

Performance and Emission Characterization of 1.2L MPI Engine with Multiple Fuels (E10, LPG and CNG)

2010-01-0740

Published
04/12/2010

R. Muthu Shanmugam
Tata Motors Ltd.

Nilesh M. Kankariya
Incat A Tata Technologies Ltd. Co.

Jacques Honvault
Valeo EES

L. Srinivasan and H. C. Viswanatha
Tata Motors Ltd.

Patrice Nicolas
Valeo EES

N. Saravanan
Tata Motors Ltd.

Dias Christian
Valeo EES

Copyright © 2010 SAE International

ABSTRACT

Most of the energy consumed in today's mobility industry is derived from fossil fuels. The demand for clean, renewable and affordable alternative energy is forcing the automotive industry to look beyond the conventional fossil fuels. Fuels options like liquefied petroleum gas (LPG), compressed natural gas (CNG) and ethanol blends are quickly finding widespread acceptance as alternative sources.

This paper presents the results of experimental studies conducted on a 1.2 litre MPI engine with three different alternate fuels. The fuels considered for the evaluation (apart from base gasoline) are 10% ethanol blended fuel (E10), LPG (gaseous propane: butane mix) and CNG (gaseous methane). Experiments were conducted to compare their effect on engine performance and emissions.

The test results show that E10 has the lowest power drop whereas CNG has the highest power drop (12%) as compared to gasoline. The maximum power drop in LPG is 4%, which is close to the theoretical predictions. Compared to gasoline, there is no major deterioration in low end and maximum torque with E10 and LPG. The usage of E10 required minimum engine hardware changes (restricted to fuel lines).

The carbon dioxide (CO₂) emission in LPG mode was found to decrease by 11% compared to 23% in CNG. The amount of carbon monoxide (CO) and hydrocarbon (HC) emissions in LPG and CNG modes were found to be a function of the gasoline to gas transition temperature (with gasoline as the starting fuel). Compared to gasoline, both the gaseous fuels resulted in higher nitrogen oxide (NO_x) emissions.

Emission tests with neat gasoline and E10 blend shows a net decrease in diluted CO and HC emissions by 13% and 19% respectively with E10 blends. On the other hand, NO_x emissions increased by 16%. There is a net reduction in CO₂ by 2% compared to neat gasoline.

INTRODUCTION

The demand for technology that provides clean, cheap and fuel efficient vehicles is increasing worldwide. These factors are becoming the key drivers for continuous technology up gradations. Gasoline, which was the preferred fuel of choice so far, is being continuously challenged by a variety of different fuels like ethanol, CNG, LPG etc as an answer to the new demands. Of the variety of gaseous fuels available, CNG and LPG have achieved widespread acceptance as auto fuel due to their inherent advantages. On the other hand, ethanol has the distinct advantage of being renewable as it can be produced from biomass. This economic advantage has prompted many governments around the world to mandate ethanol blending in gasoline (in varying percentages) to reduce the crude oil imports and decrease the dependence on fossil fuels.

This paper evaluates the performance and emission characteristics of a 1.2L, Bi-fuel (Gasoline and Gas) MPI engine with three alternate fuels - two gaseous fuels (CNG and LPG) and one blended fuel (E10). The base gasoline engine was modified to operate with CNG and LPG by incorporating suitable modifications to the fuel supply system and engine management system (EMS). The EMS was optimised individually for CNG and LPG applications to achieve the best trade-off in terms of performance, driveability and emissions. As the EMS and engine hardware used in both CNG and LPG systems are similar, the results of the experiment focuses entirely on the effect of fuel on the engine's performance characteristics. In order to eliminate the effect of engine to engine variation on performance attributes, all the test bench tests were conducted on a single engine with all the three alternate fuels options. The bi-fuel system chosen is not an add-on or 'retro fit' but an integrated system developed with an optimised performance in gas (CNG or LPG) and gasoline modes. The engine meets the existing Indian Bharath Stage 3 (BS3) norms. The paper provides details of the fuel specific engine design modifications and EMS control system along with comparative analysis of the major engine performance parameters.

FUEL CHOICES - ALTERNATE AND OXYGENATE FUELS

Oxygenates are combustible liquids containing carbon, hydrogen and oxygen in its chemical structure. These compounds mix easily and thoroughly with gasoline. Ethanol, which is from the alcohol family, is widely used in gasoline as oxygenate due to its renewable nature. The addition of

ethanol to gasoline boosts the mixture's octane level and improves the anti-knock properties. Blending ethanol to gasoline chemically en-leans the mixture and improves the combustion thereby resulting in tailpipe CO and HC emission reduction. The en-leanment is due to the additional oxygen provided by ethanol in the fuel mixture [1,2].

Increase in ethanol concentration in gasoline increases the oxygen content of the blend. This in-turn requires compensation in the fuel injection quantity to maintain air-fuel ratio (A/F) [1, 2]. This is normally taken care of by the engine's close loop fuel control mechanism which increases the fuel injection quantity to maintain stoichiometric ratio. Ethanol blending with gasoline increases the volatility of the mixture which may result in vapour lock, especially in hot conditions [3, 5]. This consequently results in hot starting / restarting difficulties, hesitation, stumbling during acceleration and in certain cases it can be severe enough to stall the engine. Ethanol blended fuels have high affinity to water leading to corrosion of fuel system components [2]. The extent to which these changes in fuel composition affect the engine performance and emissions is dependent on the engine itself, including engine design, fuel system and control system, as well as exhaust after treatment devices.

On the other hand, the use of gaseous fuels has certain distinct advantages and disadvantages compared to gasoline. The high hydrogen to carbon ratio (H/C) of gaseous fuels (2.6:1 for LPG and 3.8:1 for CNG) makes them clean burning which results in lower specific CO₂ emissions [8, 9]. Due to relatively simple hydrocarbon structure, the tendency to form aromatics and particulates is low in gaseous fuels. The hydrocarbon species reactivity and ozone forming tendency of emissions from gas fuelled vehicles is lower than from gasoline vehicles. Dedicated gas engines can operate at higher compression ratios than their gasoline counterparts due to the high RON and MON rating of gaseous fuels. This consequently improves the thermal efficiency.

The usage of CNG and LPG as auto fuel provides excellent A/F control without the issues of wall wetting, a common problem associated with liquid fuels. The need for additional enrichment during transient operations is eliminated in gas vehicles. Oil dilution, a problem associated with additional enrichment of liquid fuels, is eliminated thereby improving the oil drain interval. The absence of lead and sulphur in gaseous fuels prevents catalyst deterioration issues.

On the contrary, the volumetric efficiency is lower in gaseous fuels than in liquid gasoline due to the gas displacement of fresh air charge in the intake system. Gaseous fuels lack latent heat of vaporisation and have adverse effect on the cooling of A/F charge. These effects cascade into reduction in brake torque [9, 16, 18]. The heat release rate of gas - air mixture is lower in gaseous fuels than in gasoline. This

requires ignition timing advancement to optimise the torque which in turn increases the engine out NOx emissions [7, 8]. The volumetric fuel consumption of LPG is 27% higher than gasoline due to the density difference between the fuels. As gaseous fuels lacks lubricity, the durability of valves and valve seats is impaired [10]. Finally, in-vehicle storage requires high pressure storage tanks which increases vehicle weight and also imposes safety considerations for the system design.

SYSTEM CONFIGURATION

A 1.2L 48kW MPI gasoline engine was modified to operate with gaseous fuels (CNG or LPG) by incorporating suitable modifications in the engine hardware and engine management system. The engine specification is shown in Table 1.

Table 1. Engine specification

Engine Parameter	Specification
Bore x Stroke (mm)	75.0 x 67.5
Capacity (cc)	1193
Type	4 cylinders, Inline
Valve train	SOHC – 2V/cyl
Compression ratio	10:1
Fuel – Gasoline	Min 91 RON, Ethanol blends up to 10%
Fuel - Gas	Auto LPG, CNG
Max power (kW)	Gasoline: 48 @ 5000 rpm LPG: 45.6 @ 5000 rpm CNG: 41 @ 5000 rpm
Max Torque (Nm)	102 @ 2600 rpm (Gasoline and LPG) 91 @ 2600 rpm (CNG)

One of the main goals for the fuel system layout design [Fig. 1a, b] was to minimise the modifications to the main system and maximise the operational safety. The bi-fuel LPG vehicle consists of a *doughnut* LPG fuel tank with integrated multi-valve (with cut-off safety solenoid) located at the spare wheel well in the boot area. The vaporiser with solenoid safety valve placed under the hood supplies the regulated gas pressure to the engine through a low pressure gas filter. The gas pressure and temperature sensor is integrated on a gas fuel rail mounted on the intake manifold. The gas injectors are mounted on the intake manifold alongside the gasoline injectors.

The bi-fuel CNG vehicle consists of a cylindrical CNG tank (with integrated cut-off safety solenoid) mounted in the boot area. The high pressure gas is reduced to its operating pressure using a single stage pressure regulator.

For operation with E10, the gasoline fuel system was used without any modifications.

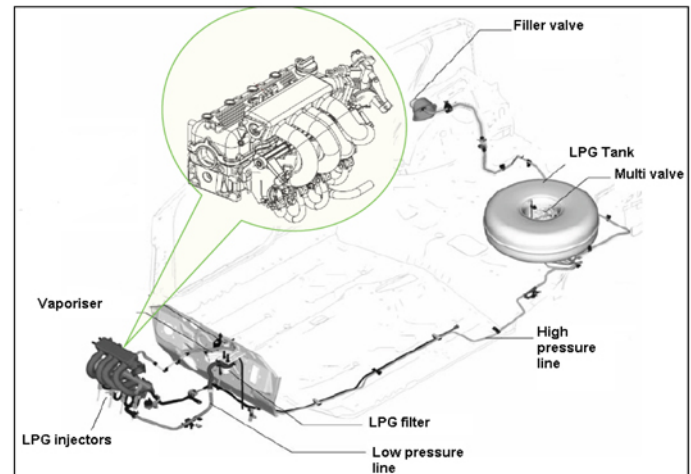


Figure 1a. LPG system layout

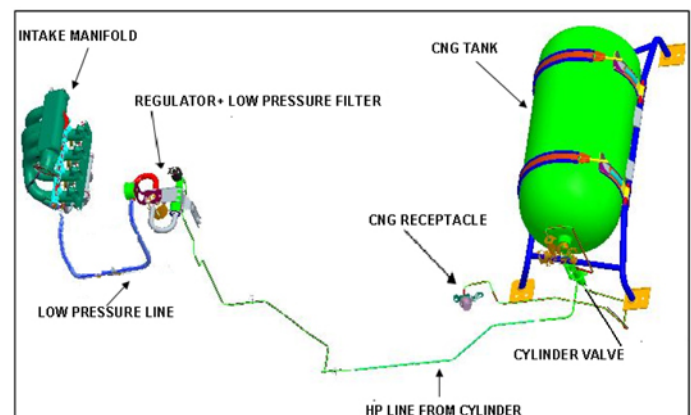


Figure 1b. CNG system layout

EMS OVERVIEW

As the experiment aims at characterising multiple fuels with the same EMS system, it is prudent to update the existing gasoline EMS with additional gas specific sensors, actuators and control unit for gas mode operation. In bi-fuel mode, equal importance was given to the performance in both gasoline and gas (CNG or LPG). Cost effectiveness in system integration, flexibility and functionality was achieved by preventing duplication of sensors /actuators and by sharing the information between the Master (gasoline) and Slave (gas) ECUs via CAN [Fig. 2]. The management of engine load, base injection demand, correction requirements etc is computed by the master ECU in both fuel modes. The data is exchanged every 8ms between the ECUs via CAN. The engine TDC information is shared between gasoline and gas ECU by a separate “hard wire” to achieve real time synchronisation of gas injection phasing.

<figure 2 here>

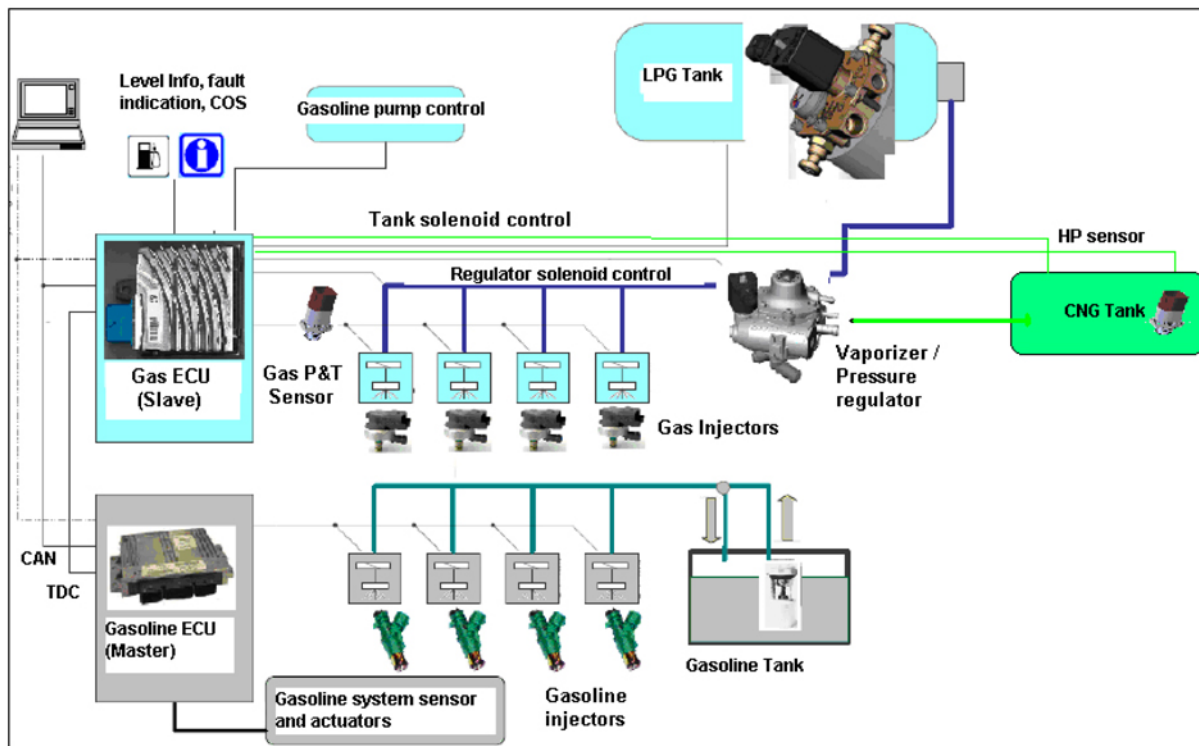


Figure 2. Control system layout for gas injection

The gas injection is controlled by the slave ECU based on load estimated by the master ECU while the fuel specific ignition timing is managed by the master ECU. The fuel mode selection is conveyed to the slave ECU by a dashboard mounted fuel selector switch which has an integrated fuel level and fuel operation mode display.

Multiple functions are integrated into the fuel selector switch which makes it cost effective and user friendly. By controlling the illumination frequency of the LEDs in the selector switch, the following modes are communicated to the driver:

- Mode of operation (Gasoline/Gas)
- Fuel transitions (Gasoline-Gas-Gasoline)
- Gas system errors (failure of gas components)
- Empty tank indication.

Table 2 describes the salient features of EMS system

Table 2. Salient features of the EMS system

Principle	Master -Slave
Injection Type	Sequential injection with Peak & Hold type gas injectors and saturated current gasoline injectors
Ignition	Wasted Spark (grouped)
Features	Low pressure leak detection in CNG or LPG by monitoring the pressure decay during power down and before transition.
	High pressure leak detection in CNG by monitoring the pressure decay during power down and before transition.
	On the fly transition from gasoline – gas and gas- gasoline irrespective of engine state (acceleration / deceleration).
	Empty tank detection and intimation by monitoring the pressure rise / decay during solenoid ON states and automatic switching to gasoline mode
	Tank and regulator solenoid management depending on the pressure in the rail.
	Automatic transition to gasoline in the event of gas system failure.
	Low pressure gas system purge during cold transition from gasoline – gas depending on pressure in the gas rail
	Automatic adaptation to CNG composition through A/F feedback monitoring
	Independent fully adaptive air fuel ratio management for gasoline and gas modes
	R110 and R67 compliant.
	Completely diagnosable system with intelligent indicating mechanism.

As the engine and EMS are common for CNG and LPG operation, test bench tests were conducted on a single engine with all the three alternate fuels thereby eliminating the effect of EMS system and engine to engine variation on performance parameters.

DESIGN AND INTEGRATION

INTAKE MANIFOLD

The gasoline engine intake manifold was modified to accommodate both gasoline and gas injectors. The location of the gas injectors was decided based on durability, packaging and accessibility aspects. Placing the injectors close to the port reduces the response lag and dead gas volume thereby improving the response to acceleration inputs.

Unlike gasoline fuel injection, engine operation in gas injection system is immune to injector installation angle and spray geometry as the fuel is injected in gaseous state. This gives additional flexibility to optimise the gas injector location. [Figure 3](#) shows the intake manifold with the dual injectors mounting scheme. Integration of gas injectors on the intake manifold had no impact on the base gasoline

performance as the port, runner and plenum dimensions remained unchanged.

The new design was validated by conducting mixture distribution analysis tests at different engine speeds and loads with different A/F ratio settings. By monitoring the richness in the individual cylinder exhaust ports and at the oxygen sensor location, inference can be made on the cylinder to cylinder richness variation and fuel distribution. The richness deviation between the average richness measured at the individual cylinders and the richness measured at common oxygen sensor location was observed to be less than 1% justifying the proper injector location and mixture distribution.

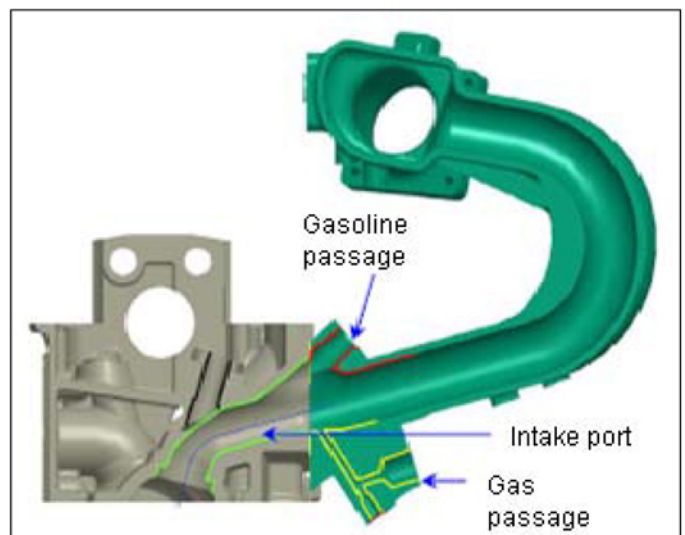


Figure 3. Intake Manifold

GAS RAIL AND HOSES

The gas rail and hoses [Fig. 4] were designed considering the following critical constraints:

- compactness (space availability)
- closeness to the injectors (shorter hose length)
- clearances for serviceability
- gas pressure & temperature sensor integration
- optimum gas rail volume

The gas rail volume was designed to dampen the pressure fluctuations during gas injection at high engine speeds and loads. The hose lengths were kept as short as possible to reduce the pressure oscillations during injector opening. Bolted design was adopted for the rail mounting to make it easier for servicing.

The design evaluation of the fuel rail was done by monitoring the pressure fluctuation in the fuel rail and hoses by

simulating injection cycles on individual injectors as well as by simulating simultaneous injection on all four injectors. Figure 5 shows the gas pressure fluctuations in the rail during simulated injection. The pressure fluctuations are damped within 0.03secs. Similar observation was made in the injector hoses [Fig. 6]. The injector hose 1 and 4 showed higher pressure fluctuations than injector 2 and 3. Longer the hose length, higher is the pressure fluctuations in the hoses.

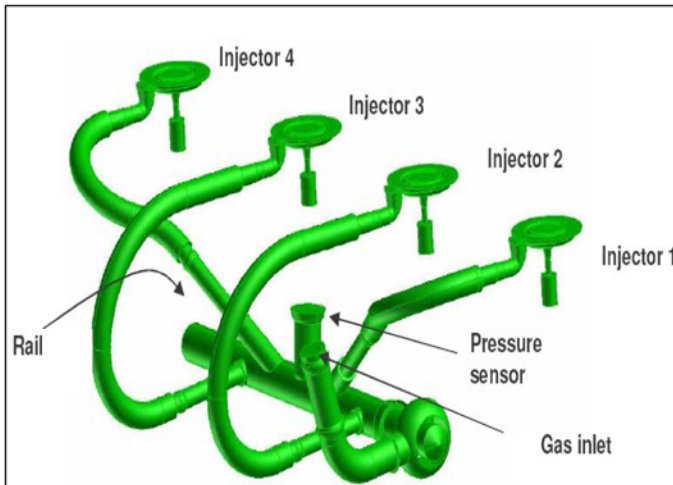


Figure 4. LPG / CNG rail and injector hose layout

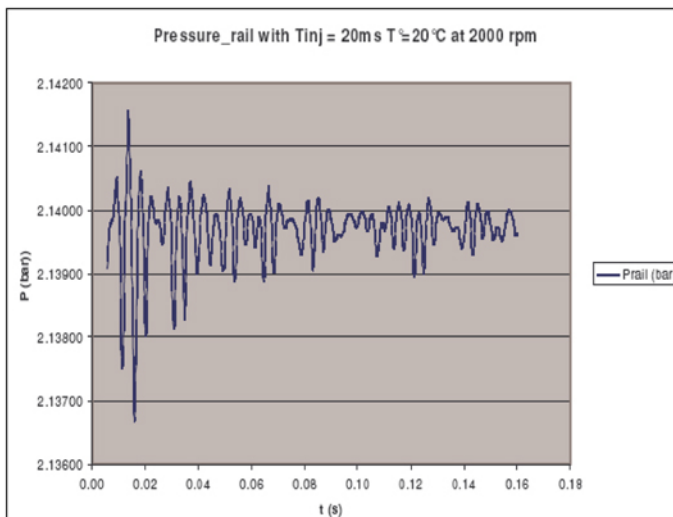


Figure 5. Pressure fluctuation in LPG rail

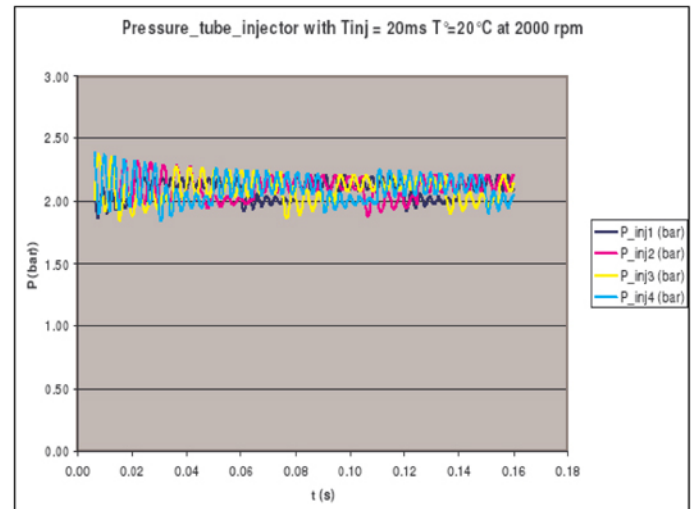


Figure 6. LPG Pressure fluctuation in the injector hoses

COOLANT CIRCUIT

Gaseous fuels undergo expansion and pressure modulation in the pressure regulator / vaporizer before injection. In fuels like LPG this expansion process is accompanied by a phase change wherein liquid LPG gets converted to vapour. This process of phase change and expansion in the vaporizer is critical due to the following reasons:

- Stiffening of the vaporizer diaphragm and fuel hoses due to cooling (Joule Thompson effect)
- Possibility of liquid carry over - specific to LPG
- Improper regulation of the output gas pressure.

To avoid these critical issues, vaporizer heating becomes an essential system integration parameter. This was achieved by circulating hot engine coolant through the vaporizer. It is important to note that insufficient coolant flow through the vaporizer can cause fluctuations in the regulated pressure and temperature. At high fuel flow zones (like wide open throttle), insufficient coolant can eventually lead to torque loss / engine stalling. The minimum required coolant flow through the vaporizer varies with engine speed with their relation being linear in normal driving engine speed range [Fig. 8]. Unlike CNG system, LPG system requires more coolant flow through the vaporizer because of the phase change process. Insufficient heating may lead to incomplete phase change resulting in "liquid carry over".

A new coolant circuit was designed to allow an uninterrupted circulation of coolant to the vaporizer.

<figure 7 here>

The functional validation of the vaporizer coolant circulation system was done by measuring the coolant flow through the vaporizer and monitoring the gas temperature and pressure at