

Parameter Optimization of a Turbo Charged Direct Injection Flex Fuel SI Engine

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ABSTRACT

With the increased interest in the use of ethanol as an alternative fuel to gasoline, Original Equipment Manufacturers (OEMs) have responded by adapting their current range of vehicles to be able to run on gasoline/ethanol blends. Flex fuel vehicles are defined as those that are capable of running gasoline up to 100% ethanol. Other than changes to materials compatibility, to enable the required durability targets to be met when running on ethanol, very little in the way of changes are performed to take advantage of the properties of ethanol. Calibration changes are typically limited to changes in fueling requirements and ignition timing.

The physical and chemical properties of ethanol/gasoline blends offer a mixture of advantages and disadvantages. Lower energy density in the form of lower heating value reduces vehicle range whilst higher octane ratings make these excellent fuels for boosted operation.

Further enhancements can be made to flex fuel vehicles that better exploit the properties of ethanol by modifications to both the base engine and calibration. This paper describes an investigation into the potential benefits of an enhanced calibration strategy. Through the use of such strategies, it is possible to improve efficiency when running on ethanol. Design of experiments (DoE) methods have been used to investigate the behavior of a turbocharged direct injected

spark-ignited engine on various blends of ethanol ranging from non-oxygenated gasoline (E0) to 85% ethanol (E85).

Enhanced wide-open throttle performance can also be realized when ethanol is combined with boosting and direct injection. Behavioral differences between gasoline and ethanol have been studied and the trade offs identified.

OVERVIEW

With desire to reduce the dependency on imported crude oil, ethanol has become a key alternative fuel particularly in the North American market. Some countries such as Brazil have adapted to running on E100 or 100% ethanol refined from sugar beets. In North America, ethanol is sold in blends up to 85% Ethanol, 15% Gasoline.

From an engineering perspective, the adaptation of an engine to run on ethanol requires design and development efforts to achieve satisfactory durability and a robust calibration. Table 1 compares the physical properties of E85 ethanol when compared to gasoline.

Fuel	Gasoline	E85
Octane RON	91-98	105
Heating Value (kJ/kg)	43105	29125
Density (kg/m ³)	598.7	648.6
Stoichiometric air/fuel	14.6	9.8
Volume % fuel in stoichiometric mixture	2	6.5
(kJ/kg) of air for stoichiometric mixture	23.3	102.5
Autoignition Temp C	257	423
Surface Ignition Temp C	899+	849
Freezing point C	-40	-114

Table 1 Physical Properties of Gasoline and E85 Ethanol

A key consideration when using ethanol blends is fuel volatility. Figure 1 shows the differences in Reid Vapor Pressure (RVP) for different ethanol content. As the percentage of ethanol increases the RVP drops, which becomes important when developing cold start calibrations. In North America E85 blends vary during the season to help with change of temperature. Winter blends are typically only 70% ethanol while summer blends are typically 80 to 83%. Discussions as to how to increase ethanol market penetration have included increasing the percentage of ethanol in standard pump gasoline to 20%. Cold start of ethanol blends remains one of the greater calibration tasks particularly with port fuel injected engines and direct injected engines at extreme cold temperatures

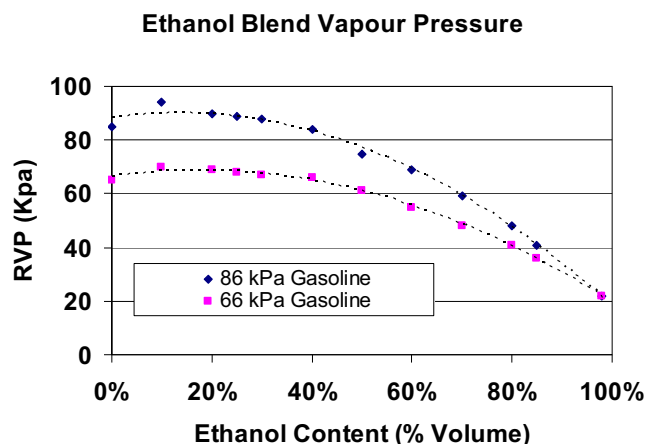


Figure 1 RVP for Ethanol/Gasoline Blends

E85 has similar density to gasoline, but a heating value that is 25 to 30% lower, which results in a significant reduction in vehicle range.

E85 is attractive as its higher octane number (RON), which whilst improving naturally aspirated engines Wide Open Throttle (WOT) performance, works exceedingly well with boosted engines. Boosted DI engines have already demonstrated great potential for improved efficiency whilst offering comparable performance to a larger naturally aspirated engine [1, 2, 3]. A boosted E85 engine has the potential to have greatly improved

specific power output. With a penalty in heating value to overcome, the improved performance when the engine is run on E85 allows the possibility of further downsizing. A smaller displacement boosted E85 engine can produce the same power and torque as a larger boosted gasoline engine with the potential to reduce the difference in cycle fuel consumption as a result of the efficiency gain. Improved knock resistance also allows the potential to increase the compression ratio, helping to improve the thermodynamic efficiency. The challenge for the powertrain engine is how to achieve a balance in these attributes for an engine that has to be capable of running on both gasoline and ethanol (flex fuel capable)

Alcohol fuels require different materials to be used in several key subsystems. Lower lubricity, high oil dilution and higher cylinder pressures all influence the base engine specification. Typically to enable an engine to run on ethanol with acceptable durability the following subsystems are modified:

- Valve and seat interface
- Bore and piston rings
- Piston and cylinder head gasket
- Bearings
- Timing drive
- Seal materials
- Fuel system materials

When calibrating the current generation of FFV, the following functions are most heavily affected by having to run E85:

- Fuel Calibration
- Spark Calibration
- Torque Structure
- Ethanol Detection*

*Ethanol detection is a unique function for FFV applications.

Fueling levels change as stoichiometric ratio changes as a function of the alcohol concentration. Spark timing requirement changes due to the difference in flame speed with alcohol concentration. There are additional issues to consider with spark timing. With E85 there is a much greater propensity for pre-ignition to occur due to the lower surface ignition temperature. In some cases spark advance has to be limited even though the spark advance is not limited by knock. Spark plug fouling during cold start is also an issue on E85 often requiring compromise between spark plug heat range selection for cold start and that required to avoid pre-ignition.

The percentage of ethanol is typically calculated using one of two methods; either directly with a sensor in the vehicle fuel line that detects the change in conductivity or an indirect method that uses the oxygen sensor. The oxygen sensor method relies on the change in fuel trim that occurs immediately after the vehicle has been refueled.

E85 burns with a faster flame speed than gasoline, which should directly enhance the engines EGR tolerance at part load. Lower percentage trapped residuals result for a given overlap area when E85 is burned compared to gasoline as the C:H ratio of E85 is much lower than gasoline. Therefore it has been speculated that greater EGR rates can be tolerated on E85 than on gasoline. Most current FFV calibrations do not change the VVT or EGR calibration as a function of percentage of ethanol. One of the objectives of work reported in this paper is to quantify this effect.

OBJECTIVES

The main objective of this work was to study the combustion characteristics of a turbocharged direct injection engine running a variety of blends of ethanol and gasoline from E0 to E85. From the results obtained it is intended to quantify the efficiency gains possible and the potential calibration strategies needed.

EXPERIMENTAL DETAILS

ENGINE CONFIGURATION

The engine selected for the experimental investigation is a 2.0L LNF L850 first introduced by General Motors in 2006 in the Pontiac Solstice [4].

Type:	Twin Turbocharged I4
Bore X Stroke:	85 X 86 mm
Displacement:	1998 cc
Boosting System	Twin Scroll Turbocharger
Compression Ratio:	9.5:1
Firing Order:	1-3-4-2
Valve train:	DOHC, 4-Valve, VVT
Combustion System:	Direct Injection Spark Ignited
Power	190 kW @ 5800 rpm
Torque	353 Nm @ 2000 – 5000 rpm

The engine used for the experimental investigation represents what can be considered as a good example of a current production DI turbocharged engine. Figure 2 shows the LNF engine.



Figure 2 General Motors LNF Engine

The engine uses a wall guided combustion system with a side mounted fuel injector and camshaft driven on demand fuel pump. The solenoid type injector is a free orientated spray beam multi-hole injector. The piston crown has a feature developed to help enhance cold start performance when using split injection. Figure 3 shows the injector and piston layout.



Figure 3 Piston and Injector

Cam phasers are present on both the intake and exhaust camshafts providing 50 crank degrees of authority for each camshaft.

The turbocharger is a twin scroll unit with a maximum turbine inlet temperature of 950 °C. The engine uses an air to air charge air cooling system (Fig 4.)

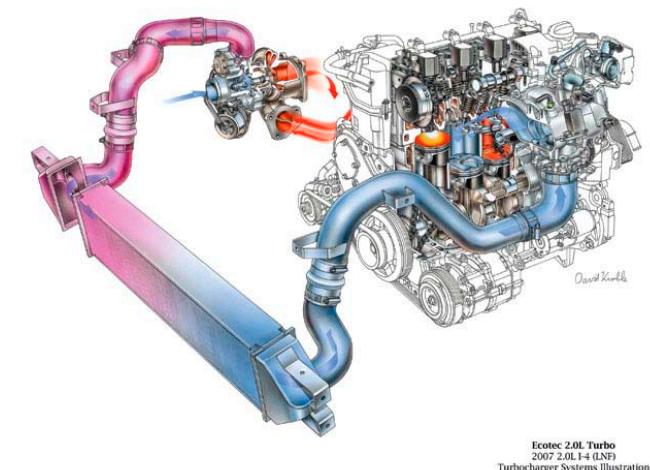


Figure 4 Inlet System Layout

The engine management system (EMS) used for this project is the Bosch DI Motronic MED9 engine control unit. It contains a 32 bit microprocessor that communicates via LAN to the vehicle.

The EMS employs a torque-based system that controls the positions of the intake and exhaust cams, throttle, and waste gate positions based on inputs from various sensors and the pedal demand of the driver. Air fuel ratio is closed-loop controlled utilizing signals from a mass-air-flow meter and a wideband lambda sensor positioned in front of the close-mounted catalyst. The EMS controls injection duration, injection timing, fuel pump delivery, fuel-rail pressure and ignition timing. A knock sensor positioned one on the side of the block is used to control knock.

In addition to the usual temperatures and pressures, the engine was instrumented for the following parameters:

- Cylinder pressure
- Engine out raw emissions
- Smoke
- Turbo speed

EMS parameters were also recorded via ASAP3 protocols.

EXPERIMENTAL APPROACH

Four fuels were specially blended for the experiment. Table 2 shows the properties of the four fuels.

	E0	E24	E55	E85
Ethanol %	0	23.17	56.44	82.8
Stoichiometric Air Fuel Ratio	14.56	13.2	11.26	10.1
Net Heating Value (MJ/kg)	43.2	38.11	34.02	29.22
Octane RON	97.2	99.8	102.1	103

Table 2 Characteristics of Test Fuels

Due to the large number of variables involved, a Design of Experiments (DoE) approach was adopted. DoE methods are effective in isolating the influence of each variable under consideration. Traditional mapping methods are not feasible given the large number of variables. Of the available advanced modeling methods, Stochastic Process Models (SPM) have been shown to be superior to the main alternatives of neural networks and radial basis functions [5]. Stochastic process models are a development of the statistical method known as Kriging. An SPM response interpolates between data points after adjustments for noise on the data. The DoE used was a global model (speed and load) in the stoichiometric region of operation with each fuel. For each fuel blend the design was an optimal Latin Hypercube design with 480 test points. The variables included in the DoE were:

- **Engine Speed**
- **Mass air flow**
- **Intake cam timing (IVT)**
- **Exhaust cam timing (EVT)**
- **Fuel Pressure**
- **Injection Timing**

Spark was not included as a DoE variable because a response of optimum spark was to be created during the experiment

Fully automated mapping routines were used to enhance data collection speed and improve test quality metrics

For each experiment, models of the following responses were created:

- **BSFC**
- **CoV of IMEP**
- **HC**
- **NOx**
- **Smoke**
- **Optimum spark**

In an additional step, a master global model was produced that combined the global models from all four fuel blends. This enabled responses to be generated as a function of ethanol percentage as well as speed and load.