Performance and Emissions of LPG Fueled Internal Combustion Engine: A Review

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Abstract- Alternative fuels for both spark ignition (SI) and compression ignition (CI) engines have become very important owing to increased environmental protection concern, the need to reduce dependency on petroleum and even socioeconomic aspects. The investigations have been concentrated on decreasing fuel consumption by using alternative fuels and on lowering the concentration of toxic components in combustion products. Realizing the gravity of the problem, steps are being taken to introduce better technologies, better fuel quality, shift to environment friendly fuels. Alternative fuels like LPG, CNG, hydrogen etc has emerged as a solution to depleting crude oil resources as well as to the deteriorating urban air quality problem. As a gaseous fuel, gains from LPG have already been established in terms of low emissions of carbon monoxide, hydrocarbon. Air-fuel ratio, operating cylinder pressure ignition timing and compression ratio are some of the parameters that need to be analyzed and optimally exploited for better engine performance and reduced emissions. In the present paper a comprehensive review of various operating parameters and concerns have been prepared for better understanding of operating conditions and constrains for a LPG fueled internal combustion engine.

Keywords - LPG, Spark ignition engines, Dual fuel engine, Combustion characteristics, performance characteristics and Emissions.

INTRODUCTION

Air pollution is fast becoming a serious urban as well as global problem with the increasing population and its subsequent demands.Finding an alternative to conventional fuels would help to reduced it. Vehicles running on cleaner fuels produce fewer harmful emissions, and can offer some savings on fuel costs, compared with petrol or diesel. In addition to cleaner, low sulphur versions of the conventional vehicle fuels petrol and diesel, the main alternatives are currently road fuel gases LPG and CNG bio-fuels and, more distantly, hydrogen fuels, including methanol; fuel cells, and electric vehicles. *Kirti Bhandari et.al [1]*LPG as a fuel for spark ignition engines, it has many of the same advantages as natural gas with the additional advantage of being easier to carry aboard the vehicle. Its major disadvantage is the limited supply, which rules out any large-scale conversion to LPG fuel. LPG is typically a mixture of several gases in varying proportions. Major constituent gases are propane (C_3H_8) and butane (C_4H_{10}), with minor quantities of propane (C_3H_6), various butanes (C_4H_8), iso-butane, and small amounts of ethane (C_2H_6). The composition of commercial LPG is quite variable. Being a gas at normal temperature and pressure LPG mixes readily with air in any proportion. Figure 1 shows that about 55% of the LPG processed from natural gas purification. The other 45% comes from crude oil refining. LPG is derived from petroleum, LPG does less to relieve the country's dependency on foreign oil than some other alternative fuels.LPG does help address the national security component of the nation's overall petroleum dependency problem. [2]To benefit from the use of LPG in IC engines, it is necessary to understand its combustion under the appropriate conditions and to study the effects of various parameters on it.

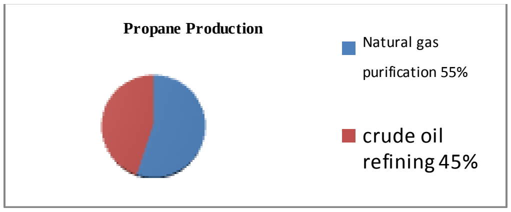

Figure 1: Propane Production

This review aims to prepare a concise state of art that provides an idea of various concerns related to employment of LPG as a vehicular fuel in order to improve the rapidly deteriorating air quality conditions in urban regions. Comparative Properties of LPG, Gasoline, Diesel and CNG as follows.

TABLE I
COMPARATIVE PROPERTIES OF LPG, GASOLINE, DIESEL AND CNG.[14][19][20

Properties/fuels	Gasoline	Diesel	LPG	CNG
Chemical strcture	C_7H_{17}/C_4 to C_{12}	C_8 to C_{25}	C_3H_8	CH_4
Energy density	109,000-125,000	128,000-30,0000	84,000	35,000 @ 3000 psi
Octane number	86-94	8-15	105+	120+
Lower heating value (MJ/Kg)	43.44	42.79	46.60	47.14
High Heating Value (MJ/Kg)	46.53	45.76	50.15	52.20
Stoichiometric air/fuel ratio	14.7	14.7	15.5	17.2
Density at 15˚C,kg/m3	737	820-950	1.85/505	0.78
Autoignition temperature °K	531	588	724	755-905
Specific Gravity 60° F/60°	0.72-0.78	0.508	0.85	0.424

Amongs the spark ignition and the compression ignition engines, diesel engines tend to be more energy efficient than Gasoline engines, provide higher torque output and operate over limited engine speeds; however, such engines typically do not provide the throttle response and flexibility desired for lighter weight vehicles. The parameters of particular interest are engine torque, power and specific fuel economy. Engines are basically air pumps,ability of an engine to pump air is called Volumetric efficiency (VE), which if reduced; the maximum power output will be reduced.

As the gaseous fuel requires 4 to 15 percent of more intake passage volume than liquid fuels which reduces the VE and hence maximum power output will also be reduced(by 4%). SI engines burn a premixed air-fuel mixture followed by compression before a spark ignites the mixture. Octane rating of a fuel indicates how slowly the fuel will burn and how well the fuel will resist pre-ignition before the spark plug fires. Higher octane fuels can be burned at high compression ratios (CR). The higher CR of an engine, the more efficient is the engine and more is the power generated with given amount of the fuel. LPG has high octane rating 110+ that allows CR to be high up to 15:1, which is in the range of 8:1 to 9.5:1 for gasoline engines.*Kirti Bhandari et.al[1]*

1. LPG AS AN ALTERNATIVE FUEL FOR IC ENGINE

The gaseous nature of the fuel/air mixture in an LPG vehicle's combustion chambers eliminates the cold-start problems associated with liquid fuels. LPG defuses in air fuel mixing at lower inlet temperature than is possible with either gasoline or diesel. This leads to easier starting, more reliable idling, smoother acceleration and more complete and efficient burning with less unburned hydrocarbons present in the exhaust. In contrast to gasoline engines, which produce high emission levels while running cold, LPG engine emissions remain similar whether the engine is cold or hot. Also, because LPG enters an engine's combustion chambers as a vapor, it does not strip oil from cylinder walls or dilute the oil when the engine is cold. This helps to have a longer service life and reduced maintenance costs of engine. Also helping in this regard is the fuel's high hydrogen-to-carbon ratio (C_3H_8), which enables propane-powered vehicles to have less carbon build-up than gasoline and diesel-powered vehicles. LPG delivers roughly the same power, acceleration, and cruising speed characteristics as gasoline. Its high octane rating means engine's power output and fuel efficiency can be increased beyond what would be possible with a gasoline engine without causing *Destructive Knocking*. Such fine-tuning can help compensate for the fuel's lower energy density.

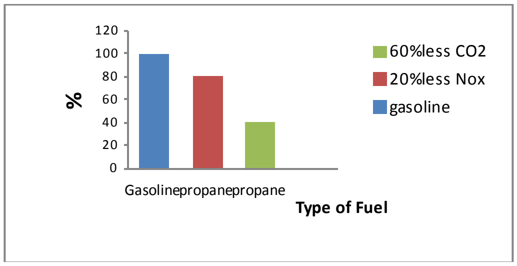

Figure 2: Vehicle Emissions

The higher ignition temperature of gas compared with petroleum based fuel leads to reduced auto ignition delays,less hazardous than any other petroleum based fuel and expected to produce less CO, NOx emissions and may cause less ozone formation than gasoline and diesel engines.

2. ENGINE MODIFICATIONS REQUIRED

Many propane vehicles are converted gasoline vehicles the relatively inexpensive conversion kits include a regulator/vaporizer that change liquid propane to a gaseous form and an air/fuel mixer that meters and mixes the fuel with filtered intake air before the mixture is drawn into the engine's combustion chambers. Also included in conversion kits is closed-loop feedback circuitry that continually monitors the oxygen content of the exhaust and adjusts the air/fuel ratio as necessary.LPG vehicles additionally require a special fuel tank that is strong enough to withstand the LPG storage pressure of about 130 pounds per square inch.

3. ENGINE TECHNOLOGY FOR LPG VEHICLES

As the LPG is stored in liquid form under high pressure,it is need to convert it into vaporized form before drawn into the combustion chamber. As engine technology for LPG vehicles is similar to that for natural gas vehicles, with the exception that LPG is not commonly used in dual-fuel diesel applications due to its relatively poor knock resistance *Hutcheson1995[21].*

For Spark ignition engine there are two types of LPG engines are primarily studied

1. LPG which is stored in composite vessel at high pressure approximately at 10-20 bar,supply to the engine is controlled by a regulator or vaporizer, which converts the LPG to a vapour. The vapour is fed to a mixer located near the intake manifold, where it is metered and mixed with filtered air before being drawn into the combustion chamber where it is burned to produce power, just like gasoline.
2. LPG fueled direct injection SI engine, especially in order to improve the exhaust emission quality while maintaining high thermal efficiency comparable to a conventional engine. In-cylinder direct injection engines developed recently worldwide utilizes the stratified charge formation technique

at low load, whereas at high load, a close-to-homogeneous charge is formed. Thus, compared to a conventional port injection engine, a significant improvement of fuel consumption, power can be achieved and these system have proven to be reliable in terms of engine durability and cold starting.

Recently, several works have been carried out for injecting the fuel directly into the combustion chamber to meet the low emission standard and high efficiency.And those methods have been used in practical gasoline engines. However, a large amount of unburned hydrocarbon emission is a new problem with GDI engines, when they operate near the Stochiometric mixing condition. Kirti Bhandari et.al[1 traditional premixed charge combustion engine has lower thermal efficiency due to high occurrence of engine knock and the unavoidable throttling at intake. Homogeneous-charge lean combustion engines can realize a high thermal efficiency due to the low pumping and heat loss and increase in the specific heat ratio, at the expense of moderately high NOx emissions due to ineffectiveness of the catalyst. However, the lean operation limit for this type of lean homogeneous engine was not high compared to the value of diesel engine. The charge stratification in the combustion chamber permits extremely lean combustion that increases the thermal efficiency but gives the penalty of high NOx. Noise, produced by the combustion process cause immediate annoyance and physiological change. Combustion noise occurs in two forms, direct and indirect. Direct noise is generated in and radiated from a region undergoing turbulent combustion. The indirect noise is generated downstream of the combustion region due to interactions between streamlines of different temperatures. Main factor that affects the combustion noise is the pressure rise rate during combustion.

4. PRESENT STATUS OF LPG ENGINES: PERFORMANCE AND COMBUSTION CHARACTERISTICS

Following literature survey is done to study the present status of LPG engines performance and combustion characteristics
Shinichi Goto 2000 [6] has been carried out to investigate the effect of various piston cavities and swirl ratio on combustion characteristics as well effect of fuel composition on engine performance with a single cylinder research engine (Nissan Diesel Co. FD1L.From the results he found that Lean burn operation of an LPG SI engine resulted in improved fuel consumption for both the full and half load cases. As the in-cylinder flow was made more turbulent by suitable piston cavity modification, the cyclic variation and combustion duration both declined. The dog dish cavity achieved the lowest thermal efficiency, whereas the bathtub cavity showed the highest value. Although the nebula cavity showed improved combustion characteristics, had the highest NOx emissions than produced with dogdish cavity. The nebula cavity showed a better thermal efficiency than the bathtub cavity, since the nebula cavity could achieve leaner combustion. High swirl improved combustion stability and thermal efficiency, and enabled engine operation at low NOx levels.

Ki HyungLee, Chang Sik Lee, Jea Duk Ryu And Gyung-Min Choi2002[8] investigate the combustion characteristics and flame propagation of the LPG (liquefied petroleum gas) and gasoline fuel.The flame propagation of both LPG and gasoline fuels was investigated by the laser deflection method and the high-speed Schlieren photography. The flame propagation speed of the fuel is increased with the decrease of initial pressure and the increase of initial temperature in the constant volume chamber. The results also show that the equivalence ratio has a great effect on the flame speed, combustion pressure and the combustion duration of the fuel-air mixture.

G.H.Choi et.al 2002[9] carried out to quantify the combustion and emissions characteristics of LPG fuelled SI engine with minor modification in original SI engine to run on LPG fuel with varying volume percentage of LPG at 5%,10%,20% with the help of PLC controller. Engine speed maintained at 4000rpm,the relative air-fuel ratio varies from 0.8 to 1.3.The exhaust gas constituents (CO_2,CO,uHC and NOx) were measured using the 5-gas analyzer. Percentage of LPG in gasoline means that the combustion shifted towards complete phase and 'greener' exhaust products were subsequently released to the atmosphere. For each proportion of LPG in gasoline investigated, it was also observed that the CO_2 emissions peaked at around λ=1 and exhibits lower percentages at rich and lean mixtures. An increasing proportion of LPG in gasoline promotes faster burning velocity of mixture and hence reduce the combustion duration and subsequently the in-cylinder peak temperature increases. At high relative air-fuel ratio, the amount of NOx measured was much higher, uHC also shows marked reduction as the relative air-fuel ratio exceeds Stochiometric.

Ki hyung Lee et.al 2005[7] study to clarify the combustion process of the heavy duty LPG engine, the flame propagation and combustion characteristics were investigated using a CVCC and a port injection type heavy duty LPLi engine system. Both the laser deflection method and the high-speed Schlieren photography method were employed to measure the flame propagation speed of LPG fuel. In addition, the single cylinder heavy duty LPLi engine was manufactured to analyze the combustion characteristics of the LPG. According to the CVCC and heavy duty LPLi engine experimental results, the flame propagation reached a maximum speed at the Stochiometric equivalence ratio, regardless of operating conditions, and the effect of the equivalence ratio on both flame propagation and combustion characteristics was greater than that of ambient conditions. In addition, we found that the coefficient of variation of combustion duration increased when the equivalence ratio decreased.

M.A. Ceviz, F.Yuksel 2006[14]compare the cyclic variability and emission characteristics of LPG and gasoline-fuelled spark ignition engine at lean operating conditions. Cylinder pressure, indicated mean effective pressure (imep), mass fraction burned (MFB) and combustion duration are presented in relation to cyclic variability. Variations in the CO, CO_2 and HC emissions are also discussed. The lean operation decreases the flame speed and the burning rate, result in an increase in the overall combustion duration, However, the increases in the combustion duration when in operation with LPG is lower than that of gasoline despite working on more lean conditions. The reason for the lower combustion duration is the higher laminar burning velocity of LPG (0.46 m/s) when compared with gasoline (0.42m/s) and lowered the emission also. ***Orhan Durgun et.al****2007[15]* Studied a quasi-dimensional spark ignition (SI) engine cycle model is used to predict the cycle, performance and exhaust emissions of an automotive engine for the cases of using gasoline and LPG. Combustion is simulated as a turbulent flame propagation process and during this process, two different thermodynamic regions consisting of unburned gases and burned gases that are separated by the flame front are considered. A computer code for the cycle model has been prepared to perform numerical calculations over a range of engine speeds and fuel–air equivalence ratios. In the computations performed at different engine speeds, the same fuel–air equivalence ratios are selected for each fuel to make realistic comparisons from the fuel economy and fuel consumption points of view. Comparisons show that if LPG fueled SI engines are operated at the same conditions with those of gasoline fueled SI engines; significant improvements in exhaust emissions can be achieved.

C-L Myung,S Park,J Kim,K Choi,I G Hwang 2011[22] focuses on the experimental comparison of combustion phenomena and nanoparticle emission characteristics from a wall-guided DI spark ignition engine for gasoline and LPG. A returnless GDI fuel supply system was reworked for the return-type liquid-phase LPG injection fuel supply system that was composed of an LPG tank with a brushless d.c. pump and a low-pressure regulator to supply the stable liquid-phase LPG for the DI engine. To verify the clean combustion characteristics of the LPG DI engine, nanoparticle concentrations obtained with a differential mobility spectrometer and the total hydrocarbon and nitrogen oxide emission levels were compared with those of a gasoline-fuelled engine.In conclusion, the nanoparticle and exhaust emissions of the LPG DI engine were much lower than those of the GDI engine. And the combustion stability in a part-load condition of LPG was better than that of gasoline because it evaporated very rapidly and mixed well with the air.

From the above literature review showed the improved combustion characteristics, performance and emissions characteristics with LPG as alternative fuel to gasoline at various condition such as changing the piston cavities, air fuel ratio, speed etc.Further research has to be carried out by changing compression ratio/ignition timing to compare the performance and emissions characteristics.

5. NOISE AND AIR POLLUTION WITH LPG ENGINES

The study of engine noise has been carried out since the early stages of engine development. In 1931, Ricardo first found a descriptive relationship between the combustion pressure rise and the noise produced . Later, a number of parameters in determining the noise developments were investigated which include the first and the second derivative of cylinder pressure . These methods were effective in revealing the relationship between engine combustion and noise. Some of them still play an important role in identifying the source of engine noise *Ando. H.et.al[3]*.Although there are a number of engine noise sources, one of the most fundamental is the combustion-induced noise. It occurs toward the end compression stroke and subsequent expansion stroke. The rapid pressure change due to the combustion transmits through engine structures and forms a part of the airborne noise . This pressure change also causes the vibration of the engine components such as the cylinder head, pistons, connecting rods and engine body.Because of its superior knock-resistance, propane is preferred to butane as an automotive fuel.The lean combustion limit of propane-gasoline mixtures is considerably leaner than for gasoline, allowing the use of lean-burn calibrations, which provides more resistant to knocking and permit the use of still higher compression ratios.LPG has many of the same emission characteristics as natural gas. Graph shows IANGV emissions comparison study between Gasoline, LPG and CNG.Switching from gasoline to LPG and CNG results in a substantial reduction in the CO emission. CNG also reduced HC and NO_X emissions.

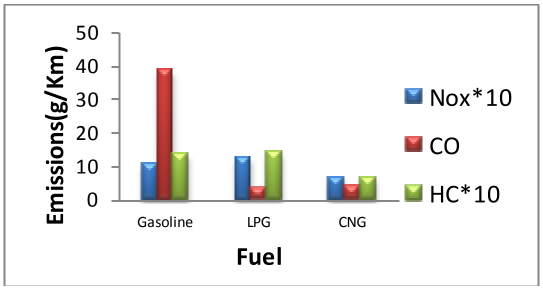

Figure 3: A Summary of Emission with Non-Catalyst Vehicle

On an energy basis LPG has a lower carbon content than gasoline or diesel fuel. When used in spark-ignition engines, LPG produces near-zero particulate emissions, very little CO and moderate HC emissions. Variations in the concentration of different hydrocarbons in LPG can affect the species composition and reactivity of HC exhaust emissions. As olefin (such as propene and butane) are much more reactive in contributing to ozone formation than paraffin's (such as propane and the butanes), an increase in the olefin content of LPG is likely to result in increased ozone-forming potential of exhaust emissions. Due to the gas-tight seals required on the fuel system, evaporative emissions are negligible.Exhaust NMHC and CO emissions are lower with LPG than gasoline. CO_2 emissions typically are also somewhat lower than those for gasoline due to the lower carbon-energy ratio and the higher octane quality of LPG. NOx emissions are similar to those from gasoline vehicles, and can be effectively controlled using three-way catalysts. Overall, LPG provides less air quality benefits than CNG mainly because the hydrocarbon emissions are photochemically more reactive and emissions of CO are higher. Modern dual-fueled LPG cars have achieved impressive results in reducing emissions. Average emissions and fuel consumption test results for five dual-fueled passenger cars fitted with closed-loop three-way catalysts and third generation LPG equipment are summarized in table 2.The tests were conducted over the EDCE+EUDC cycle. Table 3 shows the limited emissions data available for LPG vehicles.

TABLE II
PASSENGER CAR AND HEAVY DUTY ENGINE EMISSIONS FOR LPG.[20][21]

Vehicle type	NOx	NMHC	CO
Passenger car (g/mile)	0.2	0.15	1
Heavy-duty engine (g/bhp-hr)	2.8	0.5	23.2

TABLE III
COMPARISON OF EMISSIONS AND FUEL CONSUMPTION FOR FIVE MODERN DUAL FUELED CARS OPERATING ON GASOLINE AND LPG.[20][21]

Sr. no.	Emissions and fuel consumption	Gasoline	LPG
1	CO (g/km)	0.87	0.72
2	HC (g/km)	0.14	0.12
3	NOx (g/km)	0.12	0.16
4	Fuel consumption (l/100km)	8.7	11.3
5	Energy consumption(MJ/km)	2.8	2.7

Modern spark-ignition LPG-fueled engines equipped with a three-way catalyst can easily meet (Euro 2 and 3) stringent heavy-duty emission standards. Lean burn engines in combination with an oxidation catalyst can also achieve very low emission results (Hutcheson 1995). The very low levels of particulate emissions with both stoichiometric and lean-burning LPG engines continue to be their strongest point, particularly as this is attainable with low NOx emissions.

LeeS.etal [17] performed experimental study on performance and emission characteristics of an SI engine operated with DME mixed with LPG. The results they obtained showed that knocking was significantly increased with DME due to the high Cetane number of DME. The output engine power of using 10% DME was comparable to that of pure LPG. Exhaust emissions such as HC and NOx were slightly increased when utilizing blended fuel at low engine speeds. Using blended fuel, however, the engine power output was decreased and break specific fuel consumption (BSFC) was extremely deteriorated because the energy content of DME is much lower than that of LPG.

IANGV Emission Report shown that unregulated emissions like (1,3-butadiene,benzene,formaldehyde and methanol of all the alternative fuel) of LPG give vehicles are generally less than formaldehyde levels for gasoline fuels. Graph shows Three-way catalyst technology is efficient in removing not only regulated emission components but also harmful unregulated components. On gasoline, the TWC reduces 1,3-butadiene, benzene and formaldehyde emissions by a factor of more than 10. For these three components, LPG and CNG give lower emissions than gasoline.TNO data on acetaldehyde emissions from non-catalyst vehicle Switching from gasoline to gaseous fuels reduces PAH emissions by a factor of 10. However, one could estimate that the total toxic effects going from gasoline to natural gas in non-catalyst vehicles will be reduced substantially.

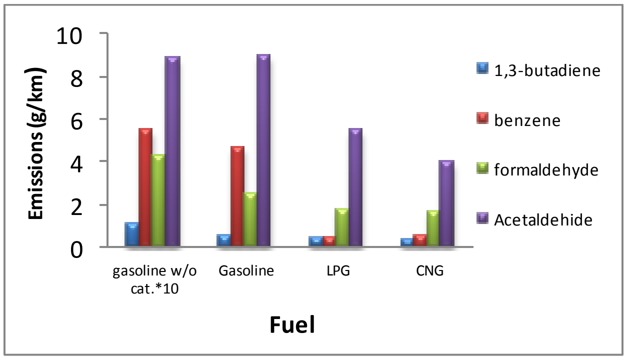

Figure. 4- Unregulated emission components (average values) for different fuel.

In all cases studied, LPG energy economy was lower than EPA certification fuel economy data for the pre-conversion gasoline vehicle (i.e. conversion appears to have reduced efficiency on gasoline). All the vehicles tested by EPA also yielded large decrease in acceleration performance, measured by 5-60 mph and 30-60 mph. Finally, each of these DF vehicles had a lower range on LPG than on gasoline, typically at least at a 50 percent reduction. Efficiency, performance and range characteristics can be improved with dedicated and optimized LPG vehicles. Using accepted relationship between weight, acceleration and fuel economy, it was estimated that a LPG with range and power equivalent to the gasoline model would be less efficient (25%). This tradeoff between efficiency, performance and range is the reason why many experts believe LPG and CNG is better suited for centralized urban fleet applications than for general public use.

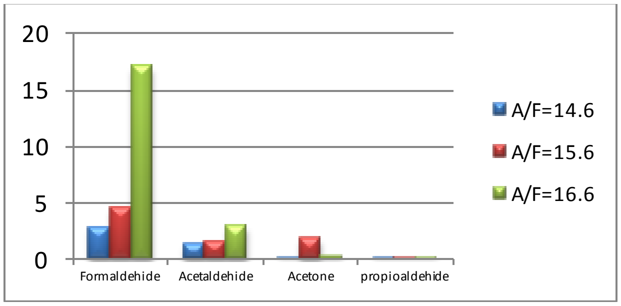

Figure. 5-Concentration (ppmv) of aldehydes in exhaust gases of LPG fuelled engine.

Figure 5 shown the concentration (ppmv) of aldehydes in exhaust gases of LPG fuelled engine at rich,stoichiometric and lean Air/fuel ratio.

From the Study done by ETSAP LPG has a relatively high energy content per unit of mass, but its energy content per unit volume is low. Thus, LPG tanks have more space and weight than petrol or diesel fuel tanks, but the range of LPG vehicles is equivalent to that of petrol vehicles. Bi-fuel LPG car tests show around a 15% reduction in greenhouse gas emissions (per unit of distance) compared to petrol operation. The best quality LPG bi-fuel engines produce fewer NOx emissions and virtually zero particulate emissions if compared to petrol. [21]

Fuel Options for Controlling Emissions. Both Stochiometric and lean-burn LPG engines have been developed with good results. Nearly all LPG vehicles currently in operation are aftermarket retrofits of existing gasoline vehicles, mostly using mechanical (as opposed to electronic) conversion systems.

CONCLUSION

Based on the reviewed paper for the emissions and performance, its concluded that the LPG represents a good fuel alternative for gasoline and therefore must be taken into consideration in the future for transport purpose. Apart from the fuel storage and delivery mechanism, LPG engines similar to petrol engines, and deliver nearly similar performance and good in combustion characteristics than Gasoline. In the short term, LPG as a alternative fuels reviewed could displace 10 per cent of current usage of oil, or bring significant reductions in CO, CO_2 emissions and help to reduce harmful greenhouse gas emissions. In the next five to ten years, LPG will be more widely available and gaining market share across vehicle ranges.

LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOLS

λ=relative air-fuel ratio

ABBREVIATIONS AND CODES

CVCC- Constant Volume Combustion Chamber
CNG - Compressed Natural Gas
DF - Duel Fuel
DI - Direct Injection
DME - Di-Methyl Ether
ECE - Economic Commission for Europe/ECE test method
EGR - Exhaust Gas Recirculation
EPA - Environmental Protection Agency
EUDC - Extra Urban Driving Cycle
EURO - European Union test method/limit value
ETSAP - Energy Technology System Analysis Programme
GDI - Gasoline Direct Injection
HD -Heavy -Duty
IANGV - International Association for Natural Gas Vehicles
LPG - Liquefied Petroleum Gas
LPLi - Liquefied Petroleum Liquid injection
NMHC - Non-Methane Hydrocarbons
PAH - Polyaromatic Hydrocarbons
TNO -TNO Road-Vehicles Research Institute (Holland)
TWC - Three-Way Catalyst
VE - Volumetric efficiency

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