

Bi-fuel System - Gasoline/LPG in A Used 4-Stroke Motorcycle - Fuel Injection Type

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Abstract. Bi-fuel-Gasoline/LPG system has been effectively and efficiently used in gasoline vehicles with less pollutants emission. The motorcycle tested was a used Honda AirBlade i110 - fuel injection type. A 3-litre LPG storage tank, an electronic fuel control unit, a 1-mm LPG injector and a regulator were securely installed. The converted motorcycle can be started with either gasoline or LPG. The safety relief valve was set below 48 kPa and over 110 kPa. The motorcycle was tuned at the relative rich air-fuel ratio (λ) of 0.85-0.90 to attain the best power output. From dynamometer tests over the speed range of 65-100 km/h, the average power output when fuelling LPG was 5.16 hp; dropped 3.9% from the use of gasoline. The average LPG consumption rate from the city road test at the average speed of 60 km/h was 40.1 km/l, about 17.7% more. This corresponded to lower LPG's energy density of about 16.2%. In emission, the CO and HC concentrations were 44.4% and 26.5% lower. Once a standard gas equipment set with ECU and LPG injector were securely installed and the engine was properly tuned up to suit LPG's characteristics, the converted bi-fuel motorcycle offers efficiently, safely and economically performance with environmental friendly emission.

1. Introduction

Since all vehicles heavily depend upon petroleum fuels, the fluctuations of fuel price are of great concern. In Asian countries like Thailand, Vietnam and Myanmar, motorcycles are popular and widely used because of affordable prices and not well support countries' infrastructure. Interestingly, Thailand, Vietnam and Myanmar are gas production countries [1,2]. Therefore clean gaseous fuels, NG and LPG, would be potential alternate fuels for gasoline vehicles. This would benefit both environment improvement and national energy development. In Thailand, fast growing car and motorcycle population cause traffic congestion and pollution problems in the capital and major cities. About two-fold lower pricing than gasoline and more gas filling stations available than NG, LPG becomes very attractive alternate fuel for vehicles nationwide. Though a standard gas equipment set for vehicle and safely installation are costly, much lower prices of both LPG and NG are justifiable for vehicle owners; passenger, light and heavy duty vehicles, to modify their vehicles for gaseous fuel use.

In Thailand, over 20 million registered motorcycles have been used nationwide, about 54.2% of total registered vehicles [3]. Motorcycle was the highest share among the registered vehicles in the country. They are needed not only for personal uses but also for public services. The bi-fuel system of gasoline/LPG fitted in a used motorcycle with fuel injection and water cooling system was therefore conducted and tested for engine performance, fuel consumption and emission. This converted bi-fuel motorcycle will be a prototype providing safe, efficient and smooth riding. Furthermore it can be



developed for transporting agricultural products in community and rural areas. However law and regulation applied to modified gaseous fuel vehicles has not yet included gaseous motorcycles.

Combustion in spark ignition engines

In spark ignition (SI) engines, the fuel-air mixture in the engine intake system enters the engine cylinder, reacts and combustion occurs inside the cylinder. Combustion of the fuel-air mixture controls engine power, efficiency, and emissions. The theoretical or stoichiometric fuel-air ratio is the ratio of fuel completely reacted with enough oxygen to produce CO_2 and H_2O . Engines can be operated under the condition of either fuel-rich mixture or fuel-lean mixture. In case of excess air or fuel-lean combustion, the non-reacted air appears in the products stream. Under the fuel-rich mixtures or insufficient oxygen environment, the incomplete combustion takes place and yields a mixture of CO_2 and H_2O and carbon monoxide CO and hydrogen H_2 and nitrogen N_2 . The composition of the combustion products is significantly difference from fuel-lean and fuel-rich mixture conditions and the stoichiometric fuel-air ratio depends upon fuel composition [4-5]. It is therefore to define an informative parameter for mixture compositions. That is, the fuel-air equivalence ratio, ϕ and its inverse, the relative air-fuel ratio, λ are as follows: [6]

$$\phi = \frac{\left(\frac{A}{F}\right)_{\text{stoic}}}{\left(\frac{A}{F}\right)_{\text{actual}}} = \frac{1}{\lambda} \quad (1)$$

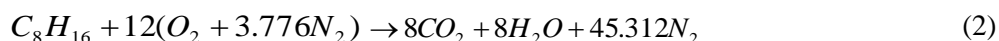
For fuel-lean mixture: $\phi < 1; \lambda > 1$

For stoichiometric mixture: $\phi = \lambda = 1$

For fuel-rich mixture: $\phi > 1; \lambda < 1$

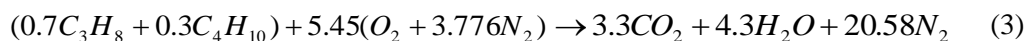
To ensure smooth and reliable operation, the SI engines have normally been operated close to stoichiometric or slight fuel-rich condition. Best torque and power will be produced at about 10-15% fuel-rich mixture and best economy will be produced at a similar amount of fuel-lean mixture. The amount of CO in the exhaust is a measure of fuel-rich condition whereas the amount of O_2 in the exhaust is a measure of fuel-lean condition. Oxides of nitrogen NO_x depend on temperature and pressure [5] and it reaches a peak with slightly fuel-lean condition.

The stoichiometric combustion reaction of C_8H_{16} is [4]



and $\left(\frac{A}{F}\right)_{\text{stoic}} = 14.8.$

The stoichiometric combustion reaction of LPG, a mixture of 70% propane and 30% butane, is



and $\left(\frac{A}{F}\right)_{\text{stoic}} = 15.7.$

In reality the combustion processes are complex and often incomplete, even in the considerable excess air environment. It is therefore more practical to analyse the products experimentally. As shown in Figure 1, the emission curves indicate the complexities of emission control. Exhaust gas composition depends on the relative proportions of fuel and air fed to the engine, fuel composition, and completeness of combustion.

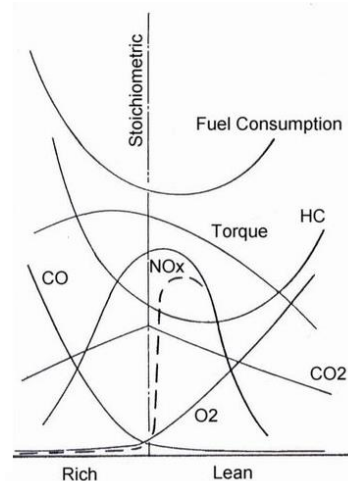


Figure 1. Relationship between torque, fuel consumption and gaseous compositions inside a SI engine with relative to air-fuel ratio [7]

Liquefied Petroleum Gas (LPG) is a non-renewable gaseous fossil fuel of propane and butane blends depending on the season - more propane in winter specification and more butane in summer. LPG is a by-product of oil refining, natural gas processing and petrochemical processes. LPG fuelled vehicles provides comparable power, acceleration and cruise speed to those of an equivalent gasoline fuelled vehicle. To be combustible, LPG must be in between 1.5% and 9.6% of the total LPG/air mixture. That is, the lower flammable limit (LFL) and the upper flammable limit (UFL) of LPG [8] is 1.5 and 9.6%. LPG is water insoluble; LPG does not pollute underground water sources. Its advantages are non-toxic, non-corrosive, having high octane rating (RON) of 102-108 depending on local specifications and, more importantly, environmental friendly fuel which produces less CO and toxics, especially benzene and butadiene emission, as well as regulated emissions. Carbon dioxide (CO₂) emission levels are reduced by up to 40% over those of gasoline vehicles [2]. With less carbon build-up, spark plugs often last longer and less frequently oil changes are needed. However there are some LPG drawbacks when fuelling vehicles which are starting problem in cold condition at below 0°C because of the low vapour pressure of propane at low temperatures, and having lower energy density than gasoline resulting in 14% consumption more than a comparable gasoline vehicle. In addition the LPG filling stations are much less than the gasoline gas station and needs more frequent refuelling, it will be more practical to keep some amount of gasoline as a back-up fuel. Gasoline and LPG characteristics are given in Table 1 [9,10].

Table 1. Fuel characteristics [9,10]

Properties	LPG	Gasoline
Chemical formula	0.7C ₃ H ₈ /0.3C ₄ H ₁₀	C _{8.26} H _{15.5}
Molecular weight	48.2	114.8
Specific gravity	0.5-0.58	0.72-0.78
Reid Vapor Pressure @38°C (kPa)	-	48-108
Boiling point (°C)	-42	27-225
RON	105	92-98
MON	97	80-90
Heat of Vaporization (kJ/kg)	435	350
Lower Heating Value (MJ/kg)	50	44
Flash point (°C)	-104	-43 to -39
Auto-ignition Temperature (°C)	360	260-460
Flame temperature (°C)	1920	2030
Combustible Limit (% gas in air)	1.5-9.6	-

2. Testing methods

The motorcycle tested, Honda AirBlade i110, was used over 70,000 kilometres; the engine conditions i.e. fuel system, transmission system, and lubrication system must be thoroughly inspected before conducting the tests [11-12].

Equipment List

1. The used 4-stroke motorcycle, Honda AirBlade i110 - fuel injection, water cooling system and CVT system
2. Test fuels: Gasoline91 and LPG ($C_3:C_4 = 70:30$)
3. Dynamometer [13]
4. VERSUS ECU (Electronic Control Unit) Gas Tuning Set
5. Emission Gas Analyzer – Gena 2000

Performance Test on Dynamometer

1. Tight the motorcycle tested firmly on the dynamometer and then calibrates the engine speed (rpm) see Figure 2.
2. Start the engine and accelerate up to full throttle.
3. Cut off the transmission system. Torque and power output were automatically computed and graphically displayed.
4. Apply brake and turn off the engine.

Fuel Consumption

Mileage and fuel consumption were collected from the following test conditions [11-12]:

1. City road test at the average speed of 60 km/h. The test data were collected from daily riding in the city at the average speed of 60 km/h.
2. Long distance riding test at the constant speed of 60 km/h. This was tested on the certain road during 16:00-18:00 hr. due to light traffic

Emission Measurement

1. While running the engine, insert the oxygen sensor right in the middle of its exhaust pipe referred to Figure 3.
2. Record data shown on the screen and then remove the sensor and turn off the engine.



Figure 2. Performance Test on Dynamometer



Figure 3. Emission Measurement

Engine Modifications

To utilize the original engine arrangement system, the bi-fuel converted vehicle was fitted with fuel-injected engine modified to control the gas flow and revised ignition timing or alternatively, fitted with a standard gaseous control system [14-17]. Similarly, the motorcycle tested which was a

fuel-injection type with water cooling system was fitted with the standard LPG equipment set for vehicle which was modified to control LPG firing properly.

1. To obtain the performance data base of the motorcycle tested using gasoline91, the motorcycle was properly tuned on the dynamometer at the relative fuel-rich ratio (λ) of 0.85-0.90 which theoretically was in the best giving power output range.

2. For the use of bi-fuel system of LPG/gasoline in the motorcycle whose compression ratio was maintained, the specific 3-litre LPG storage tank was installed and wired to the VERSUS ECU kit of 4-cylinder-4-stroke engine. Note that it is wired to only 1 cylinder and left out the others. All was in the U-box beneath the seat see Figure 4. The 1 mm diameter LPG injector was inserted close to the original fuel injector and a regulator was tightly placed near the cooling over the frame bar. The engine was tuned up on the dynamometer at the λ range of 0.85-0.90. The stoichiometric air-fuel ratio required for gasoline combustion was 14.8:1 and 15.7:1 for LPG. Therefore LPG combustion is required to be operated in the fuel-leaner condition. To be combustible, the total LPG/air mixture must be present in between 1.5 and 9.6 %.

Based on VERSUS Hi-end Technology Gas for Car manual, the calculated nozzle size for LPG used in a 1-cylinder-4-stroke 110 cc engine was approximately 1 mm and the LPG injection control diagram was shown in Figure 5. The fuel nozzle injector geometry produces optimum fuel air mixing and increase the volumetric efficiency of the engine which will promote a comparable engine performance [15]. Due to having low energy density and low engine volumetric efficiency, LPG must be compressed and stored in pressure vessel. To safely use LPG for the motorcycle tested, the relief pressure was set below 48 kPa and over 110 kPa while the operating pressure and temperature was 78-80 kPa and 35°C. If the system pressure was below or above the set pressure, ECU will automatically cut off LPG feed and switch to fuel with gasoline instead. In Table 1, heat of vaporization of LPG was 435 kJ/kg and 350 kJ/kg for gasoline, the temperature of water cooling system must be kept at 35°C or slightly above for smoothly LPG vaporization. After tuning for the use of LPG, the ECU controlled the proper air/fuel ratio injection to be within the λ range of 0.85-0.90 so as to achieve the best performance with smooth riding and low emission of CO and HC.

The motorcycle tested can be either started with gasoline or LPG. Typically, it is started with gasoline and then manually changed to run with LPG from the fuel selector switch (Figure 6). In case of having trouble with fuel pump, the engine can be started with LPG. If running out of LPG while riding, a rider can just switch to use gasoline from the fuel selector switch without any interruption. Beside that refuelling LPG gas stations are not widely available; it is more practical to keep some gasoline in the fuel tank. This was a fuel back-up arrangement. Typically, a gas-fuelled vehicle needs refuelling twice or three-times as often as similar petrol [14].



Figure 4. 3-litre LPG storage tank and ECU kit

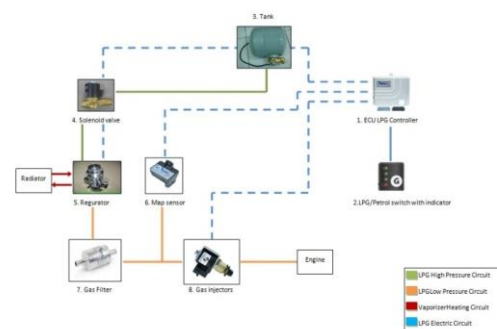


Figure 5. LPG injection control diagram



Figure 6. Fuel selector switch

3. Results and Discussion

Performance Test on Dynamometer

For the use of bi-fuel system-gasoline/LPG in the motorcycle tested, the engine was tuned up on the dynamometer at the relative fuel-rich ratio range of 0.85-0.90. When fuelling with gasoline, the engine gave the average torque 5.81 N-m over the speed range of 65-100 km/h and 5.59 N-m while using LPG (Figure 7). The average power output from burning LPG over the speed range of 65-100 km/h was 5.16 hp which was about 3.9% lower than that from using gasoline of 5.37 hp. According to Semin et al [14-17], the performance of the converted bi-fuel engine will generally drop 15-20% in maximum power from the petrol. In general, bi-fuel modified vehicles suffer power loss and encounter drive ability problems as from the design and/or the installation of the retrofit conversion packages. A bi-fuel system was arranged while retaining the petrol fuel system; the engine was prevented to fully optimize the high-octane gas. Such arrangement provides a back-up fuel where gaseous refuelling facilities are not well developed.

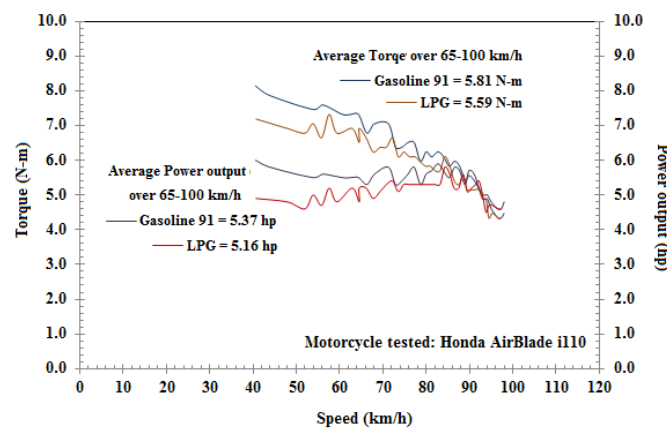


Figure 7. Comparison of Gasoline 91 and LPG performance test on SuperFlow CycleDyn Dynamometer

Gaseous fuels have low energy density resulting in low engine performance, low engine volumetric efficiency, and need of pressurized storage vessel [14,16]. However large pressure fuel tank could be utilized but weight, space, performance and cost must be compromised. For safe operation of gas-fuelled vehicles, an appropriate pressure fuel storage carried on board must be installed. The standard 3-litre LPG-pressure-storage tank was therefore installed (Figure 4). The operating pressure and temperature was 78-80 kPa and 35°C, respectively, while the safety relief valve pressure was set at below 48 kPa and above 110 kPa. It is confirmed that the bi-fuel system-gasoline/LPG can be securely and efficiently used if the engine was properly modified and tuned up. Moreover, the engine can be started with either gasoline or LPG. It is normally started with gasoline and then changed to use LPG from the fuel selector switch. In case of having problem with fuel system or run-out of gasoline, the engine can also be started with LPG. This was because the LPG vaporizer or pressure reducer was

kept at 48 kPa which was high enough to vaporize LPG. After that LPG injection is controlled by cooling water temperature, 35°C or slightly above. When switching from firing gasoline to LPG, shorter driving range was experienced see Figure 8.

Fuel Consumption Test

The comparative results between the consumption rate of gasoline91 and LPG collected from both conditions for over 2,000 kilometres was graphically displayed (Figure 8). After tuning at the λ range of 0.85-0.90, it showed that the consumption rate of LPG was about 17.7% higher than that of gasoline91. Note that LPG has heating value of 50 MJ/kg and density of 0.56 kg/l where gasoline has lower heating value of 44 MJ/kg with higher density of 0.76 kg/l. Therefore, energy density per unit volume of LPG was 28 MJ/l and 33.4 MJ/l for gasoline. Theoretically, it required more LPG about 16.2% for combustion. Like natural gas used as an engine fuel [14-17], the disadvantages of LPG were low energy density, low engine volumetric volume as a gaseous fuel, and need of pressurized fuel tank. Economically, LPG fuelled vehicles have a significant advantage over petroleum vehicles due to lower cost per energy unit. Moreover, LPG price was about 50% lower than gasoline/gasohol prices. Additional maintenance cost incurs less than USD 80; for fuel line, fuel filter required to be scheduled change at 6-80,000 kilometres and LPG nozzles to be replaced every 3 to 5 years. The fuel flexible line is required frequent inspection, typically every year and replaced every 3 to 5 years. However, conversion kits and required accessories and pressure storage tank are costly, but safety must not be compromised.

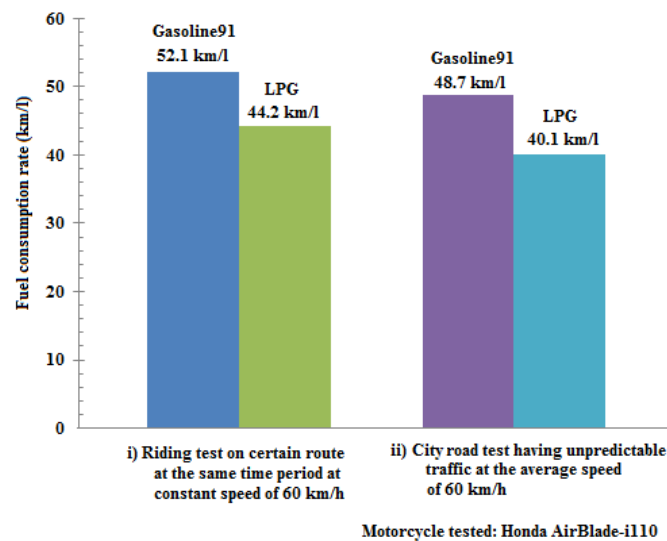


Figure 8. Comparison of the fuel consumption rate of gasoline 91 and LPG

Emission Measurement

The motorcycle tested was purposely designed for the use of gasoline91 and has been used over 70,000 kilometres. After being thoroughly inspected, the LPG equipment set with ECU was added while maintaining the compression ratio. The engine was then properly tuned up on dynamometer aiming at the best power output which was in the range of 0.85-0.90. Lower CO and HC concentrations in the exhaust were observed as shown in Figure 9 and Figure 10. Those were much below the regulations which required <4.5%vol for CO concentration and 10,000 ppm for HC concentration. This corresponded to most often cited advantage of gaseous fuels on pollutants; the percentages vary depending on the source [14,16]. It was likely that natural gas and LPG burning vehicles substantially produces lesser amounts of pollutants than vehicles burning petroleum fuel. More benefits to engine components and effective reduction on maintenance requirements were also claimed [14-17]. Since lubricating oil was not contaminated or diluted with gaseous fuels, NG and LPG; less deposits were formed in combustion chamber and on spark plugs, consequently, prolong

piston ring and spark plugs life. Therefore, LPG is an alternative clean fuel for vehicles and provides better combustion than gasoline.

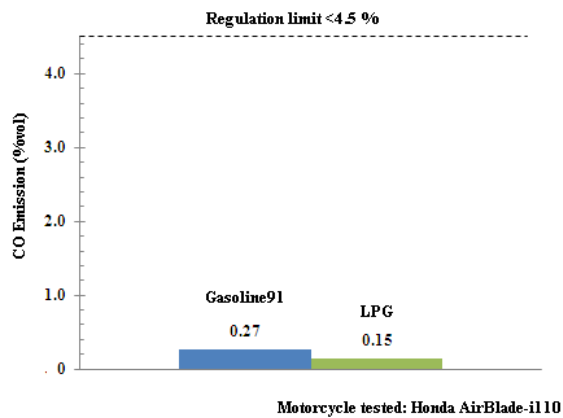


Figure 9. Comparison of CO concentration in the exhaust of gasoline 91 and of LPG.

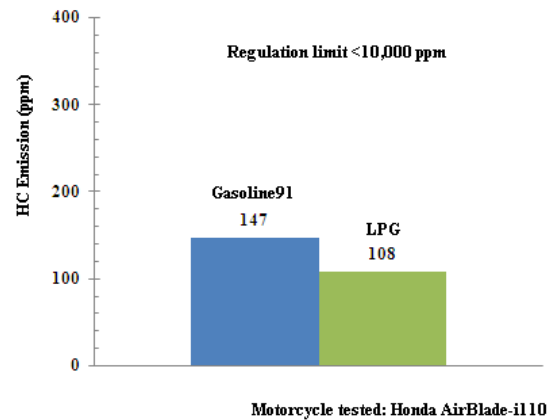


Figure 10. Comparison of HC concentration in the exhaust of gasoline 91 and of LPG.

4. Conclusion

It clearly confirmed that bi-fuel system – gasoline/LPG can be safely and effectively used in a 4-stroke motorcycle equipped with fuel injection and water cooling system. The motorcycle tested was the used 4-stroke Honda AirBlade i110 which was used over 70,000 kilometres. After being thoroughly inspected, the LPG equipment set and ECU were securely installed in the U-box under the seat. For properly LPG fuel injection, the calculated 1-mm diameter injector was inserted close to the gasoline fuel injector and the regulator was tightly placed over frame bar near the cooling system. After that, the engine was tuned up at the relative rich air-fuel ratio range of 0.85-0.90 which theoretically gave the best power output for SI engines. The operating pressure and temperature were 78-80 kPa and 35°C. For smooth LPG vaporization, cooling water temperature was controlled at 35°C while the relief valve pressure was set at below 48 kPa and above 110 kPa. If the system pressure is below or above the set pressure, ECU will automatically cut off LPG and switch to use gasoline instead.

Comparing to the use of gasoline91, the dynamometer performance test result of firing LPG showed that the average power output over the engine speed range of 65-100 km/h was 5.16 hp which was only 3.9% lower. From the road tests of both long riding and city riding at the average speed of 60 km/h, the average LPG consumption rate was 17.7% more which corresponded to LPG's energy density of about 16.2% lower than gasoline's. It therefore required more LPG to burn. The average concentrations of CO and HC in the exhaust were 0.15%vol and 108 ppm. Those were lower than in the exhaust of burning gasoline91, 0.27%vol CO concentration and 147 ppm HC concentration, but much below the regulations. In conclusion, LPG is clearly a clean fuel and safe to use as fuel for motorcycles once the engine is properly modified and tuned up to suit the fuel's characteristics, such as combustible limit. To assure smooth operation, the cooling water temperature must be regularly checked. For safety purpose, all gas equipment must be inspected as scheduled.

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