-cylinder mixing and combustion. These tools aided in the sorting and selection of the combustion chamber, ports, piston, and fuel injector. Extensive single- and multi-cylinder engine testing and development was also employed to refine and optimize the engine combustion system.

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INTRODUCTION

With vehicle fuel economy standards becoming more stringent - in the United States and globally - there has been increased focus across the industry on reducing vehicle fuel consumption. This has led to a focus on improving internal combustion engine efficiency [1]. Engines used in hybrid electric vehicles, or as range extenders in electric vehicles, place a high priority on peak engine efficiency [2,3,4,5]. These engines are typically optimized to work synergistically with the specific hybrid electric propulsion system with which they are paired.

Several original equipment manufacturers have implemented variants of production engines tailored to their hybrid electric vehicle application over the past decade [2,3,4,5]. These engines have typically employed an LIVC strategy combined with a high

geometric compression ratio for improved engine efficiency. Collectively, this combination is often referred to as an "Atkinson cycle." This strategy improves efficiency by reducing engine pumping losses and increasing the engine expansion ratio at the expense of some loss in specific power and torque. The torque loss is generally greatest at low engine speeds due to the use of a long duration intake camshaft profile [2,3,4,5]. These engines typically employ port fuel injection (PFI) and fixed exhaust cam timing, which further limits the specific output of the engine.

Externally routed exhaust gas recirculation has been an area of renewed study as the industry pushes towards improved fuel efficiency [6,7,8,9,10]. EGR improves engine efficiency by reducing in-cylinder heat loss, reducing engine pumping loss, and improving the ratio of specific heat of the unburned mixture. At higher engine loads, where engine efficiency is limited by knock and retarded

combustion phasing, the addition of an external cooler to reduce EGR temperature helps further improve efficiency by reducing engine knock [6,7,8,9,10]. For this reason, EGR has previously been employed in hybrid-optimized engines to further improve engine efficiency [2,3,4,5]. Hybrid systems enable the engine to run near their peak efficiency for a given engine power requirement, which shifts engine operation to lower speeds and higher loads and, hence, more knock-limited operation. This, combined with the high geometric CR of the usual LIVC implementation, makes EGR a synergistic technology for improving hybrid engine fuel efficiency [2,3,4,5].

Due to the time required to evacuate EGR from the intake system, external EGR poses challenges with quick engine transient response. Hybrid applications are uniquely suited to compensate for this limitation as the electric propulsion system is capable of providing or absorbing additional power to smooth the transient operation of the engine [2,3,4,5].

ECOTEC 1.5 L L-4 ENGINE OVERVIEW

Introduction and Specifications

The new General Motors' Ecotec family of small displacement gasoline engines includes 3- and 4-cylinder engines being launched globally [11]. The engine family includes naturally-aspirated and turbocharged engine variants, with either PFI or DI with centrally located injectors. All engines in the family include:

- All-aluminum construction for reduced mass
- Dual, high-authority camshaft phasers to balance fuel efficiency, emissions, and power over the engine's operating range
- An off-axis oil pump for reduced friction
- An integrated exhaust manifold for reduced engine-out exhaust gas temperatures and reduced high-load fuel enrichment
- An electric thermostat on DI engine applications

The 1.5 L range-extender engine was optimized for use in the next generation Voltec propulsion system in the Chevrolet Volt. Cooled external EGR, a higher geometric compression ratio of 12.5:1, a close-coupled, split-volume, common can (SVCC) catalytic converter for improved engine warm-up, and a combustion system design optimized for the Voltec propulsion system, including unique camshaft park positions, are enhancements that are specific to the 1.5 L range extender engine. The engine specifications are given in [Table 1](#), and the engine technologies are shown in [Figure 1](#), with range extender specific technologies outlined with a border.

Table 1. Ecotec 1.5 L range extender engine specifications.

Displacement	1490 cc
Stroke	86.6 mm
Bore	74 mm
Connecting Rod Length	128.8 mm
Compression Ratio	12.5:1
Bore / Stroke Ratio	0.85
Number of Valves per Cylinder	4
Lashed Intake Cam Duration	249 crank degrees
Lashed Exhaust Cam Duration	258 crank degrees
Intake Camshaft Phaser Authority	65 crank degrees
Exhaust Camshaft Phaser Authority	65 crank degrees

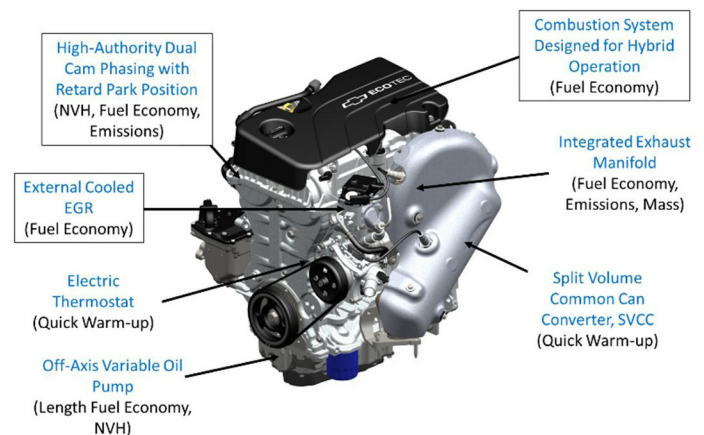


Figure 1. Key technologies applied to the new 1.5 L Ecotec range extender engine.

Combustion System Design Details

Development Process

The combustion system was developed using the GM combustion system development process. This process includes a comprehensive suite of analytical and experimental tools used to develop and sort combustion system alternatives, then refine the chosen combustion system concept. These tools include:

- Parametric design tools
- Steady-state airflow assessment:
 - 3-dimensional (3D) Computation Fluid Dynamics analysis
 - Airflow bench testing
- 1-dimensional (1D) engine cycle simulation
- Geometric flame propagation analysis
- 3D mixing and combustion analysis
- Single- and multi-cylinder combustion testing
- Vehicle-level performance and fuel economy analysis

There is an extensive interaction between these tools to enable development and refinement of the system, as is diagrammatically shown in [Figure 2](#).

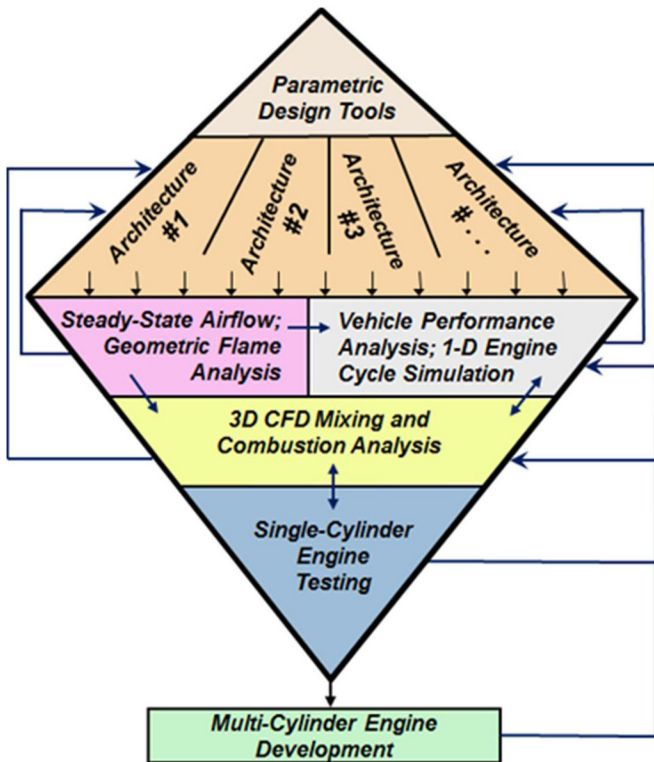


Figure 2. GM Combustion system development process.

This process has been presented in detail in previous publications, and, as such, is only summarized in this paper [12,13,14].

Combustion System Design

The new Ecotec 1.5 L range extender engine for the Voltec propulsion system employs a 4-valve combustion system with centrally located direct injection. Details of the combustion system layout are given in Table 2.

Table 2. Combustion system specifications.

Intake Valve Size	28 mm
Intake Valve Angle	20°
Exhaust Valve Size	23.3 mm
Exhaust Valve Angle	18.5°
Spark Plug	M12
Spark Plug Angle	22°
Injector	6-hole solenoid injector
Injector Angle	6°

The injector and spark plug share space in the cylinder center, in a longitudinal layout, as shown in Figure 3. The piston topology is shown in Figure 4. The piston bowl was developed to enable spray-guided direct injection to improve combustion system performance and robustness for catalytic converter light-off. This piston design is unique to the hybrid application because of the high 12.5:1 geometric compression ratio. The intake and exhaust valve angles and port trajectories are shown in Figure 5. The valve angles

are common across the engine family, and were optimized for port flow and mixture motion generation within the packaging constraints of the engine. The combustion system for the range extender engine was optimized to achieve the engine power targets, and to also be dilution tolerant to enable the inclusion of external EGR.

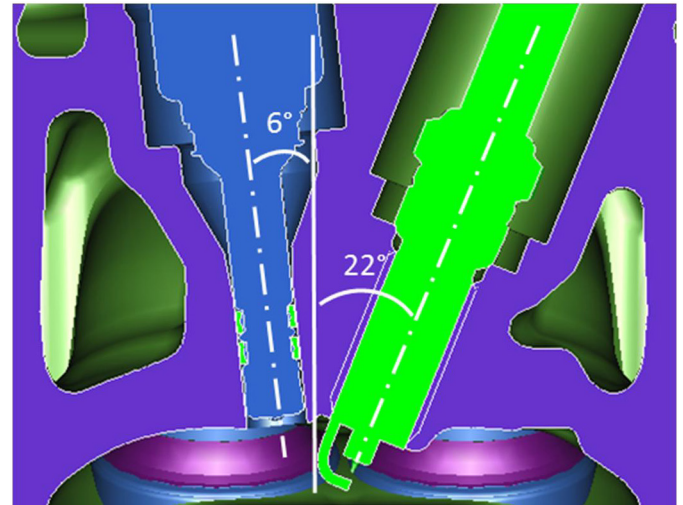


Figure 3. Fuel injector and spark plug orientation.



Figure 4. 12.5:1 CR piston topology.

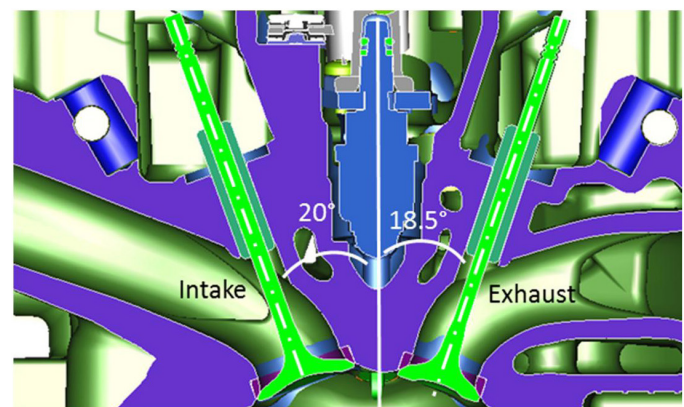


Figure 5. Engine valve layout.

Cooled External EGR System Design

Cooled external EGR was implemented to improve engine efficiency for the range extender engine combustion system. The system extracts exhaust gas upstream of the catalytic converter and downstream of the IEM outlet, passes the gas through a butterfly style EGR valve, then through an external EGR cooler, and into the intake manifold downstream of the throttle. The EGR cooler utilizes engine coolant as the heat exchange fluid. The system is shown in detail in [Figure 6](#), and in position on the engine in [Figures 7](#) and [8](#).

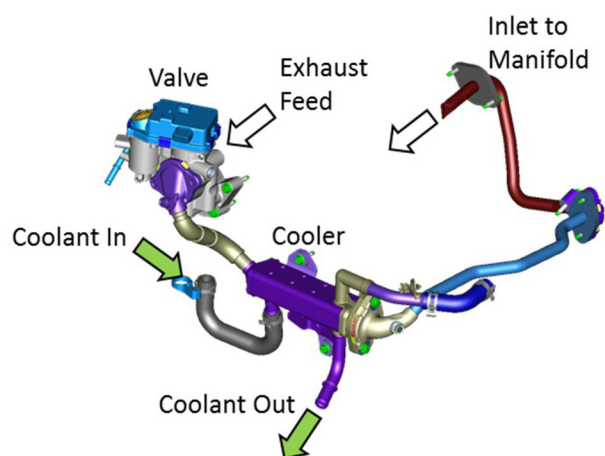


Figure 6. EGR system.

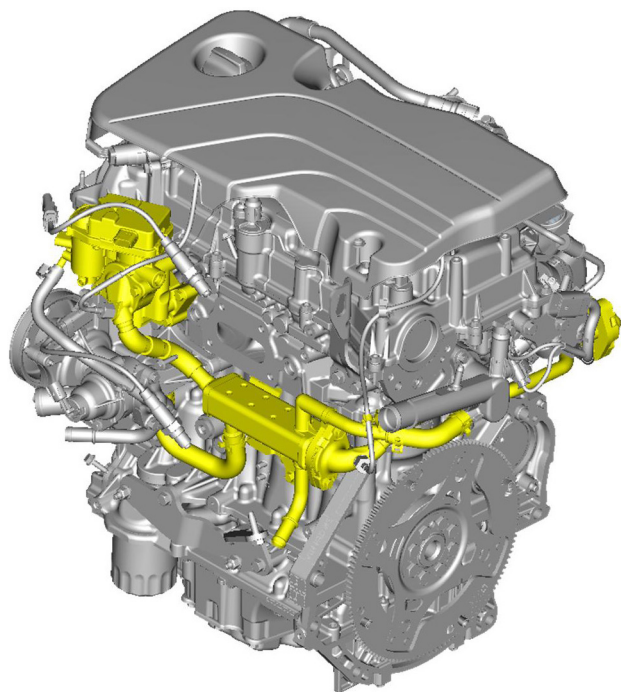


Figure 7. EGR system on engine as viewed from exhaust side.

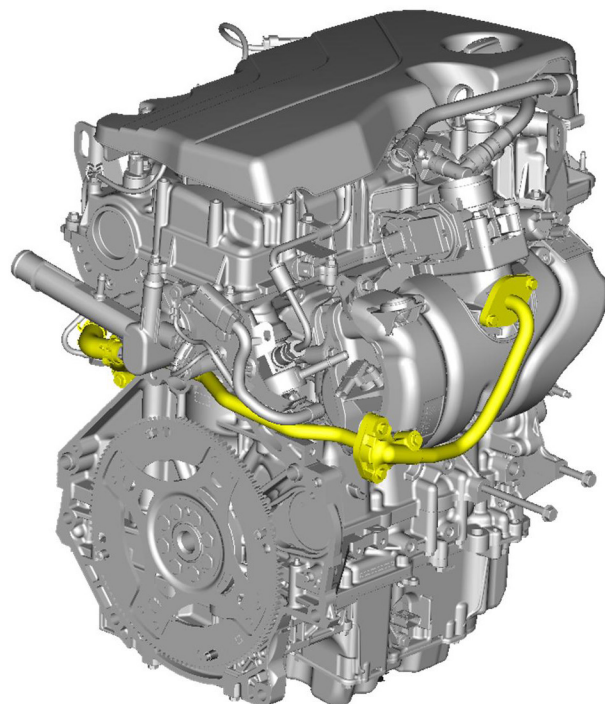


Figure 8. EGR system on engine as viewed from intake side.

Engine coolant for the EGR cooler is extracted from the engine just downstream of the water pump, prior to entering the engine, to minimize the coolant temperature used by the EGR cooler to cool exhaust gas. The cooled gas is introduced into the intake air stream in the intake manifold just downstream of the throttle body. A key goal in designing the system was to minimize pressure losses in order to maximize the amount of EGR available for introduction into the intake manifold under high load when manifold air pressure (MAP) is high. The injection point of the exhaust gas into the intake manifold is shown in [Figure 9](#).

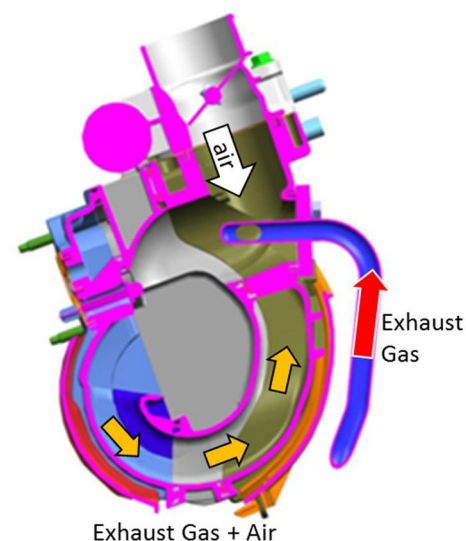


Figure 9. Exhaust gas introduction into intake manifold.

The EGR introduction point in the intake manifold and the design of the intake manifold itself were optimized to ensure uniform EGR distribution cylinder-to-cylinder.

EXTERNAL EGR SYSTEM OPTIMIZATION

Extensive analytical development of the intake manifold and EGR delivery system was performed to ensure acceptable mixing of the fresh intake air and external EGR. To verify the analytic predictions of external EGR distribution, empirical hardware testing was also undertaken. Sampling individual cylinder external EGR too close to the intake valves can give erroneously high measurements due to rebreathing of internal EGR (residual remaining in-cylinder from the previous engine cycle) into the intake port. Sampling individual cylinder external EGR too close to the intake plenum can also give incorrect measurements due to intake runner cross-talk. To avoid these difficulties in measuring individual cylinder external EGR percentage directly, a comparison of individual cylinder bulk mass fraction burn durations (10-75 percent) was used as a surrogate to direct EGR measurement to determine good versus poor external EGR distribution. Bulk burn duration will increase / decrease with increasing / decreasing in-cylinder dilution. It should be noted that the external EGR rate is not the sole determining factor for burn durations, which can also be influenced by equivalence ratio, homogeneity, turbulence intensity, and flow orientation at the plug among other factors. Nonetheless, changes in 10-75 percent burn durations were attributed to changes in external EGR percentage for each cylinder as the burn duration differences were observed to decrease as the EGR system was optimized for improved distribution. Thus, good external EGR distribution was signified by closely matching individual cylinder 10-75 percent burn durations, while poor external EGR distribution was signified by largely separated 10-75 percent burn durations.

External EGR imbalance directly impacts engine fuel efficiency.

- Engine spark advance, which is constant for all cylinders, is limited by the cylinder with the lowest knock tolerance and least amount of external EGR
- The remaining cylinders with higher external EGR amounts will display further retarded combustion phasing as a result of excessive EGR, lengthening burn durations

These compounding effects of external EGR imbalance combine to significantly reduce the realizable engine efficiency gains as a result of flowing external EGR. The CFD analysis results for a preliminary design of the intake manifold with high cylinder-to-cylinder EGR imbalance are shown in Figure 10, and the resulting measured burn durations are shown in Figure 11. A relatively high level of EGR imbalance was predicted by CFD, and a correspondingly large variation in engine burn rates was also measured.

The intake manifold design and EGR introduction location was subsequently optimized to minimize the EGR imbalance. The resultant design is shown in Figure 12. External EGR is introduced downstream of the throttle body. The introductory pipe is capped with two passages on opposing sides to direct the external EGR out

laterally to all cylinders. The throttle body and plenum are joined by a zip-tube, rather than an open volume, to direct the incoming airflow to better mix the fresh intake air and external EGR.

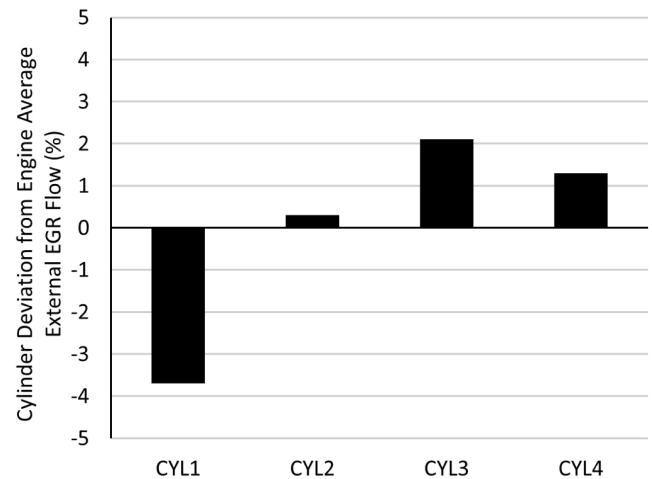


Figure 10. Analytical prediction of external EGR imbalance of a preliminary manifold design.

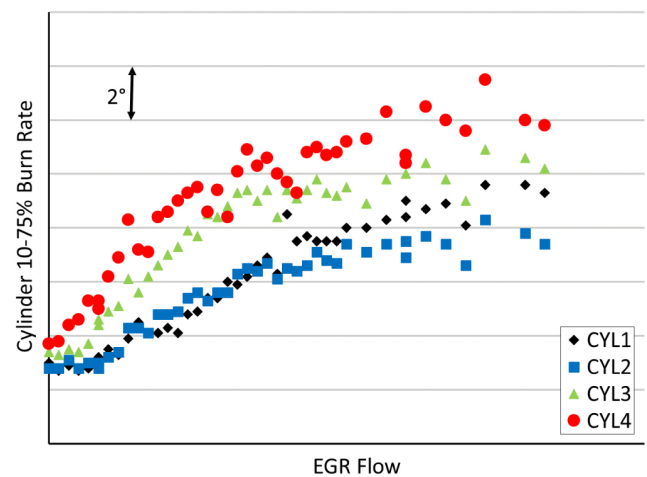


Figure 11. Impact of poor EGR balance on cylinder combustion burn rates of a preliminary manifold design.

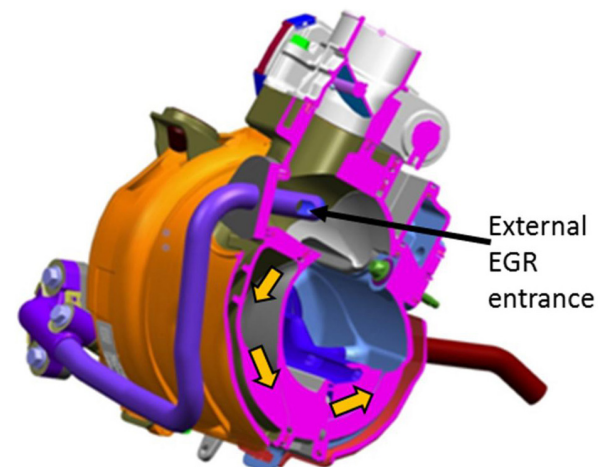


Figure 12. Final optimized intake manifold design