

Development of the Combustion System for General Motors' 3.6L DOHC 4V V6 Engine with Direct Injection

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ABSTRACT

General Motors' 3.6L DOHC 4V V6 engine has been upgraded to provide substantial improvements in performance, fuel economy, and emissions for the 2008 model year Cadillac CTS and STS. The fundamental change was a switch from traditional manifold-port fuel injection (MPFI) to spark ignition direct injection (SIDI). Additional modifications include enhanced cylinder head and intake manifold air flow capacities, optimized camshaft profiles, and increased compression ratio.

The SIDI fuel system presented the greatest opportunities for system development and optimization in order to maximize improvements in performance, fuel economy, and emissions. In particular, the injector flow rate, orifice geometry, and spray pattern were selected to provide the optimum balance of high power and torque, low fuel consumption, stable combustion, low smoke emissions, and robust tolerance to injector plugging. In concert with the injector selection, the intake port, combustion chamber, and piston bowl were designed for strong cold-start capabilities with low engine out HC emissions and quick warm-up of the catalytic converters.

The system development and optimization was facilitated by extensive use of computational fluid dynamics (CFD) for analysis of fuel sprays and their interaction with the piston bowl to achieve the desired mixture formation. The cold-start performance was further optimized through use of extensive cold-start buggy testing and analysis of designed experiment data. This paper details the analytical and empirical work done to optimize the SIDI fuel injector and the combustion system.

INTRODUCTION

Most modern spark ignition (SI) engines, typically operated on gasoline, use one of two main fuel injection technologies present in the market. The standard MPFI system employs low-pressure, generally around 0.4 MPa, supplied directly by an in-tank, electric fuel pump. Individual cylinder fuel injectors deliver a liquid spray into the intake ports, upstream of the intake valves. In contrast, the high-pressure SIDI fuel system consists of an additional, mechanically driven fuel pump which boosts fuel pressure to the range of 3 to 20 MPa. The fuel injectors are relocated to inject the fuel directly into the combustion chamber. The high pressure results in improved mixture preparation.

As early as the 1920's, research was being conducted on SIDI combustion systems. Limitations of carburetors such as the difficulty of achieving balanced distribution of fuel from cylinder-to-cylinder with a "wet" intake manifold provided many of the incentives for the earliest SIDI research. MPFI fuel systems, though, have managed to address this issue successfully.

The other main motivation for SIDI development has been efficiency. Pumping losses significantly limit SI engine efficiency when operated at a part-load, throttled condition. One means to reduce these pumping losses is to operate the engine with high levels of dilution such as excess air or residual exhaust gases. With a typical MPFI engine, the amount of dilution is limited by the ability of the mixture to support robust combustion. The dilution tolerance can be increased by running the engine in a stratified mode where a combustible air and fuel mixture is concentrated in a local volume around the vicinity of the spark plug and the remaining portions of

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the cylinder are filled with diluent. Direct injection is a key enabling technology for stratified operation.

In stratified mode, the fuel is generally injected during the latter part of the compression event after the intake valves are closed. The fuel is directed to the desired location within the combustion chamber by one of several methods. In “wall guided” systems the combustion chamber geometry is used to direct the fuel spray. In other applications, some combination of the fuel injector spray characteristics (spray guided) and the in-cylinder charge motion (air guided) are used. The relative importance of the spray characteristics and charge motion depend on the specific engine speed and operating condition.

Stratified operation, especially with modern, high-speed, electronic engine controls, has been shown to provide significant improvements in part-load engine efficiency. A number of issues such as difficulty meeting stringent NOx emissions standards have precluded wide-spread use, particularly in North America. Operation in a stratified mode over wide ranges of engine speed and load tends to require higher levels of calibration and controls investment due the critical relationship between fuel injection and spark timing. Additionally, the combustion system features required to support robust stratified operation, such as relatively deep piston bowls, can reduce full-load engine output [1].

Most recent applications of SIDI, especially in the North American market, are homogeneous charge systems. Homogeneous SIDI - the technology selected for the GM 3.6L DOHC V6 - provides a moderate improvement in fuel economy while simultaneously increasing torque and power and enabling reduced emissions. Vaporization of injected fuel within the combustion chamber provides an effective measure of charge cooling, increasing charge density and improving volumetric efficiency. In addition, the cooler charge and lower residence time of the fuel at higher temperatures enables higher geometric compression ratios for improved thermal efficiency.

Achieving these gains requires a flexible set of cost efficient SIDI components. Adaptable high pressure injectors and pumps represent the centerpiece of this component set [2]. Applicability of these components for diverse combustion methods and packaging situations is rounded off by an electronic control unit with increased computing power. This capability renders possible their application on homogeneous and stratified naturally aspirated engines as well as on turbocharged engines [3] and even on SULEV and PZEV projects [4]. Direct injection represents the ideal basis for the further development of existing or new combustion methods such as further development of spray guided combustion, further downsizing of gasoline engines and development of new combustion methods such as

controlled auto-ignition (CAI) / homogeneous charge compression ignition (HCCI).

GM 3.6L DOHC V6 ENGINE OVERVIEW

INTRODUCTION

The GM 3.6L DOHC V6 engine is part of a family of 4V DOHC V6 engines introduced in the 2004 model year in the first generation Cadillac CTS. The engine family includes displacements of 2.8L, 3.2L, and 3.6L with both normally aspirated and turbocharged variants. All share a 60 degree bank angle.

UPGRADE SUMMARY

Development goals for the engine upgrade, relative to its MPFI predecessor, included increased torque and power, improved fuel economy, and the ability to meet future emissions standards without additional, complex aftertreatment systems.

Initial versions of the GM 3.6L DOHC V6 engine with direct injection are normally aspirated and feature side-mounted, solenoid injectors. While architected to operate predominately in homogeneous mode, a shallow piston bowl feature enables partially stratified operation under certain conditions as described later in this paper.

Table 1 shows the basic specifications for the GM 3.6L DOHC V6 engine with direct injection. The engine maintains the same basic engine architecture as the base MPFI engine – including bore, stroke, intake and exhaust valve diameters and valve angles.

Table 1 – GM 3.6L DOHC V6 engine with direct injection specifications

Displacement	3564 cc
Bore	94.0 mm
Stroke	85.6 mm
Compression Ratio	11.3:1
Intake Valve Diameter	37.0 mm
Exhaust Valve Diameter	30.6 mm

A cutaway view of the new SIDI engine is shown in Figure 1. The drawing represents the engine as used in the 2008 Cadillac CTS.

As noted, the fundamental engine change was a switch from traditional MPFI to SIDI fueling. The SIDI injectors are located under the intake ports and inject the fuel from the side of the combustion chamber as shown in Figure 2. This choice of architecture provided the ability to maintain commonality with the base, MPFI cylinder

head and valvetrain in key areas for component sharing and manufacturing flexibility. Valve angles, locations and diameters are carried over as is the intake camshaft lift profile. The exhaust cam profile was redesigned to optimize full-load performance and part-load fuel economy for the SIDI engine upgrade. The exhaust camshaft on one bank was extended to provide an additional, three lobe profile to drive the high-pressure, direct-injection fuel pump. The pump is mounted to cylinder head and actuated via a hydraulic roller follower.

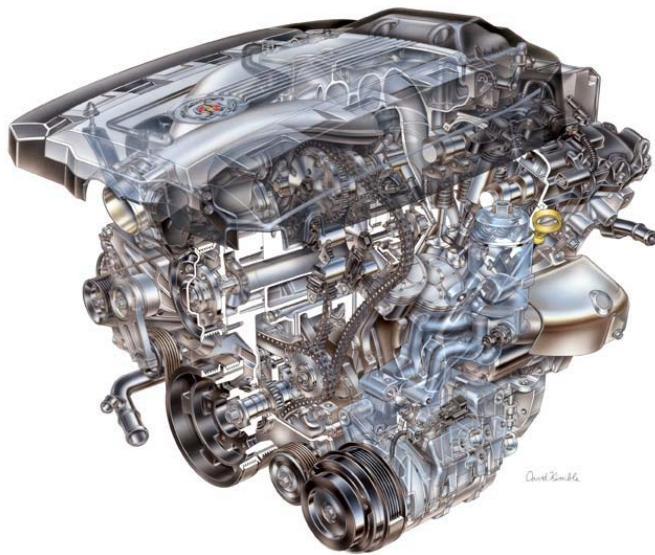


Figure 1: General Motors' 3.6L DOHC 4V V6 Engine with Direct Injection

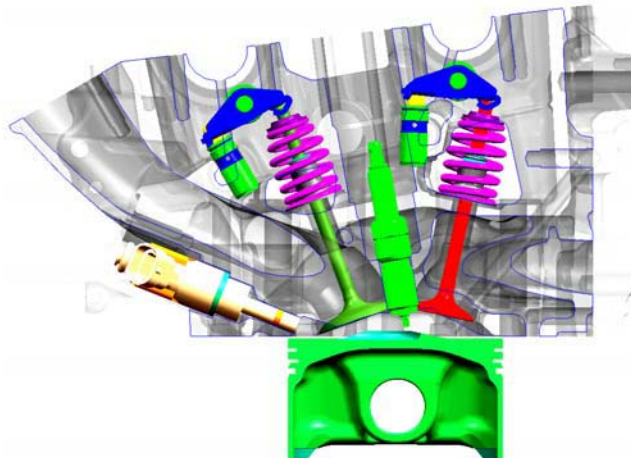


Figure 2: Cross-section view of combustion system

The intake ports, shown in Figure 2, were changed from the MPFI variant. Modifications were made to the port location within the cylinder head to provide clearance for the SIDI fuel injectors and rails. Within the existing packaging constraints the port shape and cross-sectional area was optimized through a combination of physical air flow bench testing and CFD analysis.

Additional design freedom was allowed in the region of the intake port to intake manifold interface due to the removal of the MPFI fuel injectors. Goals of the optimization were to minimize airflow restriction while still providing the charge motion characteristics required to enable homogeneous mixture formation and desirable flame propagation and combustion characteristics.

Figure 3 shows the combustion chamber which was modified from the base MPFI version. A pocket was added on the intake side of the chamber to accommodate the SIDI fuel injector. The combustion chamber volume was adjusted – along with the piston – to enable a compression ratio increase from 10.2:1 for the MPFI baseline to 11.3:1 for the SIDI upgrade.

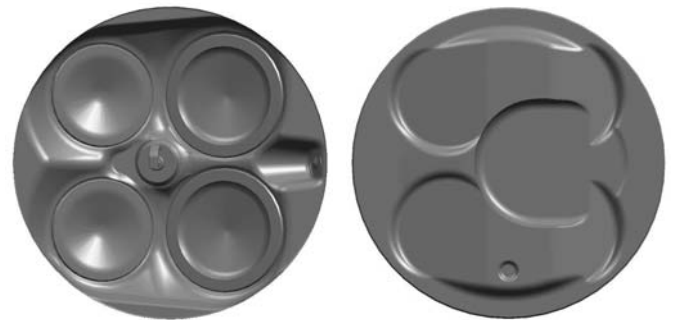


Figure 3: Combustion chamber showing location of DI injector (left); Piston with mild bowl to support partially-stratified operation (right)

As noted above, one of the goals of the intake port optimization was to provide homogeneous mixing. While SIDI is an enabler for increased volumetric efficiency, the air and fuel must be well mixed in order to fully utilize the extra oxygen and realize a benefit in terms of increased engine output. This mixing can be especially challenging at high engine speeds and loads due, in part, to the high fuel mass and short time scale available for vaporization and mixing. Through dynamometer testing and detailed CFD analysis the combustion chamber shape - especially in the areas controlling intake valve flow and shrouding - and the fuel injector characteristics were developed in concert with the intake port design discussed earlier. The resulting combustion system achieves high levels of oxygen utilization at full load without sacrificing flow capacity and volumetric efficiency.

In normal operation the GM 3.6L DOHC V6 engine with direct injection operates with a homogeneous air / fuel mixture. Under certain operating conditions – specifically the period immediately following engine start when the catalytic converter is below normal operating temperature – the engine is run in a “partially stratified” mode. In this mode the bulk of the fuel is injected during the intake stroke to create a homogeneous but overall lean mixture in the entire cylinder. The remaining mixture is injected during the latter part of the

compression stroke. The SIDI piston, shown in the right hand side of Figure 3, incorporates a shallow piston “bowl” feature to direct this fuel and create a locally rich mixture in the vicinity of the spark plug gap. This rich mixture promotes a strong ignition and flame initiation event for robust combustion even with significantly retarded combustion phasing. Optimization of the piston bowl design is covered in a later section of this paper.

The SIDI engine upgrade utilizes the same exhaust ports and manifolds as the base MPFI variant. The intake manifold is unique to accommodate the SIDI fuel system and vehicle packaging constraints. The MPFI intake manifold incorporates an intake manifold tuning valve (IMTV) which effectively splits the intake manifold into two separate plenums for enhanced tuning at low engine speeds. The SIDI intake manifold is a passive design with a single, open plenum. Both variants of the engine utilize hydraulic camshaft phasers for independently variable valve timing for both intake and exhaust.

PERFORMANCE COMPARISONS

Both the original MPFI (base) and the newly upgraded SIDI (optional) variants of the engine are offered in the 2008 model year Cadillac CTS. Both engines utilize common exhaust and induction systems with identical flow restrictions and are designed and calibrated to use regular grade unleaded gasoline.

Table 2 compares the peak WOT performance values for both variants of the engine as measured during SAE certified witness testing. The SIDI engine generates approximately 15% greater peak power and 8% greater peak torque than the base MPFI engine.

Table 2 – WOT performance comparison between SIDI and MPFI variants of the GM 3.6L DOHC V6; 2008 Cadillac CTS application

	SIDI	MPFI
Peak Power (kW)	227	196
Peak Power (HP)	304	263
Peak Power Speed (rpm)	6400	6400
Peak Torque (Nm)	370	343
Peak Torque (lb-ft)	273	253
Peak Torque Speed (rpm)	5200	3100

Figure 4 shows a comparison of the full torque and power curves for both variants. Note that the torque is improved even at lower engine speeds even though the SIDI variant uses a passive intake manifold.

2008 Cadillac CTS 3.6L DOHC V6

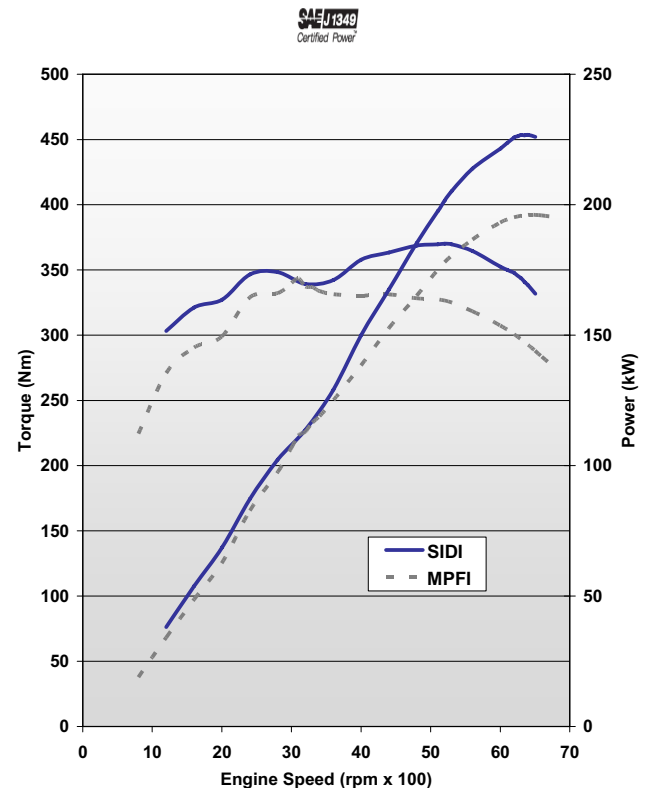


Figure 4: Power and torque curves for the GM 3.6L DOHC V6

In addition to the full-load performance gains, the SIDI upgrade provides a measurable improvement in engine brake efficiency – even after accounting for the additional parasitic loss of the high-pressure fuel pump. As noted, the SIDI engine utilizes a mild piston bowl to enable use of a split-injection, partially-stratified mode during the period following engine start when the catalyst is not up to operating temperature. The reduction in unburned HC emissions and improved catalyst warm-up enable the engine to meet all applicable emissions standards with standard 3-way catalytic converters. No additional aftertreatment devices such as secondary air injection reaction are used.

DI FUEL SYSTEM SELECTION

DI FUEL SYSTEM DESCRIPTION

The GM 3.6L DOHC V6's DI fuel system is based on components adaptable to different combustion concepts seen in the market today and in the future. The high-pressure fuel injectors and the high-pressure fuel pump have been developed as one component set. The high-pressure injector, fuel rail and pressure sensor are being assembled as a fuel rail module (Figure 5). All components are made out of stainless steel to meet world-wide fuel standards.

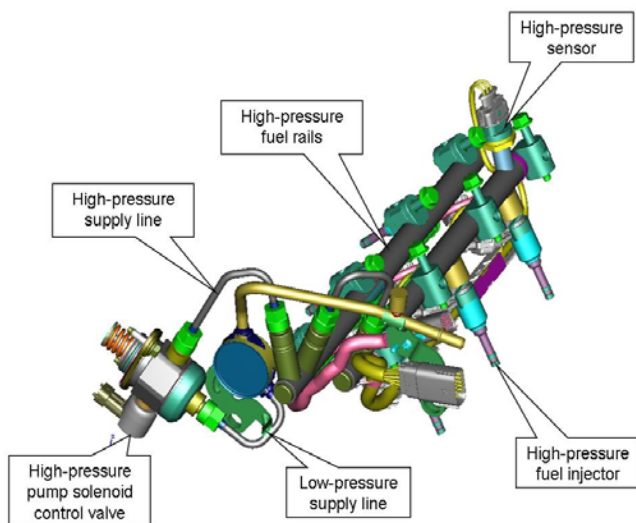


Figure 5: High Pressure fuel system

High-Pressure Injector

The central component responsible for mixture preparation and combustion quality is the high-pressure fuel injector. A second generation injector with a multi-hole (MH) design orifice plate has been applied, which allows for a much more flexible alignment and adaptation of the spray geometry parameters to individual combustion concepts. By means of spray targeting design tools, analysis, and engine validation, it is ensured that fuel wetting of inlet valves, the spark plug, the cylinder walls and the piston is minimized.

As stated previously, the fuel system operates at fuel pressures between approximately 4 and 12 MPa. System pressure can be increased to 20 MPa for spray guided engines or for concepts with high pressure turbo charging. This higher pressure range allows for a wider spread of the fuel quantities used under low and high loads and enables a finer spray quality to meet the requirements of spray guided concepts.

The mechanical design of the injector provides for maximum resistance of the nozzle to deposits. The chosen design has been validated by engine and vehicle endurance testing with a variety of fuel qualities and additives. The chosen MH injector represents a cost efficient and flexible injection system capable of adaptation to future combustion concepts.

High Pressure Fuel Pump

The high fuel pressure is generated by means of a single-cylinder, radial-piston fuel pump. The pump is attached to the side of the cylinder head and driven off an additional 3-lobe cam profile on the left bank exhaust camshaft. The pump is demand-controlled employing an integrated flow control valve. Fuel is supplied to the high-pressure fuel rail only in the amount that is required

to operate the engine at a demanded load. The power draw of the high-pressure pump is thus reduced significantly in comparison to a pressure regulated pump.

One low-pressure feed line and one high-pressure outlet connection are used for the fuel flow to and from the pump. A leakage return line to the tank is not necessary due to the sealing concept as well as the integrated variable fuel-pressure damper. Benefits of this level of integration are smaller overall system size and less weight. A cross-over fuel line connects two stainless steel fuel rails.

MULTI-HOLE VERSUS SWIRL INJECTORS

The centerpiece of this component set is an injector with a solenoid drive and a MH nozzle suited for all mounting configurations and combustion methods [5]. The first generation component design had a swirl-type spray design and was well suited for fuel economy concepts with lean burn engine operation. Spray atomization quality of swirl and MH injectors are comparable but the MH injector shows superior performance relative to back pressure resistance. The cone angle of swirl injectors can be varied within a range, whereas MH injectors allow for a very high geometric variability of the spray configuration. The MH injector spray pattern can be adjusted to any given combustion chamber geometry in an optimum manner (Figure 6).

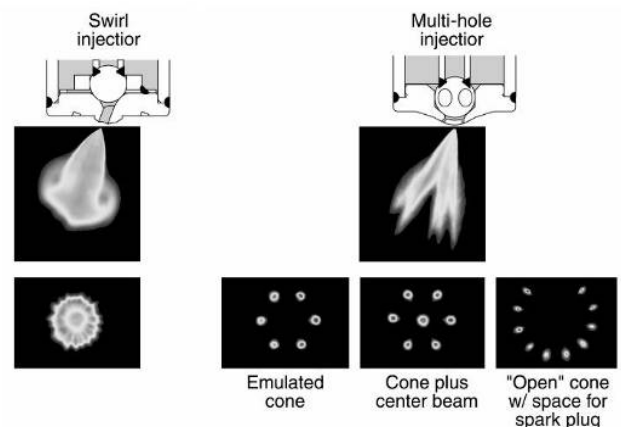


Figure 6: High pressure injectors and variability of spray geometry [2]

Choosing a spray pattern that is not symmetrical about the spray pattern centerline allows raw, engine-out emissions to be reduced drastically compared to an emulated hollow cone. In combination with control of the injection timing, spray targeting of the individual beams in a MH injectors can minimize wetting of the inlet valves, the spark plug, the cylinder walls, and the piston.