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Robert Bosch LLC

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ABSTRACT

Robert Bosch LLC North America has developed and calibrated an engine management system for gasoline direct injection engines. This system controls the General Motors 3.6L DOHC 4 valve V6 engine which features direct injection, variable valve timing and electronic throttle control. This engine powers the 2008 model year Cadillac CTS and STS. It is the first GM production direct injection V6 engine in North America. It produces 304 HP at 6500 rpm and 370 Nm torque at 5200 rpm. Emissions meet LEV2 Bin5 standards. Interesting features include wall guided direct fuel injection, homogeneous split injection for fast catalyst light off and one of the industry's first isolated injection systems for noise reduction. This paper provides an overview of the features of this system and focuses on the calibration development.

INTRODUCTION

Robert Bosch LLC North America developed a full turn-key Motronic MED9.6.1 Engine Management System (EMS) for the GM 3.6L Double Overhead Cam (DOHC) 4 valve V6 gasoline engine which features Direct Injection (DI) technology. The engine continues with Variable Valve Timing (VVT), Electronic Throttle Control (ETC) and full torque structure since initial engine introduction in the 2004 Model Year. Bosch worked in close cooperation with GM to meet and exceed the expectations and goals for the project. This engine went into production in June 2007 in the 2008 Model Year Cadillac CTS and STS.

The 3.6L is GM's first Direct Injected V6 engine in North America. Robert Bosch LLC North America also developed a full turn-key EMS for the GM 2.0L Ecotec four-cylinder DI Turbo engine in the 2007 Pontiac Solstice GXP, Saturn Sky Red Line and Opel GT. Bosch direct injection is also used since 2003 on an Opel 2.2L Ecotec engine and since 2005 on a GM supplied Alpha Romeo 3.2L V6 engine.

With direct injection, torque can be increased with the same or reduced fuel consumption as compared to a conventional Port Fuel Injection (PFI) combustion system. By injecting fuel directly into the cylinder the charge is cooled due to vaporization of the fuel, charge density is increased and volumetric efficiency is improved. In addition, the cooler charge and lower residence time of the fuel at higher temperatures enables higher compression ratios for improved thermal efficiency. Typically the compression ratio (CR) for a DI engine can be selected about one point higher than for a PFI engine. In the case of this DI engine the CR has been increased to 11.3:1 from 10.2:1 for the PFI baseline engine [1]. Another enhancement for improved emissions is stable combustion at extremely retarded ignition angles through the introduction of a second stratified injection. This is known as Homogenous Split Injection (HSP) [2, 3]. The second stratified injection enables a steep temperature gradient in the exhaust system and fast catalyst light-off. These DI features allow this package to meet LEV2 Bin5 emissions standards without using external EGR or secondary air injection and using a catalyst with reduced precious metal loading and only 400 cells per square inch.

PROJECT GOALS

POWER AND TORQUE: Goals for this DI engine were 300 Horsepower and 365 Nm of torque as compared to the PFI version of the engine with 260 HP and 340 Nm of torque. Both engines use 87 octane regular fuel.

FUEL ECONOMY: Targets were 15.2 mpg City / 25.4 mpg Highway for a combined fuel economy of 24.5 mpg.

EMISSIONS: Emission levels were LEV2 Bin5. These levels were specified to be achieved without the use of secondary air injection or external EGR.

NOISE: GM required that PFI levels of engine noise be maintained. Direct mounting of the high pressure fuel pump, injectors and fuel rail on the cylinder heads of this engine made this goal a particular challenge.

ENGINE CONFIGURATION

The GM 3.6L DOHC V6 is a direct injected 4 valve engine. A cutaway view is shown in Figure 1. It retains fully independent variable intake and exhaust camshafts and ETC as introduced in the 2004 MY Cadillac CTS. Now, in the 2008 Model Year, DI allows the compression ratio to be increased to 11.3:1 from 10.2:1 in the PFI version. The increase in compression ratio is a major contributing factor to the many benefits observed. This new engine option for the CTS/STS delivers 304 horsepower (227 kW) at 6,400 rpm, which is an increase of 16% over the PFI version and 370 Nm (273 lb-ft) of torque at 5,200 rpm, which is an increase of 8% over the PFI version [1]. The power and torque curves of the DI and PFI versions of this engine are compared in Figure 2. EPA fuel economy for the 2008 CTS model is 17 mpg city and 26 mpg highway. These results were achieved with 87 octane regular fuel and exceed GM's targets by +11.8% City and +2.4% Highway. Figure 3 shows a 2008 Cadillac CTS equipped with this engine.

Figure 1: GM 3.6L DOHC V6 SIDI Engine Cutaway

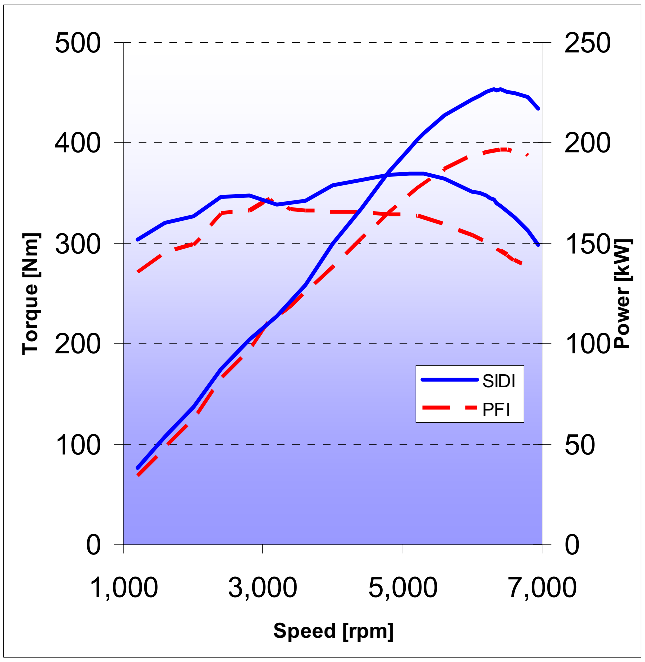


Figure 2: GM 3.6L DOHC V6 SIDI SAE Net Power and Torque Curves compared to the PFI version [1]

Figure 3: 2008 Cadillac CTS equipped with GM 3.6L DOHC V6 Engine

BOSCH MOTRONIC ENGINE MANAGEMENT SYSTEM CONFIGURATION

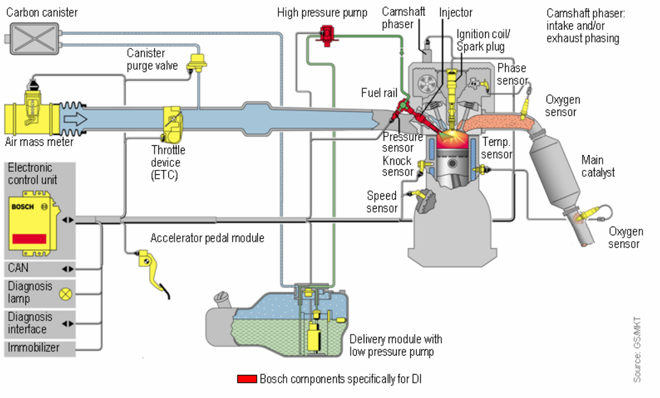
The Motronic Electronic Control Unit (ECU) used on this engine is designated MED9.6.1 (Motronic, Electronic throttle control, Direct injection). This controller uses a Printed Circuit Board (PCB) design with a Motorola Silver Oak 66MHz 32 bit microprocessor with 2 megabytes external flash memory, 32 kilobytes internal RAM, 32 kilobytes external RAM and a 1 kilobyte EEPROM. It is intended for off-engine mounting and has 154 pins in 2 connectors. One connector is focused on engine connections and the other on vehicle connections. It is a state of the art controller designed for the latest emissions and OBD II requirements and incorporates General Motor's Local Area Network (GMLAN) for intra-vehicle communication with over 20 different networked control modules distributed strategically around the vehicle. These include the transmission control module, ABS, traction control and body control modules. The ECU is shown in Figure 4.

Figure 4: Bosch Motronic MED9.6.1 Engine Control Unit

The Bosch MED9.6.1 Engine Management System (EMS) is a torque-based system that controls the throttle and the positions of the intake and exhaust camshafts based on inputs from various sensors and the pedal demand of the driver. Air fuel ratio is controlled utilizing the signals from the mass airflow sensor and switching type oxygen sensors positioned in front of and behind the close coupled three way catalytic converters. The EMS controls injection duration, injection timing, number of injections per combustion, fuel pump, fuel rail pressure and ignition timing. Knock sensors are positioned on each side of the block and are utilized to minimize knock.

Engine speed and crankshaft rotational angle are determined using a (60-2) target wheel and digital crankshaft position sensor. Camshaft phase angles are sensed with 4X quick start target wheels and digital sensors mounted on the front of each camshaft. Ignition is provided by multiple high energy coil on plug units, one per cylinder. The EMS also controls other functions such as evaporative emission canister purge control, diagnostics, component protection, cruise control, etc.

An overview of the components in the EMS is shown in Figure 5. Refer to the appendix for a larger version of this diagram.



Source: GS/MKT

Figure 5: Bosch Motronic MED9.6.1 Gasoline Direct Injection Engine Management System with Components; see appendix for enlarged copy of this figure

BOSCH DIRECT INJECTION FUEL SYSTEM COMPONENTS

The key components that enable the Bosch DI system to function are the High Pressure Pump (HDP5) with integrated Flow Control Valve (MSV), fuel Pressure Sensor (DS-HD-KV) and the 6 High Pressure Fuel Injectors (HDEV5). The high-pressure injectors, fuel rail and pressure sensor are combined as a fuel rail module as seen in Figure 6 and as mounted on the engine in Figure 7. All components are made out of stainless steel to withstand fuel requirements with particular focus on alcohol blended fuel compatibility and the demands of the underhood environment.

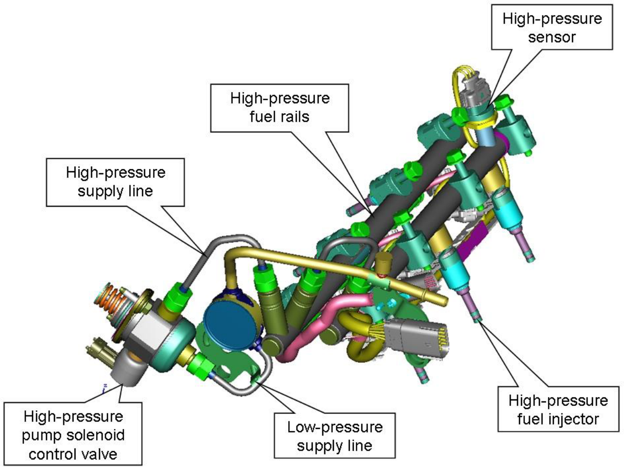


Figure 6: High Pressure Fuel System

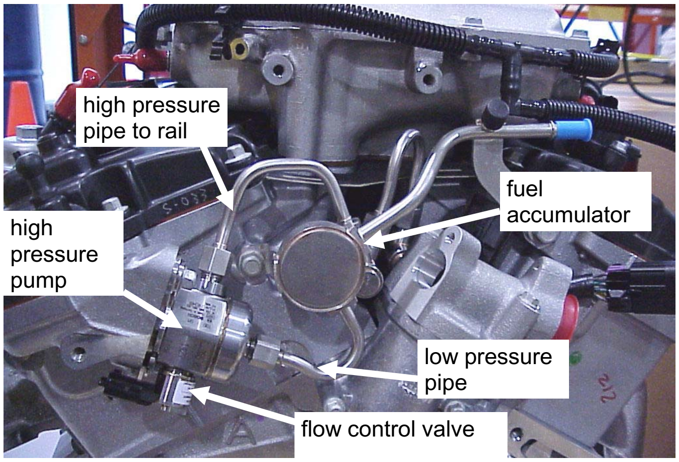


Figure 7: Bosch HDP5 High Pressure Pump and Fuel System Mounted on the Cylinder Heads of the 3.6L V6

HIGH PRESSURE PUMP

The system supplies variable fuel pressure from 3 MPa (30 bar) to 12 MPa (120 bar) depending on engine conditions. The feed pressure (inlet pressure into the high pressure pump) is 0.4 MPa (4 bar) on this engine. The compact high pressure pump, Figure 8, is driven by 3 lobes on the exhaust camshaft and can operate up to 7000 rpm engine speed. It can deliver up to 0.9 cm^3/rev. It has the potential for higher pressures up to 20 MPa.

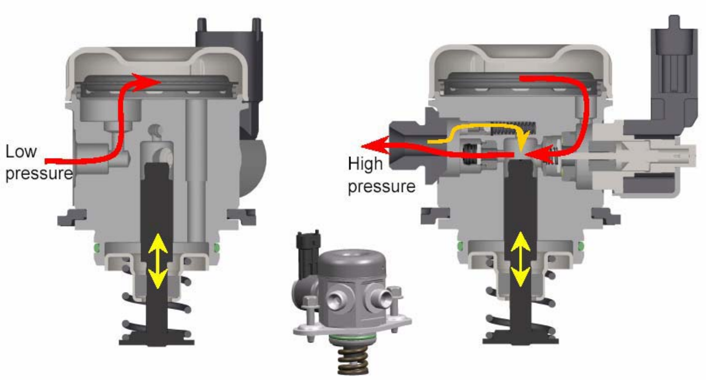


Figure 8: Bosch Motronic Direct Injection High Pressure Pump (HDP5) Showing Fuel Flow through the Pump

The demand control principle of the high pressure pump is illustrated in Figure 9. During the intake stroke and part of the delivery stroke the flow control valve is open. Based on engine operating conditions the valve closes at the appropriate time to allow only the necessary quantity of fuel to be delivered to the fuel rail which results in more efficient operation of the high pressure pump and therefore reduces energy consumed by the pump. The control is relative to the cam angle during VVT movements of the camshaft.

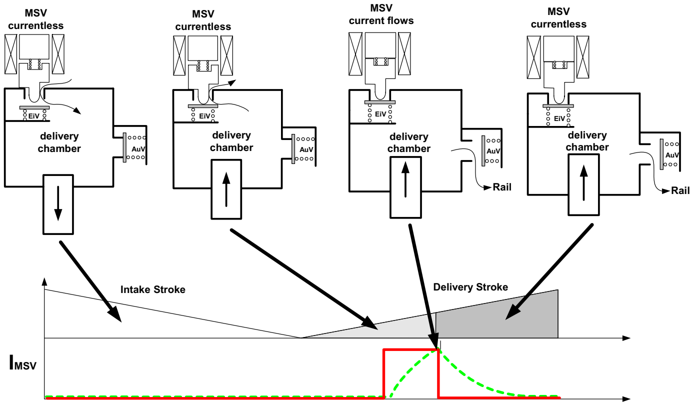


Figure 9: Bosch HDP5 Demand Control Principle

HIGH PRESSURE FUEL INJECTORS

The high pressure fuel injectors are Bosch HDEV5 as seen in Figure 10. The injectors are side mounted such that the fuel enters from the side of the combustion chamber. During HSP the fuel spray is designed to be wall-guided, which means the fuel droplets are guided by the piston bowl walls to form a rich mixture around the spark plug for the moment of ignition. The injectors use a 6 hole orifice plate design for good spray preparation and good atomization during typical operation for thorough distribution of a homogeneous fuel air mixture. The injector, piston and combustion chamber were all designed to provide desired targeting, spray pattern, atomization and also to resist deposit formation. The injector flow is linear to a minimum pulse width of 0.5 ms. End of injection timing can be controlled precisely for optimum balance of performance. More details on injector spray and combustion development are given in [1].

Figure 10 Bosch HDEV5 Direct Injection Fuel Injector

FUEL SYSTEM NOISE DEVELOPMENT

GM's goal was to achieve PFI levels of noise from the high pressure fuel system. With DI the injectors and high pressure pump are mounted directly to the cylinder heads and therefore transmit noise to the rest of the engine. The U.S. market is demanding in this regard and early system designs were not acceptable. GM and Bosch worked together to achieve noise goals. Rubber isolators and spring loaded washers were developed to isolate the fuel injectors. Additionally the fuel injectors, fuel rail and fuel pump were surrounded by noise insulating foam. The engine cover and belly panel were also designed with sound deadening material to absorb radiated noise. Fuel pump control software was modified to minimize the energy to drive the pump and reduce the action of the pump at idle. These combined features led to a refined level of noise that is comparable to the PFI system.

CALIBRATION

BASE ENGINE CALIBRATION

DOE Mapping

Due to the numerous independent control variables a Design Of Experiments (DOE) was used to reduce the amount of data collected and time required. DOE mapping techniques were used to produce the camshaft control maps, fuel pressure control, injection timing and the HSP maps. The main DOE factors and responses that were measured on this engine are listed in Figure 11. A fractional factorial design was used. Without this type of approach the number of test points could become prohibitively large as shown in the example in Figure 12 [4].

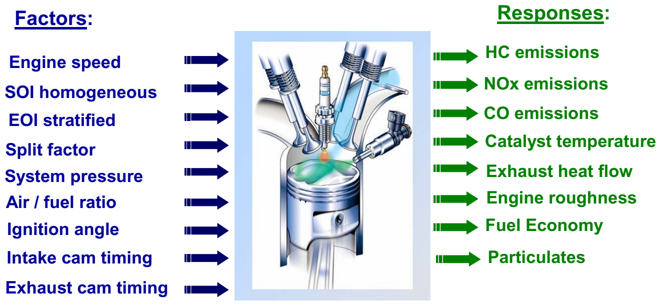


Figure 11: Typical DOE Factors and Responses

Parameter	Number of variation steps	Total number of mapping points
Engine Speed	16	16
Engine Load	12	192
Ignition Timing	10	1,920
Injection Timing	6	11,520
Manifold Pressure	4	46,080
Split Factor	3	138,240
Intake Cam	10	1,382,400
Exhaust Cam	10	13,824,000
Fuel Pressure	5	69,120,000

Figure 12: Conventional Mapping - Number of Data Points

The DOE process generated coefficients which estimated system responses at each set of operating conditions. Suspicious results, those with potentially poorly fitting responses, were checked to verify or correct any poor data points. A software tool was used to determine the best compromise for the control variables given operating constraints (BSNOx, BSHC, CO, Particulates). The remaining responses (Catalyst Temperature, Exhaust Heat Flow, COV, BSFC) were then optimized. First cut calibration tables were defined. Predicted results were then verified. An example of the data output from the DOE is presented in Figure 13. Note: due to the detail of this figure it is reproduced in the appendix section in a larger format.

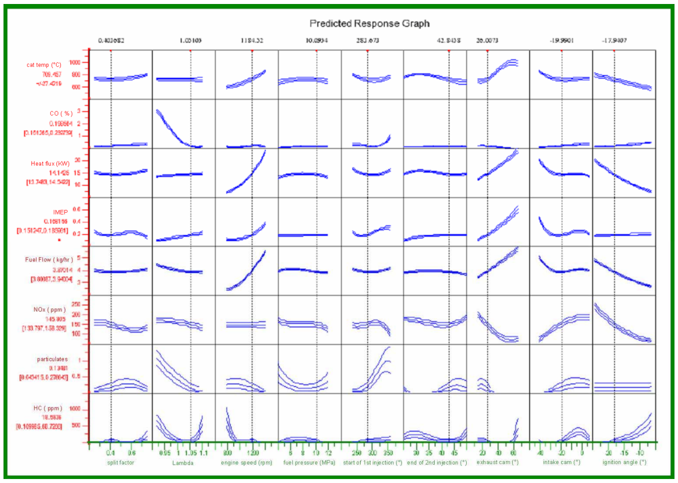


Figure 13: DOE Predicted Responses; see appendix for enlarged copy of this figure

Cam Maps

Cam maps were optimized by GM for best torque, power, fuel economy, low emissions and low particulates using a DOE. Operating conditions determined which factors were optimized. In most regions fuel economy and emissions had the highest priority. Peak torque was optimized near full load operating conditions. A broad torque curve was emphasized where possible given the constraints. After reduction of all the data the optimized cam maps were defined. During later in-vehicle development, under transient conditions, specific areas in the maps were revisited by Bosch to further refine them with respect to emissions and drivability. Please refer to figures 14 and 15 below for the final intake and exhaust cam maps. The resulting valve overlap is shown in Figure 16.

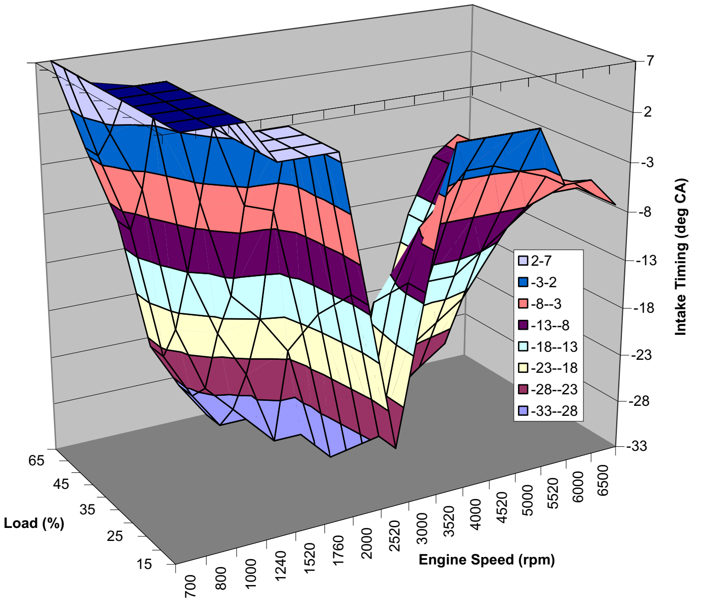


Figure 14: Intake Cam Map in Degrees ATDC Intake Valve Opening

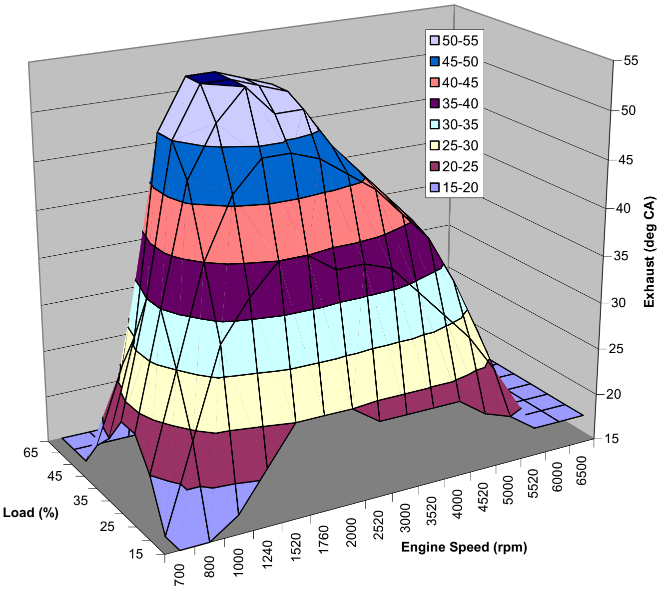


Figure 15: Exhaust Cam Maps in Degrees ATDC Exhaust Valve Closing

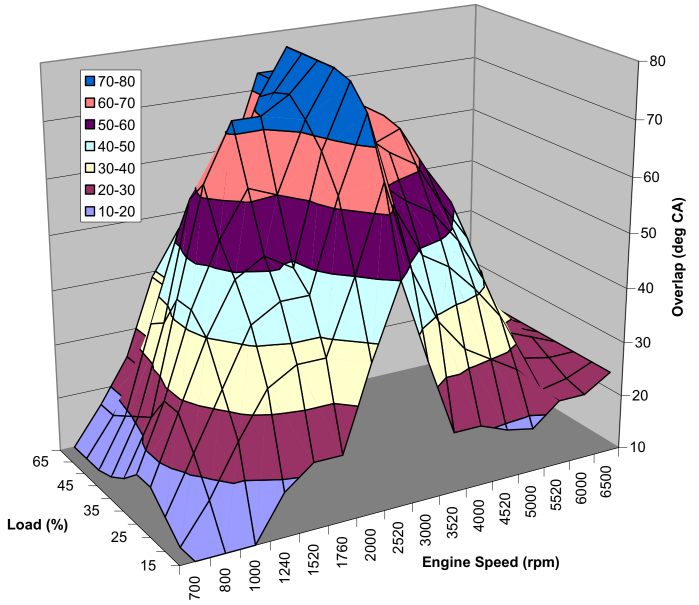


Figure 16: Cam Overlap Map – Total Crank Angle Degrees

Charge Determination and Pressure Model

Charge determination is important for precise torque calculation. After the cam maps were optimized, charge determination was calibrated. The airflow was back-calculated using measured lambda and measured fuel flow and the necessary maps were adjusted. The next step was to develop the intake manifold pressure model on the engine dynamometer. Over 1200 data points were collected and reduced with a custom Bosch tool to determine the pressure model. The pressure model is used to predict transient airflow to ensure that charge is accurately calculated under all conditions including transients.

Torque Structure

The torque structure in the Bosch system is the foundation for control of the engine. It is designed to be accurate to within 5% under all conditions and is transmitted to other control modules in the vehicle such as the transmission and traction control modules. A key input to the torque structure system is the ignition timing efficiency curve presented in Figure 17. This curve shows the engine efficiency relative to the optimal best torque ignition timing. This curve is empirically determined on the engine dynamometer. The interesting point about this curve is that it applies to all engine speeds and loads. A similar curve modifies torque for lambda (air/fuel ratio) efficiency.

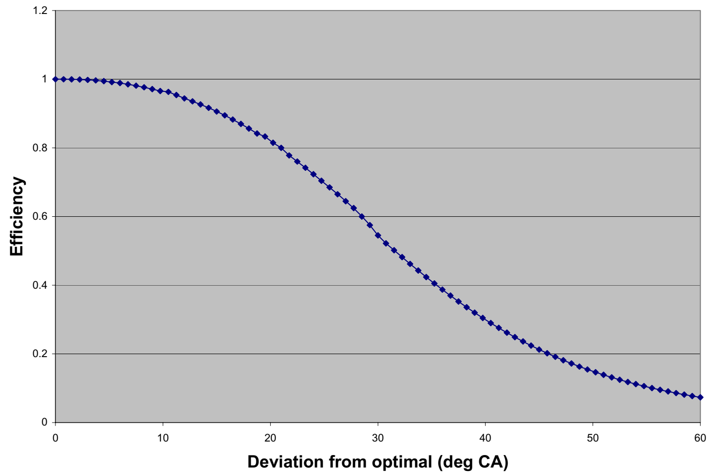


Figure 17: Ignition Timing Efficiency Curve for Torque Structure.

In Figure 18 the optimal torque map gives the indicated or internal torque as a normalized percentage of the maximum available engine torque. This value is then modified for ignition efficiency, lambda efficiency, engine temperature and other conditions. The friction torque map is shown in Figure 19 and this is subtracted from the indicated torque to get the net or clutch torque.

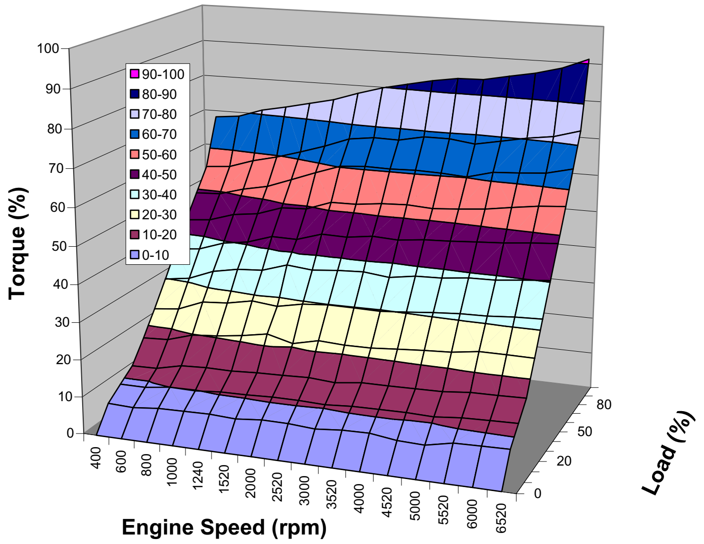


Figure 18: Optimal Torque Map

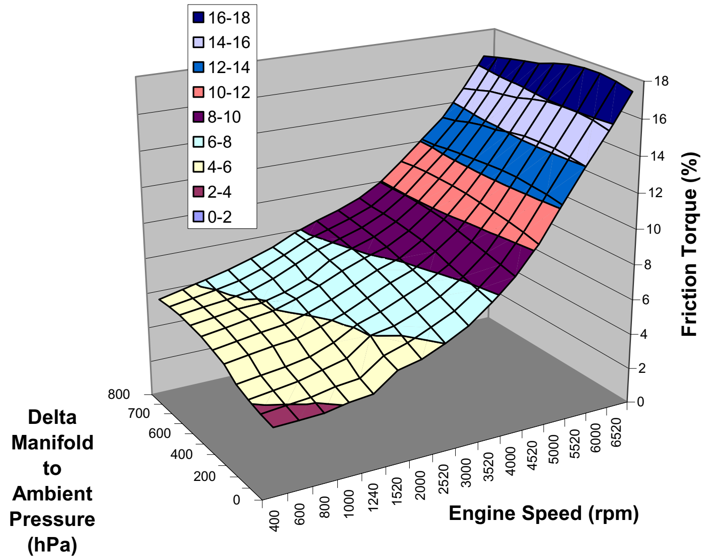


Figure 19 Friction Torque Map

Fuel Injection

After the air path calibration was optimized the fuel pressure and end of injection timing were optimized using a DOE matrix. Fuel pressure is typically lowest, around 3 MPa (30 bar), near idle conditions and it is highest, around 12 MPa (120 bar), at high load and high engine speed conditions as seen in Figure 20. The system is designed to be capable of pressures up to 20 MPa. End of injection timing was optimized mainly for low emissions and particulates and can be seen in Figure 21.

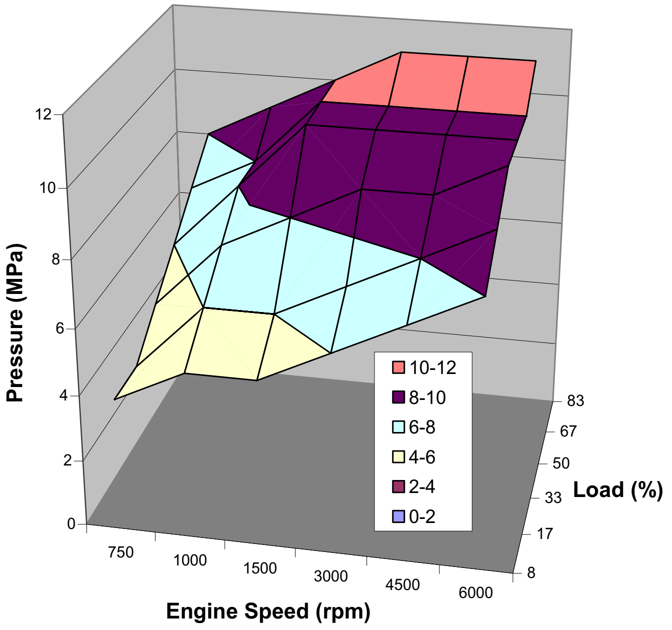


Figure 20: High Fuel Pressure Map

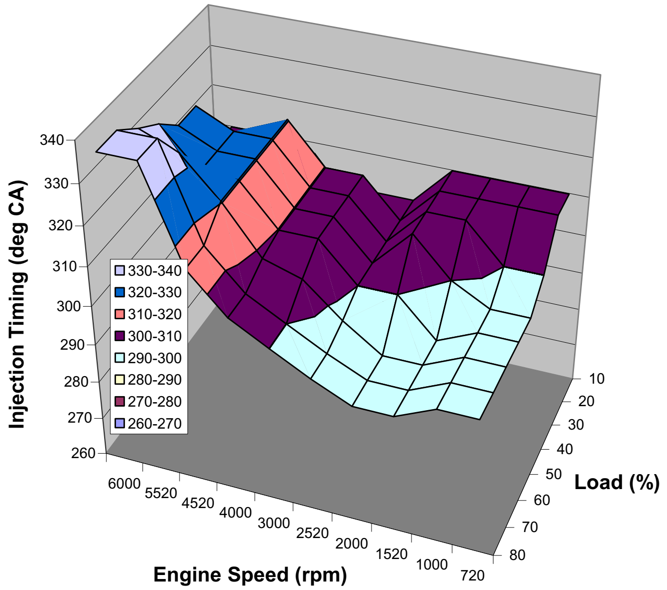


Figure 21: End of Injection Timing in Degrees BTDC Compression

STARTS

The initial start calibration was developed on a cold buck rig as shown in Figure 22. The rig was fully instrumented with fast FID emissions, Combustion Analysis System, Lambda meters, thermocouples and other instrumentation. A forced cooling system was used to reduce the cool down time and allow for multiple daily cold starts at a controlled temperature. The initial calibration determined several parameters, such as fuel amount, fuel pressure, injection timing, catalyst heating idle speed, catalyst heating request, HSP split factor, HSP transition to homogeneous mode, etc. The calibration was further developed in the vehicle and verified at different temperatures, barometric pressures and with various fuel types.

Figure 22: Cold Buck Rig

Due to the direct injection, the start fuel was reduced by about 50% as compared to port fuel injection. This greatly contributed to emissions reduction. This was possible due to the good fuel atomization and reduced wall wetting with direct injection. This also improved combustion robustness to limit fuels with low vapor pressure characteristics.

EMISSIONS

The Cadillac CTS and STS vehicles equipped with this engine were developed to LEV2 Bin5 standards: 0.090 gm/mile NMOG, 0.070 gm/mile NOx, 4.2 gm/mile CO, 0.01gm/mile PM. These levels were easily achieved without the use of external EGR or secondary air injection and using a catalytic converter with only 400 cpi and reduced precious metal loading.

A major enabler for the low emissions is the capability of DI to run in HSP mode during catalyst light-off after cold start. During HSP the fuel injected is split into two injections. The first portion is timed such that a lean mixture is distributed throughout the combustion chamber. The second portion forms an enriched cloud around the spark plug to allow late ignition and combustion which results in elevated exhaust temperatures. Figure 23 shows a basic sequence of the events during HSP. A DOE was used to optimize the control parameters during HSP. Smoother operation and a reduction of hydrocarbon emissions by approximately 25% during the cold-start and initial warm-up were realized using HSP [2, 3].

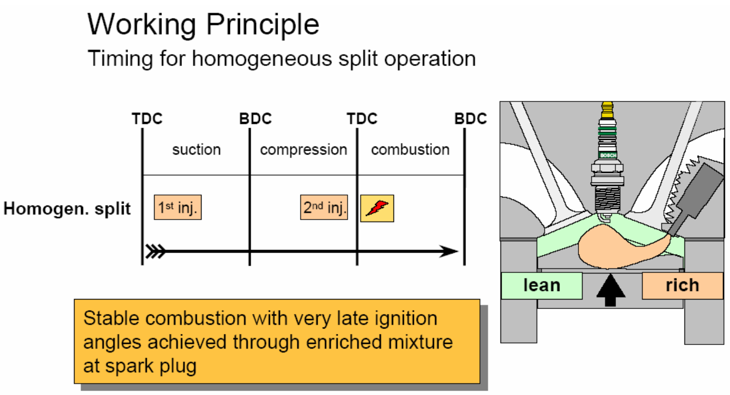


Figure 23: HSP Results in Smoother operation and a Reduction of Hydrocarbon Emissions by Approximately 25% During the Cold-start and Initial Warm-up [2, 3]

Figure 24 shows typical exhaust temperature profiles for the first 20 seconds of engine operation illustrating the very fast catalyst light off enabled by HSP.

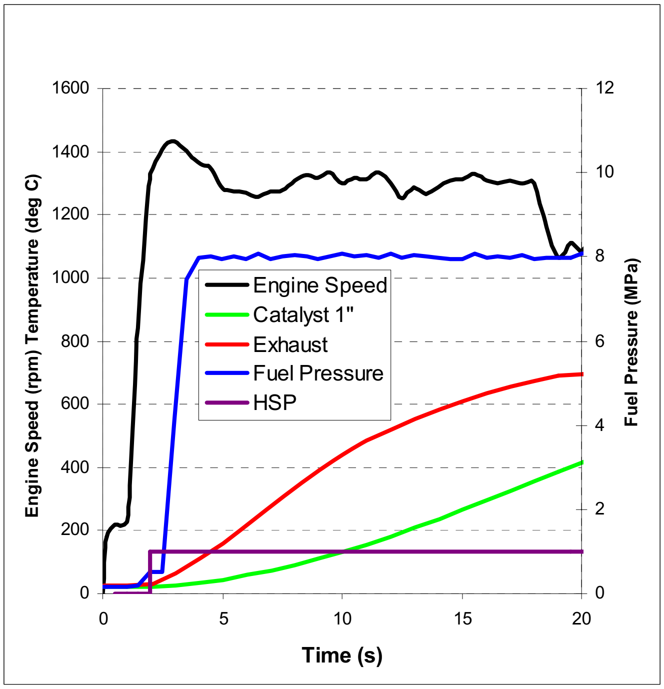


Figure 24: Exhaust Temperature Profiles; First 20 sec. of Engine Operation

FUEL ECONOMY

Fuel economy goals were exceeded on this project having achieved 17 mpg EPA City and 26 mpg EPA Highway versus goals of 15.2 City / 25.4 Highway. This was accomplished using 87 octane regular fuel. Enabling this fuel economy were the higher compression ratio, charge cooling, advanced ignition timing, reduced wall wetting, reduced start fuel and better fuel preparation.

DIAGNOSTICS

A key operating feature of the DI System is that it must continue to operate in a predictable manner, even in the event of failure and it must satisfy On Board Diagnostics 2nd Generation (OBD II) requirements. In addition to the basic requirements which are satisfied by PFI systems, the DI system has several unique requirements for OBD II, which are primarily related to the unique hardware which is utilized in the system. Several of the unique aspects related to DI are described.

Fuel Rail Pressure Sensing Diagnostics

Basic Diagnostics are performed on the fuel rail pressure sensor, including: electrical circuit diagnosis (minimum and maximum voltage faults). To ensure the sensor does not exhibit deviation within the normal operating range, a 2-sided rationality check of the fuel pressure sensor is included at engine start. Figure 25 shows the concept of this diagnosis.

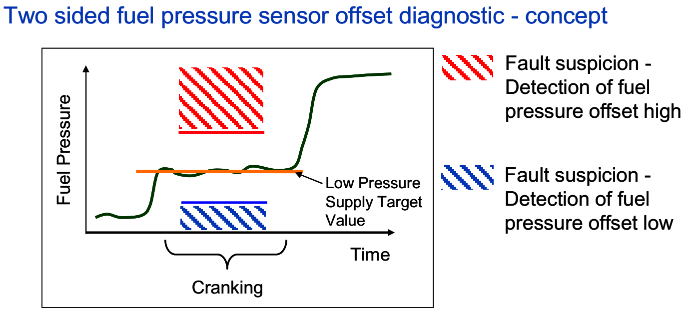


Figure 25: Fuel Pressure Sensor Rationality Diagnosis

Fuel Rail Pressure Control Diagnosis

The control of the fuel rail pressure is monitored with two basic control parameters: actual fuel rail pressure versus commanded pressure; and PI controller output versus plausible limits. Figure 26 shows the basic diagnostic signals along with their corresponding failure limits for a sample operating condition.

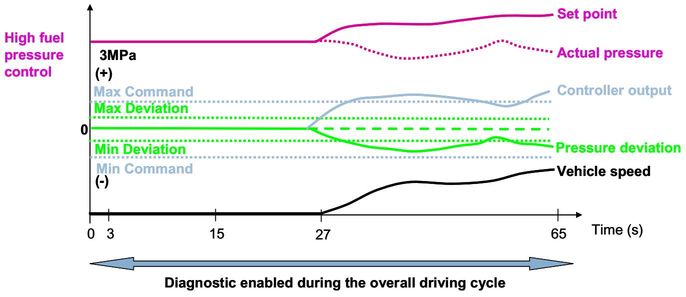


Figure 26: High Fuel Pressure Control Diagnosis

Failsoft Operation Without High Pressure

With the important requirement that the DI System must continue to operate in a predictable manner, even in the event of failure. Basic system operation was ensured using a backup control. In the event that high pressure is not available due to component failure, the system limits maximum torque output of the engine. This limit is set to not exceed the flow capacity of the fuel injectors at low fuel feed pressure. Low pressure fuel can flow directly through the high pressure pump without the pump being activated. The vehicle operator is warned with a “Reduced Engine Power” warning message if this action must be taken.

Diagnosis of Fuel Injectors

A specific fuel injector diagnostic is required with DI systems. This is in addition to the basic circuit diagnostics and system diagnostics like misfire detection. The high pressure DI fuel injector requires much higher voltage, near 80 volts, rather than the typical 12 volt operation for PFI injectors. Due to this higher voltage requirement, the design is set up with the ECU wired to directly supply voltage to the injectors. In the system shown in Figure 27, the high voltage circuit connected to the injector can be diagnosed directly for circuit continuity problems, thus allowing improved fault isolation.

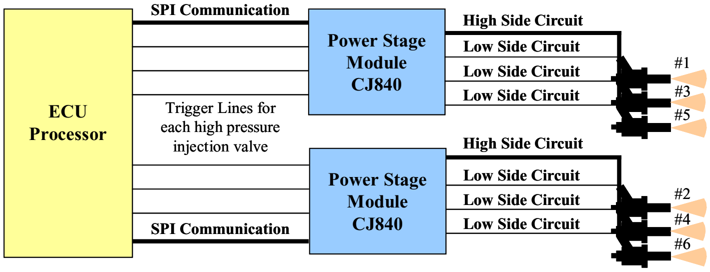


Figure 27: Fuel Injector Circuits with High Side ECU Feed

Misfire Diagnostic – Misfiring Cylinder Detection Misalignment During HSP - Alternate Window

An alternate misfiring cylinder detection window is required for HSP operation due to the extremely retarded ignition timing causing the peak cylinder pressure to occur much later than during normal homogeneous combustion. It was found that using this alternate window for detection of late peak pressure during HSP caused cylinder identification that was offset by 1 cylinder from the expected cylinder. A revised calculation had to be developed to properly identify the correct cylinder. Figure 28 shows the relationship of the non-HSP and HSP operation, and the original software specified cylinder alignment windows. Using the revised cylinder number calculation provided correct identification of the misfiring cylinder.

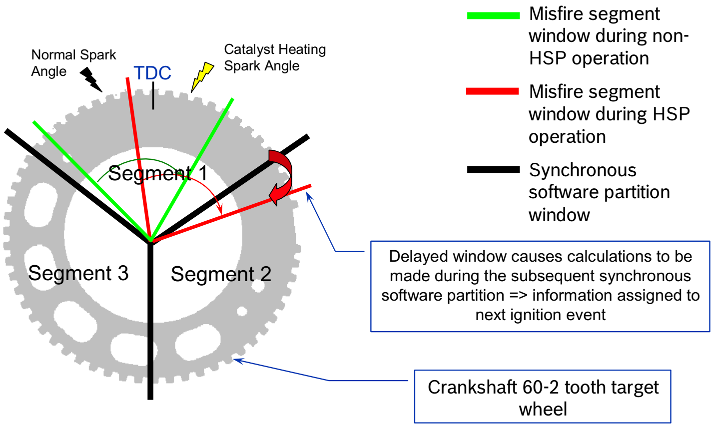


Figure 28: Cylinder Misalignment Alternate Window

CONCLUSION

The calibration and development of the Bosch Motronic MED9.6.1 EMS for the GM 2008 Model Year 3.6L DOHC V6 Direct Injection Engine has met or exceeded all development targets, including power, torque, fuel economy, emissions, diagnostics, cold start and refined operation. At 304 Horsepower it exceeded the baseline PFI by 16% and at 370 Nm torque it exceeded the PFI by 8%. The fuel economy exceeded program goals and is comparable to the less powerful PFI at 17 mpg EPA City and 26 mpg EPA Highway. The engine accomplished this while operating on 87 octane regular fuel and complying with LEV2 Bin5 emission standards without requiring the use of external EGR or secondary air injection.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ABS: Anti-lock Braking System

ATDC: After Top Dead Center

BHP: Brake Horsepower

BMEP: Brake Mean Effective Pressure

BSFC: Brake Specific Fuel Consumption

BSHC: Brake Specific HydroCarbons

BSNOx: Brake Specific NOx

BTDC: Before Top Dead Center

COV: Coefficient Of Variation

DI: Direct Injection

DOE: Design Of Experiments

DOHC: Double OverHead Cam

DS-HD-KV: Fuel pressure sensor

ECU: Engine Control Unit

EGR: Exhaust Gas Recirculation

EMS: Engine Management System

ETC: Electronic Throttle Control

FID: Flame Ionization Detector

GMLAN: General Motors Local Area Network

GDI: Gasoline Direct Injection

HDEV5: High pressure fuel injector

HDP5: High pressure pump

HSP: Homogenous Split injection

IMEP: Indicated Mean Effective Pressure

MAF: Mass Air Flow sensor

MPG: Miles Per Gallon

MSV: Flow control valve

PCB: Printed Circuit Board

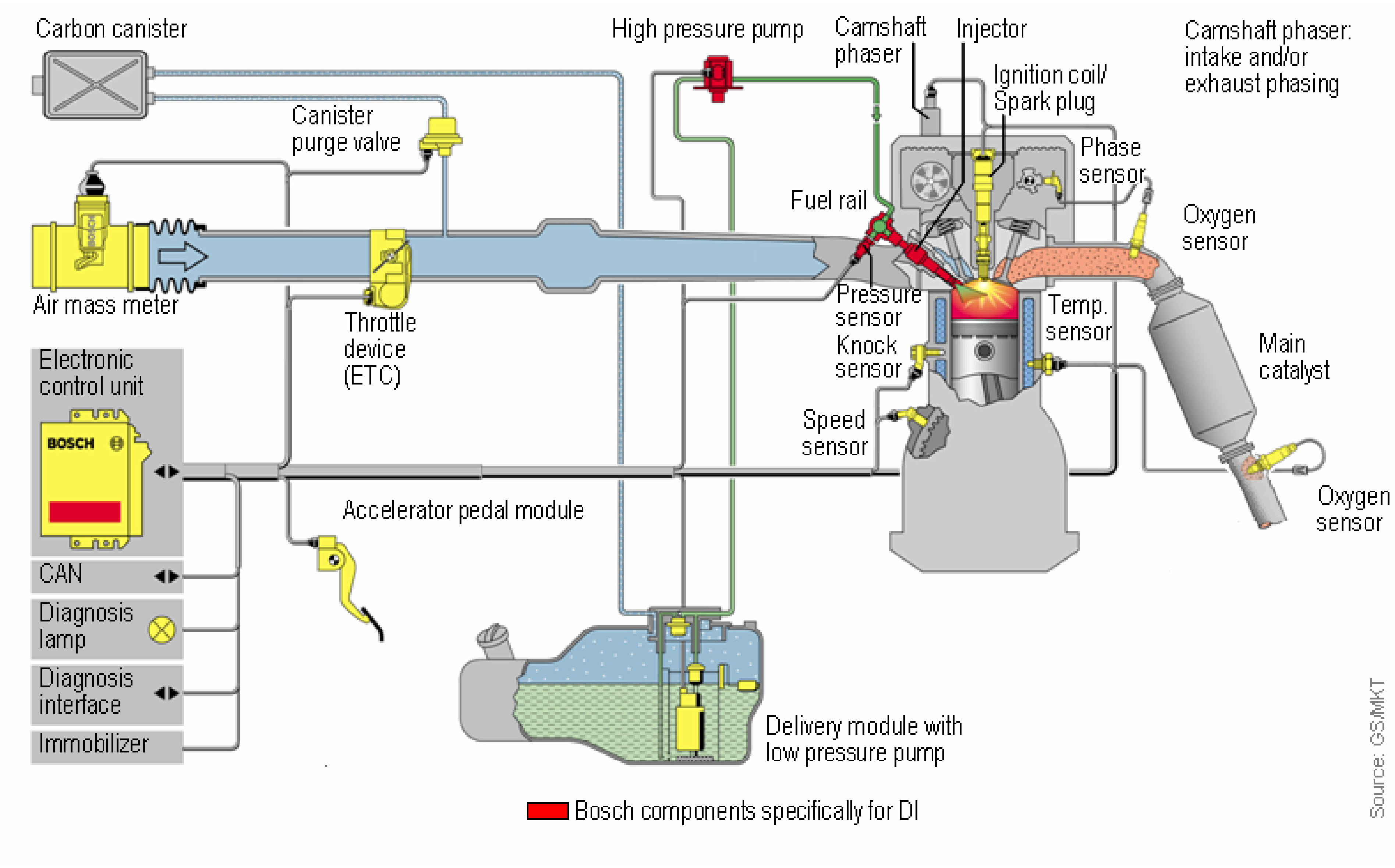
PFI: Port Fuel Injection

SIDI: Spark Ignition Direct Injection

VVT: Variable Valve Timing

WOT: Wide open throttle

APPENDIX



Source: GSMKT

Figure 5: Bosch Motronic MED9.6.1 Gasoline Direct Injection Engine Management System with Components; reproduced here for greater clarity

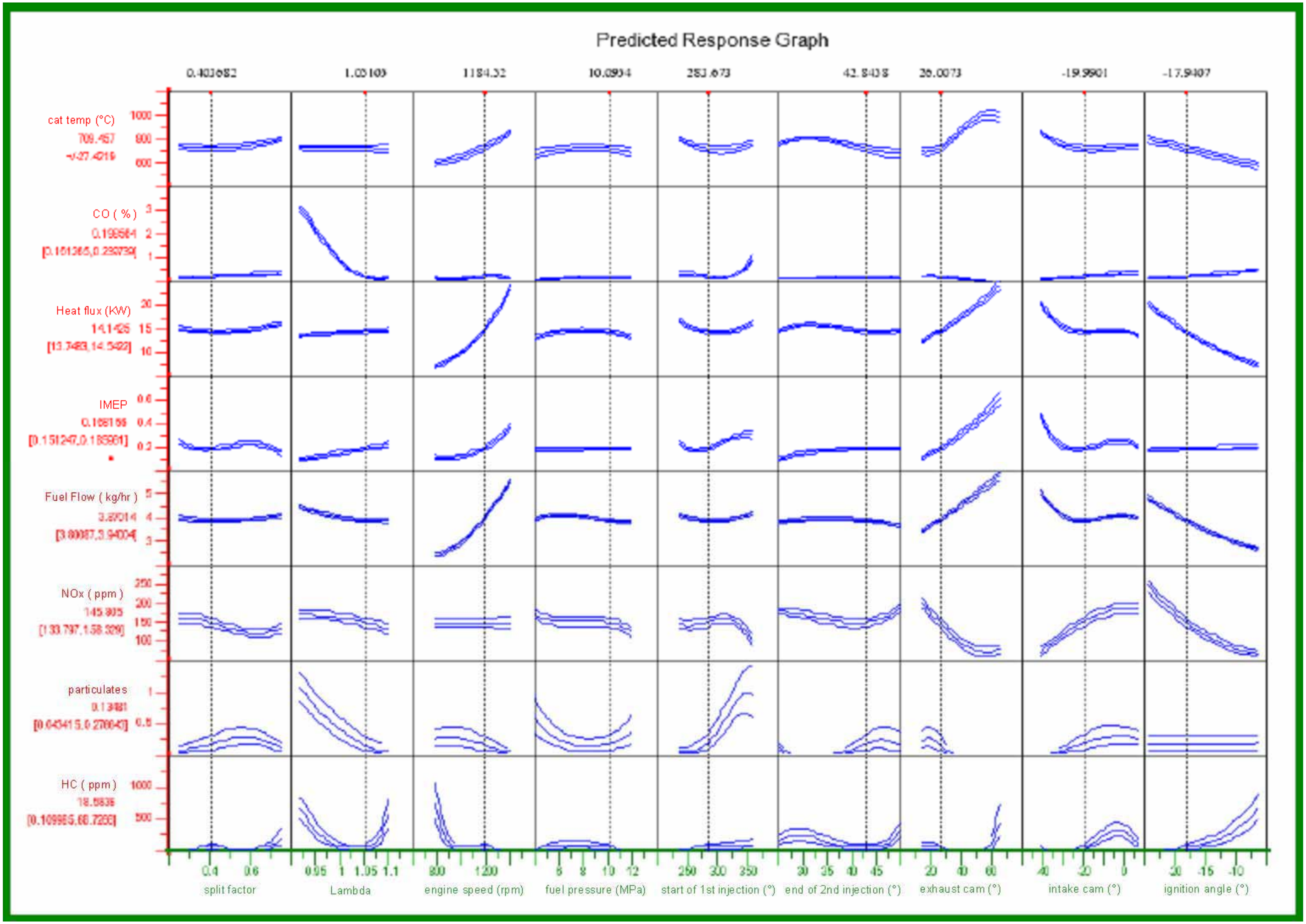


Figure 13: DOE Predicted Responses; reproduced here for greater clarity