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Comparative Evaluation Of The Performance Of A Bi-Fuel Vehicle On Biogas And Natural Gas

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ABSTRACT

This paper assesses the performance of a retrofitted bi-fuel passenger car running on enriched biogas and natural gas with a view to investigating the similarities between both fuels. A sweep test was conducted using a chassis dynamometer which simulated actual driving conditions showed that the vehicle recorded similar maximum power outputs at 55kW and 54kW for natural gas and biogas respectively while similar acceleration times from 0 to 100km/h were also recorded.

Keywords: *Biogas, Natural gas, Performance, Car.*

1. INTRODUCTION

For Man's insatiable need for energy since creation has seen the exploitation of various resources most of which are fossil based. These fossil-based fuels have been central to industrialization and immensely improved the living standard of mankind. Fossil fuels are crude oil (and its derivatives), coal and natural gas; these fuels are constantly being tapped and have helped to meet the energy and electricity demands of today's world. They are formed from the decomposition of organic matter over a long period of time from the carboniferous era (fossilization) (Mohr et al. 2015). Fossil fuels are economically viable to produce and use, and they have high energy contents per unit mass produced compared to other fuels that can be produced at similar costs. These advantages have somewhat made man overdependent on the use of fossil fuels to produce energy and power as they account for over 80% of the world energy demands.

In recent years, there has been widespread advocacy for reduction in the use of fossil fuels as well as the creation of alternative energy carriers because of numerous problems associated with their exploration, refining and use to the ecosystem (Mohr et al. 2015; EIA. 2013). A large percentage of the environmental issues the world is faced with today stem from the production and combustion of fossil fuels. Some of the problems include climate change, air pollution, oil spills that pollute arable land and water, and acid rain. Furthermore, the combustion of fossil fuels yield heat-confining gases (CO_2 and NO_2) that absorbs and emits radiation within the thermal infrared range. The process is the primary cause of greenhouse effect which is the causative factor of the rising temperature of the earth known as global warming. The destructible consequences of global warming include rising sea levels (linked to floods), ocean's acidification, drought, frequent heat waves, melting of glaciers, poorer air quality, climate change and alteration of seasons. These problems have not only threatened the existence of the human race but also depleted specific resources they depend upon for their livelihood and culture (IEA. 2015). Furthermore, according to Hubert King postulate theory, we are past the peak production and also at a terminal state of decline which means that providing energy from fossil fuels to cater the ever-growing population might cause the world to run out of these resources within the nearest few decades. Apart from the dwindling fossil reserves and their negative effects of the on the ecosystem, unstable oil prices, stringent emission legislations, unpredictable supply, increased demand that usually outweighs supply and energy security are some of the political and economic factors motivating the need for alternative sources of energy (Beil and Beyrich. 2013).

As the world continues to evolve, it is expected that different sectors that help to drive the world's economy reduce their dependence on fossil fuels and turn to cleaner alternatives which are renewable, sustainable and environmentally compatible. The transport sector which consumes the largest fossil fuel portion after the industrial sector and also attributed to producing a high percentage of the world's greenhouse gas emissions keeps looking to explore avenues to decrease its reliance on petrol and diesel and other crude oil derivatives. 98% of the total energy used to power the different modes transportation are from fossil sources. The sector recently turned to natural gas and liquefied petroleum gas which could be accommodated to work in conventional compression ignition and spark ignition engines. However, they are both of fossil origin and do not fully satisfy the sustainability and renewability criteria for alternative fuels despite being cleaner combusting and cost-effective fuels than petrol and diesel (Yang et al. 2014). Biogas (a leading candidate amongst all biofuels) on the other hand can be used in place of petrol and as a supplementary fuel for diesel in engines, it can also be employed in all natural gas applications and it is easily derived from a wide range of biomass including wastes. It is the cheapest fuel on the energy market and can be integrated in existing natural gas infrastructure for transportation from production site to consumers (Gajendra and Subramanian. 2013).

As stated in the preceding paragraph, biogas is said to be a supplementary fuel to natural in many applications, this is primarily due to the similar chemical constituents especially when biogas is enriched (upgraded to have more than 90% methane content) with the only difference being the source where these fuels are derived. In fact, comparisons have been drawn in literature between the performances of both fuels at constant speed internal combustion engines with the experiments reporting similar engine performance in terms of brake power output, specific gas volume, thermal efficiency, fuel economy and emissions. Also, some natural-gas vehicle customers have listed that one of the motivations for spending extra monies to purchase natural gas vehicles rather than their cheaper petrol models is because of their hope to use a renewable fuel like biogas. However, this is still need for more data particularly in retrofitted systems with varying speed and load requirements where it is somewhat more rigid to tweak engine properties and component to influence performance as is the case with constant speed stationery engines or in dedicated systems where optimum burning conditions are integrated into the designs to improve system efficiency. It is pertinent to state that the criteria which was considered in this paper while comparing performance was torque, power and acceleration and no consideration was given to transient emissions.

2. NATURAL GAS

Natural gas which has similar characteristics as other fossil fuels; are deposits generated from the decay of animal or plant matter over a long period of time due to intense heat and pressure on the decaying matter. It is made up of various hydrocarbons obtained from reservoirs found beneath the earth surface close to oil, rock formations and coal beds. Its major constituent is methane, and it contains other hydrocarbons like ethane, butane and propane. Nitrogen, hydrogen sulphide and carbon dioxide are inclusive in the raw fuel gas with traces of helium, carbonyl sulphide and various mercaptans (Gajendra and Subramanian, 2013).

Natural gas is extracted with contaminants (water, carbon dioxide and hydrogen sulphide) and purified before using it as a fuel to generate energy and power. These contaminants reduce the fuel’s thermal efficiency and causes damage to transporting pipes and, engine parts during combustion (corrosion, cracking, embrittlement and permanent failure). This relatively cheaper fuel compared to diesel or petrol, has a higher octane number (MON=130). Octane numbers denote the ability of a fuel to resist auto-ignition which can cause engine knocks. This also means that ICEs which run on this fuel because of its high octane number can attain very high temperatures without damage to engines and systems specifically designed to make use of natural gas, and can attain better thermal and engine efficiencies than petrol and diesel engines. Natural gas is a cleaner fuel which burns completely leaving little or no soot; it requires a simple carburetion system and can be employed in conventional spark and compression ignition engines with little modification on their fuel and ignition systems [Dincer & Zamfirescu, 2014; Gajendra and Subramanian, 2013].

Natural gas which was more popular with the industrial sector for the production of heat and electricity has recently been turned to by the transport sector to ease demand on the conventional fuels. Similar to the use of LPG in engines,

natural gas is denser than air, it is a colourless, non-toxic, non-corrosive fuel, odourised to aid leak detection and compressed for storage or for on-board use in vehicle applications (Engerer & Horn, 2010). Combustion of natural gas is cleaner hence it extends the longevity of the engine. In vehicle applications, natural gas has been extensively utilized as a substitute fuel, though a fossil fuel, it’s use has helped reduce the rising pressure on the extraction of crude oil to meet up the demands for petrol and diesel and the technologies to accommodate its use in vehicle engines are readily available. Natural gas burns silently in internal combustion engines (ICE) and yields lower percentages of air pollutants like nitrous oxides (NO_X), carbon monoxides (CO), carbon dioxide (CO_2) and particulate matter (PM) (Kirk et al, 2014) when compared to the conventional fuels in the transport sector.

Natural gas performs excellently in dedicated systems and can be used in existing petrol or diesel engines with slight modification to the fuel systems to accommodate the gaseous fuel. Its use is very popular and relatively acceptable like liquefied petroleum gas and it has been used to power almost every means of transportation. Table 1 highlights it’s acceptance in vehicular applications as there are currently over 14.8 million natural gas vehicles around the world (Masebinu et al, 2014). It is cheaper than petrol with cleaner exhaust emissions and an enormous reserve. However, its fossil origin, similar to that of LPG remains a deterrent in future usage (WLPG, 2015).

A typical natural gas powered or modified system consists of a cylindrical tank (made of steel, aluminum, glass fibre or composite materials), fuel lines, reducer (regulates high pressure gaseous fuel from the tank at 200 bars – 250 bars to about 1 bar – 1.5 bars for use in the engine), and a gas mixer or gas injectors. In vehicles, the system is usually connected to the vehicle's electrical control system to ease dedicated, alternative or simultaneous use of the fuel in mono-fuel, bi-fuel and dual-fuel systems respectively [Gajendra and Subramanian, 2013; Engerer & Horn, 2010).

TABLE 1: STATISTICS OF NATURAL GAS VEHICLES IN 20 COUNTRIES

Countries	**No. NGV**	**Total no. of vehicles**	**%NGV of total vehicles**	**Average monthly consumption (Million Nm^3)**
Argentina	2,487,349	12,400,000	20.06%	447.72
Bangladesh	220,000	1,155,535	19.04%	79.64
Bolivia	300,000	685,653	43.75%	54.00
Brazil	1,781,102	48,899,365	3.64%	320.60
China	3,327,500	140,108,779	2.37%	3,238.20
Colombia	500,000	4,912,963	10.18%	173.45
Egypt	207,617	4,472,945	4.64%	39.41
Germany	97,619	49,283,087	0.20%	21.84
India	1,800,000	81,697,000	2.20%	1,190.00
Iran	4,000,000	14,450,000	27.68%	737.03
Italy	883,000	47,823,333	1.85%	165.20
Nigeria	3,798	7,600,000	0.05%	0.93
Pakistan	3,700,000	4,481,799	82.56%	642.60
Peru	183,786	1,580,698	11.63%	33.11
South Africa	937	7,915,214	0.01%	0.55
Sweden	44,322	5,285,597	0.84%	13.60
UK	663	33,639,528	0.00%	0.49
USA	142,000	253,701,808	0.06%	150.80
Uzbekistan	450,000	2,000,000	22.50%	81.00

3. BIOGAS

Biogas, a first-generation biofuel is a clean and renewable fuel produced from the anaerobic digestion of a wide range of biomass and organic waste. Feedstock used to produce biogas includes energy crops, manure, feed waste, household waste, vegetable and pack house waste, municipal waste, animal slurry, sewage sludge, food processing and abattoir waste to name a few. Biogas may also be collected from landfills, marshes and swamps that undergo natural decomposition processes to produce a methane-rich- flammable gas. Biogas is primarily methane (45 – 75% CH_4) with traces of other gases like carbon dioxide, nitrogen, hydrogen sulphide, ammonia and water as shown in Table 2. When produced from anaerobic digesters, the system is controlled to enhance the methane content of the biogas because the other components of biogas adversely affect the performance of the fuel as seen in Table 2. There is a direct relationship between the efficiency of the anaerobic digester, the methane content of the biogas and the calorific value of the fuel. Though biogas may be fed directly from the digester to power some applications like boilers and combined heat and power engines, applications which require high gas quality like in vehicles will require the methane content of biogas to be similar to that of natural gas. To achieve this, there are various commercially available methods of upgrading biogas to biomethane (CH_4>90%). The methane enrichment process rids the fuel gas of every other constituent except combustible methane and low levels of carbon dioxide which is usually less than 10%. In vehicle applications, this enrichment process increases the fuel's driving distance per unit volume while also reducing the fuel's affinity to corrode or damage the mechanical working parts of the vehicle's engine. Water scrubbing is the most common method of upgrading biogas to biomethane although it is highly energy intensive (Kukoyi et al. 2015). Biogas in its purer form has similar energy content to natural gas, petrol and diesel (Table 5) (Masebinu et al, 2015)

TABLE 2: BIOGAS CONSTITUENTS.

Constituent	Content
CH_4	40 – 75%
CO_2	15 – 50%
H_20	5 – 10%
H_2S	0.005 – 2%
N_2	0 – 2%
O_2	0 – 1%
NH_3	<1%
CO	<0.6%
VOC	<0.6%
Density	0.9145kg/m^3
LHV	26.17MJ/kg
(A/F) stoichiometric CH_4	17.23

TABLE 2: THE EFFECT OF BIOGAS IMPURITIES IN TRANSPORT APPLICATIONS

Constituents	Content	Effects
CO_2	25-30%	• Reduces heating value of the fuel • Increases methane number and anti-knock properties of the fuel in an internal combustion engine • Causes corrosion when mixed with vapour
H_2S	0-0.5% by vol.	• Corrodes equipment and piping system, a maximum of 0.05% by vol. is allowed by most OEM. • Complete combustion emits SO_2 while incomplete combustion emits H_2S. Maximum emission limit for H_2S in fuels is 0.1% by vol. • Damages the catalyst in the exhaust system
NH_3	0-0.05% by vol.	• Impairs the efficiency of a fuel cell • Increases engine's anti-knock properties of the fuel
Water (vapour)	1-5% by vol.	• Corrodes equipment, piping and instrumentation systems, storage tank and engines • Condensate damages instrument and equipment • Possibility of freezing in piping system and nozzles due to high pressure
Dust	>5 µm	• Blocks nozzles and fuel cells • Damages compressors and instrumentation systems due to clogging
N_2	0.5% by vol.	• Reduces heating value • Increases the anti-knock properties of engines
Siloxane	0-50 mg/m^3	• Has abrasive effect and damage engines • Formation of SiO_2 • Formation of deposit on valves, spark plugs and cylinder heads
HC's, Cl^-, F^-	Trace	• Cause corrosion in combustion engine

Compared to other popular alternative fuels biogas ticks all the criteria as a viable alternative fuel in the transport sector. Biogas is said to be the cheapest fuel on the energy market, it can be produced from a wide array of feedstock, including non-edible energy crops and biodegradable waste. It is clean, environmentally-friendly, renewable, sustainable, safe to handle and store, and compatible with fossil fuel natural gas. Compared to popular alternative fuels in the transport sector, hydrogen is the only commercial available fuel cleaner than biogas when burnt to produce energy. However, hydrogen and its technologies are relatively expensive and is often referred to as a futuristic fuel. Also, though the tank to wheel assessment

(TTW) of hydrogen is better than that of biogas, the well to wheel analysis of biogas which takes into consideration the total CO_2 emissions of a fuel from sourcing it to its eventual use to produce energy which is a more comprehensive assessment favours biogas (Gajendra and Subramanian, 2013; DENA 2010).

Biogas use as fuel is also free from the food versus fuel arguments which currently plagues the use of ethanol and biodiesel as fuels because it mostly produced from organic waste in countries where it is used as a vehicle fuel. The argument supports that cultivatable lands and food crops should not be used for fuel production at the detriment of having sufficient food supply across the world and this amongst other factors has limited the use of these fuels to supplements and additives rather than singular fuels (RFA. 2015).

Biogas has been adopted to power passenger cars, light-duty vehicles, heavy duty vehicles and even trains successfully. Such is its efficiency that it is currently used to power about 50% of the public vehicle fleets in Sweden. The same country aims to ensure that her transport sector is -completely independent of fossil fuels by 2030 with biogas being a leading-candidate replacement fuel. Conventional petrol and diesel vehicles could be converted to bi-fuel and dual fuel modes respectively to accommodate biogas as a supplementary fuel. Dedicated vehicle models which may use natural gas or biogas are also produced by major vehicle manufacturing brands for popular commercial diesel and petrol models (Persson and Wellinger. 2006; Arnorsson, 2011)). Dedicated systems may outperform similar petrol and diesel models because their engine designs take into consideration the excellent specific burning properties of methane to produce better engine performance and lower exhaust emissions when compared to their petrol and diesel models. However, the retrofitted systems are somewhat more popular on the roads today than the dedicated systems.

Off-the-shelf natural gas (CNG) conversion kits which can also be used for biogas are readily available and relatively inexpensive but overall conversion cost may run between $2700 to $20000 depending on the vehicle type and the expertise contracted for the conversion (Samson et al, 2014).

The conversion process (same for CNG applications) in its simplest form consists of a cylindrical tank (mounted in the trunk of the vehicle for passenger cars and on the roof, load compartment or under the chassis of the vehicle for heavy duty vehicles), a pressure regulator, and a gas mixer or gas injectors. The cylinder houses compressed biogas at high pressure (200- 250 bars) for on-board vehicle use. More than one cylinder can be mounted on the vehicle to accommodate more fuel to allay range anxieties since biogas possess a lower energy density than liquid fuels but this comes with an extra weight penalty. The lower energy density of biogas implies that more volume of biogas is required to get an energy equivalent of petrol. The cylinder is made from aluminum, steel and recently from reinforced carbon and glass fibre for their strength to weight ratios. Adsorbent technologies are also used to increase the volume of the gaseous fuel in the cylinder (Chandra et al, 2011; Debabrata & Mururgan, 2012).

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Gas flows from the cylinders via high pressure steel tubes to the gas regulator which through a 3-stage process which reduces the pressure of the gas from 200 – 250bar to an allowable engine gas pressure of about 1 bar. The gas regulator also known as the gas reducer is kept functional by hot water from the engine coolant since the sudden pressure drop should freeze the mechanical components of the reducer. The regulated gaseous fuel then travels via the low-pressure tubes to the gas mixer where the fuel is completely homogenised in air before entering the combustion chamber via the intake manifold. For the more efficient gaseous injection conversion kits, the kit is made with an electrical control system which is integrated into the electrical control unit of the vehicle and works with the closed loop system of the vehicle to improve engine performance, fuel economy and exhaust emissions (Persson & Wellinger, 2006; Da Costa Gomez, 2013).

TABLE 3: ENERGY CONTENT OF SOME VEHICLE FUELS

Vehicle fuel	**Energy Content (MJ)**
1 Nm^3 biomethane (97% CH_4 concentration)	34.8
1 Nm^3 of natural gas	39.6
1 litre of petrol	32.6
1 litre of diesel	35.3
1 litre of E85 (85% ethanol and 15% petrol)	22.9 (summer, 85% ethanol) 23.7 (winter, 79.5% ethanol)

4. LITERATURE REVIEW

The use of natural gas and biogas in motor vehicles dates back to World War II when the shortage of petrol became unbearable due to the conflict amongst nations. Natural gas and biogas were bagged or bottled for vehicles and farm machineries in place of the popular petrol (Omid et al, 2011). That being said, works from literature have cited both fuels as not only being functional fuels but also viable replacement fuels with optimal performance derived when engine configuration are altered to improved turbulence or to negate the low volumetric density of the fuels. Generally, to improve the performance of biogas and naturals gas in ICE's, engine compression ratios are increased (to about 15:1) to improve combustion as the high-octane number of biogas implies that engines running on the fuel can attain high compression ratios and extreme temperatures with less susceptibility to knocking or pre-ignition (required in high performance and high speed engines) (Omid et al, 2011). Furthermore, the cylinder head, the combustion chambers and the ignition system may be tweaked to improve turbulence and combustion. Supercharging is also used to improve combustion by increasing the quantity of fuel burnt per unit time and liquefaction (at -162°C) in more complicated dedicated systems is employed to reduce the energy density disadvantage of the gaseous fuels. With respect to the similarities of both fuels, Muller claims that Caterpillar (company) using the pre-chamber concept and spark advance in a spark ignition engine powered by landfill gas recorded, similar power, BMEP and BSFC when pitched with natural gas. Cassiano et al. (2013) tested an otto cycle 1.8 litre Volkswagen engine running on biogas using natural gas as a reference parameter. The engine which was connected to a J M motor power 800V hydraulic absorption dynamometer which was tested at various compression ratios and spark advance. They found that the optimum ratio and spark advance for biogas and natural gas were 12.5 and 45^o respectively with a long gas mixer. With respect to ignition alteration, Chandra et al (2011) on a 5.9 KW modified CI to SI engine, compared operations when fuelled with CNG, enriched biogas, and low quality biogas, by fixing the compression ratio at a close-to-optimum value (12.65) while varying the ignition advance at TDC at 30^o, 35^o, and 40^o. Advancing the spark by 35^o resulted in significant reduction in maximum brake power when compared to the engines original fuel (petrol). The percentage power reductions were 31.8%, 35.6% and 46.3% for natural gas, biomethane and biogas respectively. Biomethane scored similar values with respect to specific gas consumption, engine performance, thermal efficiency and brake power output as compared to natural gas.

Many of the work in literature rather than compare natural gas and biogas in ICE's usually investigate the workings and efficiency of biogas and biogas blend fuels (example; biogas and hydrogen) in ICE's with natural gas as the reference fuel. Hence, the need to investigate or validate the similarities in performance especially in a simple retrofitted passenger car with an aim to promote the ease of use of biogas and enhance acceptability.

5. METHODOLOGY

The vehicle which was a 2009 model Toyota Yaris was converted to a bi-fuel vehicle using a relatively inexpensive closed loop gas mixer conversion kit (conversion kit and conversion cost was less than $1500). The closed loop conversion kit taps signals from the oxygen sensor in the exhaust line of the vehicle and meters biogas for combustion relative to the oxygen content in the exhaust gas and load requirement. The process improves combustion efficiency and reduces exhaust emissions. The vehicle's specification is seen in Table 4. Vehicular quality biogas was simulated by mixing 95% methane gas with 5% carbon dioxide which is similar to knows specifications.

TABLE 4: VEHICLE SPECIFICATIONS

Details	
Engine Type	4 cylinder in line SI engine 16 valves
Swept Volume (cc)	1496
Compression ratio	10.5:1
Length of stroke (mm)	75
Bore (mm)	84.6
Valve train	DOHC
Fuel system	Sequential type MPFI
Maximum power (hp)	Petrol 140 @ 4200 RPM
Maximum Torque (Nm)	Petrol 106 @ 6000 RPM
Kerb weight (kg)	1055

The test to assess performance of the test vehicle on biogas and compare with natural gas was done at Esterigate Nigeria Limited. A schematic representation of the test set-up is shown in Figure 1. The facility housed an inertia chassis dynamometer (single roller). Tests to compare performance was done in succession while the engine was well warmed up to give accurate readings. Before mounting the vehicle on the dynamometer, preliminary checks were done to ensure that there was no leakage or droppings from the lubrication lines, transmission lines and that there was no escape of gas via the high and low pressure gaseous fuel lines and joints. Care was taken to ensure that the restraining straps which held the car in place during the "dyno run" were securely fastened and tightened. However, the straps were not too tight to distort reading generated at the wheels of the vehicle. The dynamometer was calibrated based on roll speed and was connected to the electrical control unit of the vehicle via the on-board diagnostics (OBD) port. A sweep test which is an evaluation to deduce the maximum power output of an engine by accelerating from idle to the redline of the engine of a vehicle, was used to compare the performance of the vehicle on both fuels (petrol and biogas). During the sweep tests, vehicle speed was increased and at set data points, the corresponding torque and power values were deduced from the computer software connected to the dynamometer.

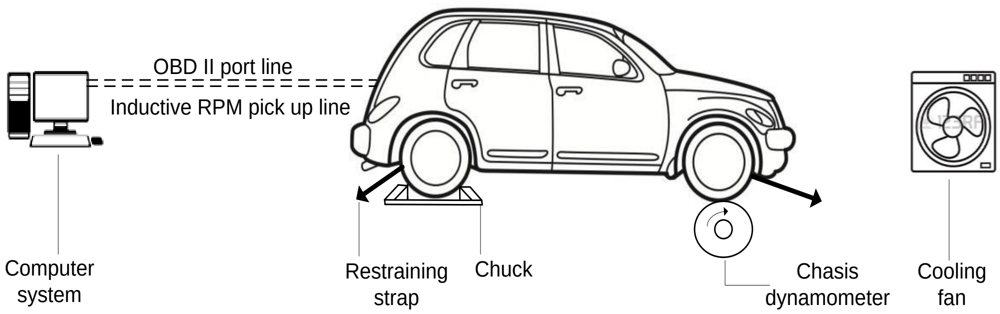

FIGURE 1: SCHEMATIC REPRESENTATION OF THE EXPERIMENTAL SET-UP

6. RESULT

The results as seen in the Figure 2 shows the maximum power developed at the wheel during the dyno run to be 55kW and 54kW on natural gas and biogas respectively. The maximum torque developed at the wheels was 100Nm at 4000RPM on natural gas. This value decreased by 2% when biogas was the operating fuel while the maximum torque was also attained at 4000RPM (Figure 3). Acceleration from 0 to 100km/h also showed great similarity between both fuels although the vehicle on natural gas reached the mark slightly quicker at 11.98 seconds when compared to when the vehicle was running on biogas which was 12.24 seconds as depicted in Figure 4. The slightly quicker acceleration was influenced by the performance of the vehicle on natural gas between 0 to 60km/h. Although the vehicle had a slightly even performance between 60km/h to 100km/h on both fuels, the vehicle reached at 0 to 60km/h at 0.37 seconds faster than when the vehicle ran on biogas. Notwithstanding the fact that this time difference is negligible, the quicker time reach during the first part of the acceleration test which was also evident in the slightly higher power and torque readings from the dynamometer particularly between 0 to 2500 RPM may be due to the prescience of other combustion enhancing compounds present in natural gas like ethane with promotes turbulence and improve thermal efficiencies even at low speeds (Chehroudi, 1993: Semin, 2008).

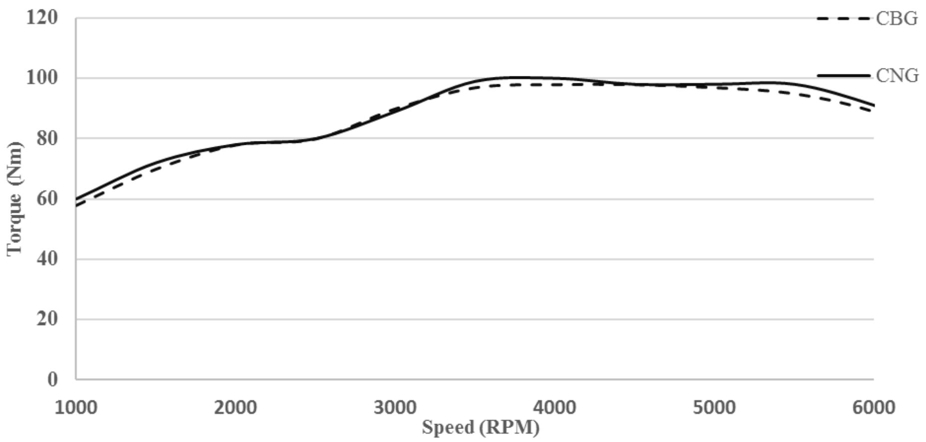

FIGURE 2: CHASSIS DYNAMOMETER PEAK TORQUE OUTPUT PLOT

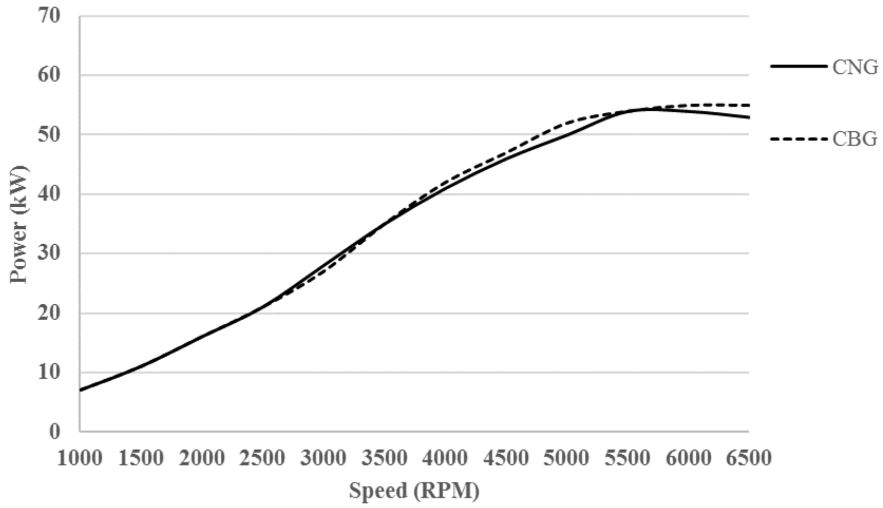

FIGURE 3: CHASSIS DYNAMOMETER PEAK POWER OUTPUT PLOT

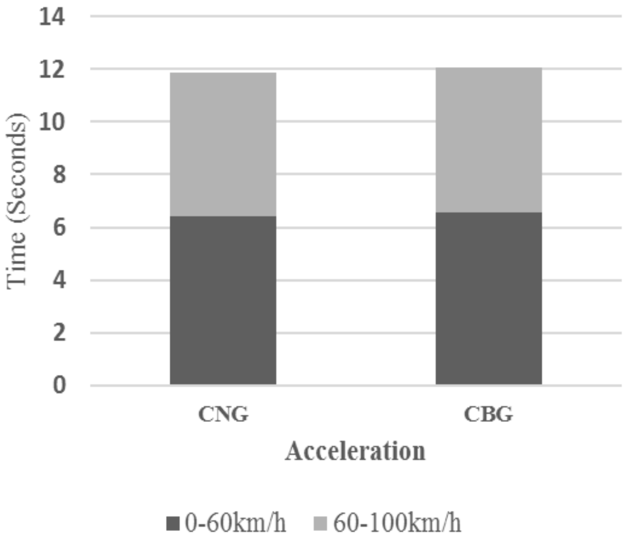

FIGURE 4: VEHICLE ACCELERATION ON THE DIFFERENT FUELS

7. CONCLUSION

The experiment validates the similarity and interchangeability between biogas and natural gas with respect to performance since both fuels recorded similar values for torque outputs, power outputs and acceleration times when used as running fuels for the passenger car. It also shows that biogas like natural gas would perform efficiently in existing on-road spark ignition vehicles with simple modification to accommodate the gaseous fuel. Future works would investigate the similarities or distinction in transient emissions when both fuels are considered and system optimization by the addition of small quantities of hydrogen to renewable biogas to improve turbulence and subsequently performance.

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