Performance Evaluation of a Biogas Fuelled Bi-Fuel Vehicle

Temitope Kukoyi, Edison Muzenda and Charles Mbohwa

***Abstract*—This paper assesses biogas as a viable alternative vehicle fuel particularly in the more popular petrol vehicle which was retrofitted to a bi-fuel system. Biogas was compared to other popular substitute fuels used in spark ignition systems with the aim to justify it as the ideal replacement fuel for petrol. Furthermore, a sweep test was employed to evaluate the performance of biogas in a bi-fuel vehicle and compared to the performance of the same vehicle when it ran on petrol. A 16% drop in power output was experienced when biogas was used to power the vehicle. Simulated biogas was used in the study and it was produced by mixing methane and carbon dioxide of 95% and 5% by volume respectively.**

***Index Terms*—Biogas, Energy, Fuel**

I. INTRODUCTION

A wide range of issues has plagued man's insatiable need for energy for the past century. The energy providers which are derived primarily from fossil sources have helped to sustain human existence as well as facilitate development [1]. However, population explosion has put enormous strain on these resources and according the Hubbert King's theory buttressed in fig 1, the world is past the peak production of these resources after which is a terminal state of decline [2-4]. Fossil fuels are formed from the decay of plants and animal matter over an extended period of time, usually millions of years (fossilization). Fossil fuels (crude oil, coal and natural gas) have finite reserves and currently account for about 80% of the energy consumed by humans [5]. Apart from the finite nature of fossil fuels, an imbalance in demand and supply which was evident in the energy crises of the 70's coupled with energy security initially brought the need for a shift from the primary fuel sources. Furthermore, also motivating the shift is the adverse effect of fossil fuels on the eco-system. Production and utilization of these fuels have been directly linked with environmental degradation and global warming.

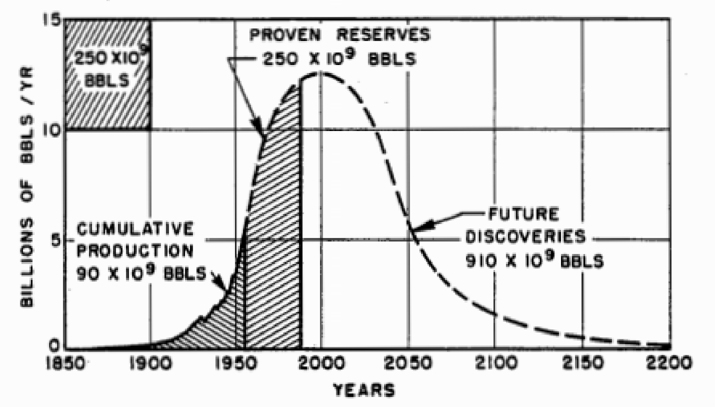

Fig. 1. Hubbert King's peak oil theory

Exploration and refining have led to land and water contamination while combusting to produce power or heat yield toxic gases that adversely affects human health as well as greenhouse gases (methane CH_4, carbon dioxide CO_2, nitrous oxide NO_X). Greenhouse gases prevent heat from escaping through the atmosphere, raising the temperature of the earth. The rising temperature of the earth has led to a number of environmental and social changes; They include rising sea levels, glacier retreat, tropical cyclones, alteration of the timing of seasons, floods, droughts, ocean acidification to name a few [6], [7].

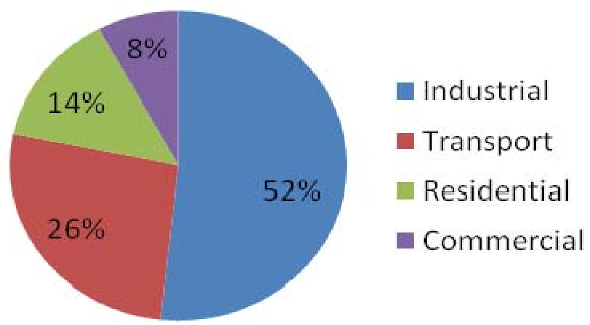

Fig. 2. World energy consumption by sector

It is safe to say that energy drives the development of the world's economies. That being said, different sectors come together to make up these economies and the effectiveness of these sectors ensures development. It is almost impossible to highlight the world's dependence on fossil fuels without mentioning its effect on the transport sector as they are inextricably linked [8]. The transport sector primarily deals

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with the movement of man and goods from one place to another and it consumes a third of the world's energy; which is the second largest share after the industrial sector as shown as shown in fig 2 [5], [9]. 60% of the total oil consumed per day is employed to power different modes of transportation. 98% of energy used in this sector comes from fossil fuels, it is also expected to be the fastest growing oil-consuming sector by 2030 with the number of cars expected to be 1.25 billion from the 700 million currently plying our roads [10].

The transport sector has immensely felt the pinch associated with the unstable supply and sporadic cost associated with fossil fuels and the sector also contributes exceedingly to the greenhouse gases emitted into the atmosphere. The massive energy need, coupled with stringent emission limits in the transport sector have made pertinent the need to find a viable replacement fuel to keep powering this sector as it remains an important driver of the economy [11]. The conventional fuels in this sector are petrol and diesel, produced from distillation of crude oil. The sector recently turned to liquefied petroleum gas and natural gas as alternative fuels which perform comparably to the conventional fuels in dedicated systems. They are cheaper and emit lesser harmful emissions when compared petrol and diesel. However, they do not fully tick all the criteria for the ideal alternative fuel [11], [12]. This paper will focus on biogas's use as a replacement fuel, particularly its usage in spark ignition engines which is more flexible and popular than the compression ignition engine. This work further tests the performance of the fuel in a passenger car powered by the spark ignition engine with a multiport injection system retrofitted with the most affordable venturi mixer natural gas vehicle conversion kit with an aim to compare performance of the bi-fuel system on biogas and petrol.

II. Alternative Fuels in the Transport Sector

Alternative fuels are generally referred to as "energy carriers" other than derivatives of crude oil. However, for a fuel to be a practical substitute for petrol and diesel in the transport sector it should be safe to handle and store, renewable, environmentally friendly and sustainable. It should perform comparably or better than the conventional fuels. It should also be economically appealing (cost competitive with petrol and diesel) with infrastructure readily available or can be developed a reasonable cost. It will be of added benefit if the fuel can be integrated into existing fossil fuel infrastructure with an example being biogas utilization in natural gas infrastructure [11].

Some of the alternative fuels that have been noted, under development or extensively used in the transport sector includes; ethanol, butanol, methanol, p series, hydrogen, vegetable oils, biodiesel, propane, synthetic fuel, biogas, electricity, solar energy, natural gas etc. These fuels are developed to mitigate the diverse issues associated with mainstream transport fuels and it would be of importance to note that while some of these fuels are not in the same liquid state as petrol and diesel, others are still fossil based fuels, like natural gas and liquefied petroleum gas (LPG) which were employed recently due to their availability, performance and improved exhaust emissions when burnt to produce power [13].

Ethanol, hydrogen, LPG, natural gas and biogas are very popular and commercially available fuels in the transport sector. Hence, their acceptability is more widespread. Biodiesel certainly falls within this category but since our focus in on spark ignition systems, there would be no discussion about biodiesel in this study [11].

A. *Ethanol*

Ethanol is a renewable and sustainable cost effective fuel, derived from the fermentation of sugar and hydrolysis of lignocellulosic materials. Its high octane number ensures it performs excellently in combustion applications. Its hydroxyl content also enhances combustion to produces lesser harmful emissions than petrol [14]. However, it is mostly used as an octane enhancer in gasoline rather than a mono fuel and its usage as fuel is also plagued with the food versus fuel debate [14, 15]

B. *Hydrogen*

Hydrogen is a renewable gas with the highest energy content of any fuel per unit mass. Hydrogen is commercially produced from electrolysis of water and natural gas reforming. It possesses a high octane number (MON>120) making it relevant in high speed and high performance systems. In dedicated systems, it performs better than the traditional transport fuels. However, its production from fossil fuel natural gas and a scarce resource like water which are its main production methods questions hydrogen's renewability and sustainability. Furthermore, the production process and technologies to use this fuel remains very expensive and remains a deterrent for its extensive application and acceptability [16].

C. *Liquefied petroleum gas*

Liquefied petroleum gas (LPG) is a replacement fuel derived from crude oil refining and natural gas processing. It constitutes of combustible hydrocarbons which are essentially propane and butane with isomers of butane and sulphur. LPG which is also referred to as autogas especially when used in vehicle applications contains about 33% to 90% propane [17]. It is a cost-effective fuel and currently cheaper than petrol on the energy market. Conventional spark and compression ignition engines can use LPG as a substitute fuel due to its higher octane number, higher heating value and similar wobbe index when compared to petrol and diesel. LPG is a dense fuel which is gaseous at ambient temperature and liquid at moderate pressure (1.5 Mpa), thus the need for modification of conventional systems to be able to accommodate this fuel [18]. A simple retrofitted system consists of a gas tank fitted with a pressure relief valve, a fill limiter (which allows refueling to a limit that will adequately allow expansion of the compressed liquid fuel with respect to a slight change in temperature), fuel lines (usually steel), a reducer (it facilitates vaporisation and causes a pressure drop of the fuel from the gas tank at 10 bars to atmospheric pressure for use in the engine) and a gas mixer which employs a venturi system to homogenize the gaseous fuel with air and deliver the mixture for combustion in the engine cylinders via the intake manifold. In place of the gas mixer, recent and more efficient systems may integrate the use of gas injectors which is more efficient leading to improved performance and low exhaust emissions [18], [19]. Generally, LPGs use is motivated by the quest to improve system performance due to the high octane number of LPG, and to reduce exhaust emissions when compared to emissions from the combustion of petrol in similar systems. About 3% of the world's vehicles are currently powered by LPG served by 73,000 LPG refueling stations. However, it is fossil origin remain a deterrent to it long term use [17], [18].

D. Natural gas

Natural gas, also of fossil origin is a fuel consisting of various hydrocarbons obtained from reservoirs found beneath the earth surface close to oi, rock formations and coal beds. Its major constituent is methane, and it contains other hydrocarbons like ethane, butane and propane. Hydrogen sulphide and carbon dioxide are also inclusive in the raw fuel gas with traces of helium, carbonyl suphide and various mercaptans before refining [11]. It is relatively cheaper than petrol and diesel while possessing a higher octane number (MON=130). Octane numbers denotes the ability of a fuel's resistance to auto-ignition and engines operating on a fuel with high octane numbers can run at higher compression ratios and attain higher temperatures than conventional systems running on petrol and diesel without damage thereby attaining higher efficiencies [11]. 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 which is colourless, odourless in its pure form (but odourised in engine applications to aid leak detection), and non-toxic requires a simple carburetion system to accommodate the gaseous fuel. A typical system modification 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 [11], [20].

Despite the use of these alternative fuels to tackle different issues currently associated with petrol in the transport sector, the do not currently tick all the requirements to satisfy the ideal replacement fuel since they are either expensive, contentious or of fossil origin [11]. However, biofuels have drawn enormous attention worldwide as eventual substitutes for petroleum based transport fuels. Biofuels are renewable and combustible materials extracted from a wide range of biomass including wastes produced by living organisms. These fuels may be solid, liquid or gaseous energy carriers with numerous environmental and economic benefits. The first generation biofuels are the most common and commercially produced. The popular ones are bioethanol, biodiesel and biogas [12]. Fig 3 shows some of the advantages of biofuel utilization as a substitute for fossil fuels.

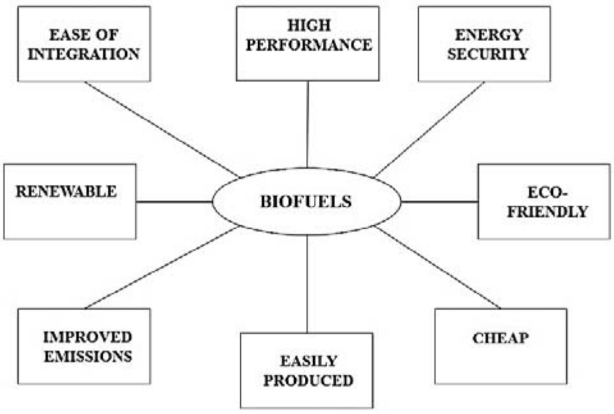

Fig. 3. Advantages of biofuels

Biofuels are expected to be major contributors to the world's fuel demands after oil by 2030 and can currently be used with or substitute current conventional fuels. Petrol can be used with or substituted by ethanol, butanol, mixed alcohols, methanol and Fischer Tropsch Liquid (FTL) while diesel can be supplemented by FTL, biodiesel, and dimethyl ether made from lignocellulosic biomass [11, 21].

Amongst all biofuels, biogas seems to be a very interesting candidate and its development for use has been quite rapid and extensive over the past few years primarily because it ticks all the criteria to be a viable alternative fuel in the transport sector. Unlike ethanol and biodiesel, it is not plagued by the food versus fuel argument which has limited their use to supplements rather than primary fuels [15]. Biogas is relatively cheap, renewable, sustainable and performs efficiently when used in existing spark and compression ignition engines [25]. When biogas is purified, it performs efficiently in dedicated engines since its high octane number (MON=130) allows it to yield higher thermal efficiencies when paired with conventional spark and combustion ignition engines. Biogas is a clean fuel which when burnt produces no particulate matter and reduced greenhouse gas emissions [11]. Besides its numerous positive combustive qualities, it can also be derived from a wide range of biodegradable sources including organic waste and does not have to compete with food and the direct use of land as is the case with most biofuels; when upgraded, it is very similar to natural gas and can be used in place of the fuel or as supplement [22]. Upgraded biogas can be used in all existing natural gas applications and infrastructures cutting down on costs that would have been necessary to develop a framework for a new fuel [23].

III. Biogas Production

Biogas, a clean, versatile, renewable and sustainable energy source, is a product of the decomposition of diverse biomass in the absence of oxygen. Biogas may be derived naturally through landfills and swamps or in a controlled environment which employs the use of anaerobic digesters. To generate biogas from anaerobic digestion, biomass which may be used as feedstock include 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. Most of these feedstocks can be digested as single substrates or mixed to enhance biogas production (co-digestion). Depending on the substrate employed, a substantial amount of energy can be generated from biogas to drive the world's economy [24].

The major component of biogas is methane and it determines the energy content of the gaseous fuel produced. The percentage of methane generated in biogas depends on the feedstock and system optimisation [25]. Methane in biogas fluctuates between 40% to 75% as shown in Table I, with the balance being carbon dioxide and traces of other gases like hydrogen, oxygen, nitrogen, carbon monoxide and hydrogen sulphide [26], [27].

The bacteria which aid digestion function optimally at temperatures of 25 – 40°C (mesophilic temperature) and 50 – 65°C (thermophilic temperature). The digestion process to yield useful methane consists of four phases namely hydrolysis, acidogenesis, acetogenesis and methanisation. In hydrolysis, the substrates are broken into smaller useable molecules like amino acids, fatty acids and simple sugars. The acidogenic process allows further disintegration of the products obtained from hydrolysis. Here, fermentative bacteria act on the products in an acidic environment to create organic acids and low alcohol. In the third and fourth phases acetogens act on what is left of the previous phases, converting them to acetic acid, carbon dioxide, and hydrogen and subsequently methane is generated with other trace gases [28]. The combination of these gases is known as biogas and the phases are synchronized if system is well balanced. It is important to ensure optimum process conditions (absence of air, adequate temperature, rich nutrient supply and uniform PH) during the digestion process to ensure to high quality biogas which is rich in flammable methane, the essential constituent of the gas which determines the energy content of the gas [29]. The closer the methane content to that of natural gas the better the energy content and subsequently the efficiency of the gas in engine applications [30]. Other process conditions which may be altered to improve the yield and quality of biogas include hydraulic retention time, pH value, carbon-nitrogen ratio, toxicity, agitation, air tightness, moisture content and substrate total and volatile solid [29].

TABLE I: 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)stiochometric CH_4	17.23

IV. Biogas as an Alternative Fuel

Biogas satisfies all the criteria to be a replacement fuel in for petrol. It is relatively cheap, renewable, sustainable, safe and performs excellently in engines with improved exhaust emissions. Its' production has the added benefit of aiding efficiency in extending the lifespan of landfills and general waste management [25].

Biogas is currently regarded as the cleanest renewable biofuel on the energy market, requiring none of the extensive refining and subsequent pollution associated with fossil fuels and its combustion to produce energy is cleaner than most energy sources available with hydrogen being a notable exception [11, 14].

The sustainability of biogas is enhanced by numerous renewable feedstock used to generate the gas and in many countries, it is generated from waste. There are enormous waste reserves around the world and unlike fossil fuels, these reserves continue to grow daily with human activities. Apart from the different organic wastes being generated on daily basis, biogas can also be derived from various non-edible energy crops and with fallow lands across the globe, the potential to generate feedstock and subsequently biogas is endless [11].

Biogas usage and its technologies also aid efficient waste management since unwanted or undesired materials and substances associated with dumpsites and landfills which cause soil and water pollution, are collected with the degradable content which could be as high as 65%, used to produce useful fuel [11], [31]. Citing South Africa as an example, of the total municipal solid waste generated in South African cities, between 21% - 40% (by weight) is organic and if we consider paper, cardboard and soil components, the organic waste would be between 45% - 50% which could be used to generate biogas at the detriment of allowing escape to the atmosphere [32].

Landfills naturally emit methane, even years after they have been decommissioned. Methane is 21 to 25 times more potent than CO_2 in increasing the earth's temperature and causing global warming. Apart from methane, hydrogen sulphide, a highly toxic colourless gas is also generated from landfills along with low concentrations of sulphur or nitrous compounds capable of causing respiratory problems in humans, and death in higher concentrations. Nitrous oxides possess 296% - 298% of the global warming effect of CO_2 [16], [33]. Generally, gases produced from landfill sites are dangerous and some are soluble in the atmosphere contributing to acid rain while others are recorded as having adverse effects on the environment which causes health problems for life on earth. However, these gases emitted naturally from landfills make up biogas and can be trapped for use in various constructive applications [25]. In summary, controlled biogas production helps with efficient waste management (whether household, farm or industrial waste), with pollution reduction (atmospheric, land and water) and in the provision of a relatively cost effective sustainable energy source [26], [34].

Biogas like natural gas is safer than petrol. Its ability to dissipate into the atmosphere during leaks and low flame velocity makes it a safer fuel. It is also easy to handle and transport, although it requires high energy for storage [9].

V. Biogas Use in SI Engines Vehicles

Biogas, with its major constituent as methane is employed in all natural gas applications. A very important factor to note in the use of biomethane as a vehicle fuel is its wobbe index, which is the main indicator of the interchangeability of gases. Similar Wobbe indices signify that the gaseous fuels could be interchanged for a given pressure and valve settings with similar energy output [35]. However, a variation of 5-10% in performance is accepted [36]. Biomethane like natural gas is interchangeable with petrol in conventional vehicle engines [37].

$$W = Q / \sqrt{d} \qquad (1)$$

The Wobbe index (W) is a function of the heating value (Q) and relative density (d) as shown in equation 1. "Q", also known as the calorific value, is the amount of heat energy released when a given amount of fuel burns. The heating value of biogas is directly proportional to its methane content, hence the need for enrichment of biogas to biomethane [37]. This is achievable through different simple and commercial methods such as physical and chemical absorption, cryogenic upgrading, pressure swing adsorption and high pressure membrane separation. These methods are capable of yielding biogas of about 98 percent methane content [38].

In stationary engines, especially combined heat and power (CHP) engines, biogas can be fed directly into an engine from an anaerobic digester to power it with simple modifications on the fuel system to accommodate the gaseous fuel if it was primarily designed for a liquid fuel. In vehicular applications with high gas quality requirements, biogas is upgraded to biomethane to rid the raw gas of other constituents apart from combustible methane and traces of carbon dioxide. Depending on the country where biogas is to be used, it may contain little amounts of nitrogen and oxygen. Upgraded biogas usually has its methane content greater than 90 percent with carbon dioxide, nitrogen and oxygen accounting for less than 6 percent of the fuel [34].

Strict gas standards are set in countries which employ biogas as a vehicle fuel primarily because constituents apart from methane have adverse effects on the efficient workings of an engine as seen in Table III. Also, these countries usually inject biomethane into natural gas grids to complement fossil-natural gas because of the similarities in major constituent and combustion characteristics of both fuels and injecting low quality biogas into the gas network would pollute the grid. Table II shows the Swedish Gas Standard for the use of biogas as a vehicle fuel and for injection into their natural gas grid and the standard is very similar to what is obtainable in most European States that have maximised the use of this high octane fuel in vehicles [34].

TABLE II: SWEDISH NATIONAL STANDARD FOR BIOGAS AS A VEHICLE FUEL

Parameter	Unit	Demand in standard
Lower wobbe index	MJ/Nm3	43.9 - 47.31
Methane content at STP	%	95 – 97
MON (motor octane number)		>130 calculated according to ISO 15403
Water dew point	°C	<t – 5 (at ambient temperature)
$CO^2 + O^2 + N^2$	% vol	<5
O^2	% vol	<1
Total sulphur	mg/n m^3	<23
NH3	mg/n m^3	20

TABLE III: THE EFFECT OF BIOGAS IMPURITIES ON INTERNAL COMBUSTION ENGINES

Component	Content	Effect
CO_2	25-30%	• Reduces heating value • Increases CH_4 number and anti-knock properties of ICE • Causes corrosion when mixed with vapour • Damage alkali fuel
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. • Spoils catalyst
NH_3	0-0.05% by vol.	• Damages to fuel cell when combusted • Increases engine's anti-knock properties

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

Biomethane with a heating value (HV) of 32.3 MJ/m^3 can be efficiently used in natural gas applications but original equipment manufacturers (OEM) of CNG vehicles recommend that the energy content should not be less than 34 MJ/Nm^3 when employed in NGV vehicles [38]. Table IV shows a direct relationship between the energy value of biogas and other fuels with respect to energy content.

TABLE IV: 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)

While biogas has been found to deliver similar or better performanaces in dedicated systems when compared to petrol, comparsions have also been drawn in the performances of enriched biogas and natural gas at constant speed internal combustion engines citing similar brake power output, specific gas volume, thermal efficiency, fuel economy and emissions [26], [27].

Biogas in SI systems is employed in bi-fuel and dedicated modes. In the bi-fuel mode, the system uses both biogas and petrol alternatively. The system combines the flexibility of the gasoline system with the added advantage of the use a cheaper and high-octane gaseous fuel. In dedicated systems, system efficiency is improved beyond that of a bi-fuel system because the positive burning qualities of biogas are factored into the design to yield higher power outputs and thermal efficiencies [39]. 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) [39]. 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 biogas [40].

Biogas is stored at 200 bars to 250 bars in pressurized cylinders made from steel to lightweight aluminum and composite materials for their strength to weight ratio. The use of adsorbents is also used to increase the volume of gas which would have been stored in a cylinder under normal circumstances. The storage system is somewhat more complex when using liquefied biogas with the incorporation of heat exchangers and an insulation system to prevent explosion and evaporation [16].

The more popular mode of the use of biogas in SI engine powered vehicle is the bi-fuel mode. Conventional SI systems are retrofitted to accommodate biogas by modifying their fuel systems. In simpler designs, the system consists of a gas tank or more to house reasonable amounts of the energy (because of the lower energy density of biogas when compared to petrol), high pressure fuel lines, a gas regulator, low pressure fuel lines and a gas mixer. When biogas is needed to power the vehicle, a switch is used to activate the gas flow which moves from the tank at storage pressure via the fuel lines to the pressure regulator. The regulator or reducer drops the gas pressure from the tank to useable pressure (1-1.5bars) for the engine to combust. The gas from the regulator travels via the low-pressure lines to the gas mixer where it is homogenized in atmospheric air before being inducted for combustion via the intake manifold. In recent conversion kits, the gas mixer is replaced with the more efficient electrically controlled gas injectors which is integrated into the electrical control unit of the vehicle for more precise and efficient fuel delivery to improve system efficiency [13].

Conversion kits for conventional petrol vehicles are cheap readily available. However, the cost of conversion which is usually done by a certified professional is somewhat expensive and may range from $2700 to $20000. It is important to note that bi-fuel vehicles are not optimised to use this high-octane gaseous fuel, so it is expected that lower power would be generated in the engine when the vehicle runs on biogas while performance is expected to remains the same when the vehicle runs on petrol before and after conversion [13], [38].

VI. 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 V. Vehicular quality biogas was simulated by mixing 95% methane gas with 5% carbon dioxide which is similar to knows specifications.

TABLE V: 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 petrol was done at Esterigate Nigeria Limited. A schematic representation of the test set-up is shown in fig 4. 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. The results obtained is discussed in section VII.

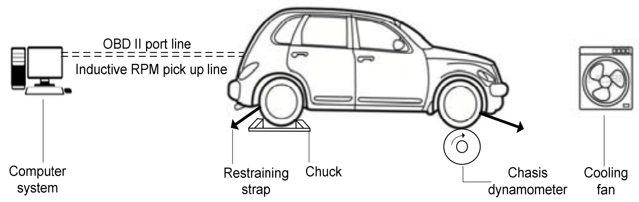

Fig. 4. Schematic representation of the experimental set-up

VII. Result and Discussion

The results as seen in the Fig 6 shows the maximum power developed at the wheel during the dyno run to be 66kW on petrol. The result from Fig 6 shows a 15% reduction in maximum power output (with petrol as the operating fuel) when compared with the rated engine horse power of the engine of the vehicle, specified by the manufacturer. This percentage loss could be attributed to drivetrain losses between the power produced by the engine (at the flywheel) and the power transmitted to the wheels which is largely due to friction. Power is also lost to transmission (gear), drive shaft, and the axles. The torque curves in Fig 5 represents the torque developed after drivetrain losses. It was measured directly from the wheels, and recorded on a computer connected to the dynamometer. The maximum torque developed at the wheels when running on petrol was 117Nm at 4000rpm. With biogas, as operating fuel, a 16% percent drop was experienced in the maximum torque and maximum power readings when compared to the readings derived from the test vehicle when running on petrol. This reduction in maximum power output when biogas was tested in the vehicle was in line with expected percentage reduction range prescribed in literature [41], [42].

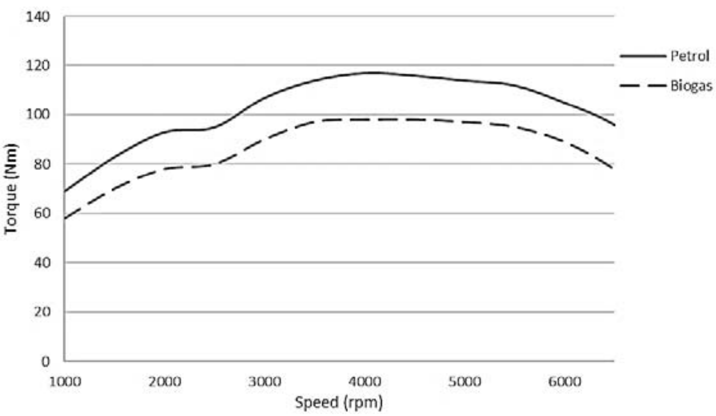

Fig. 5. Chassis dynamometer peak torque output plot

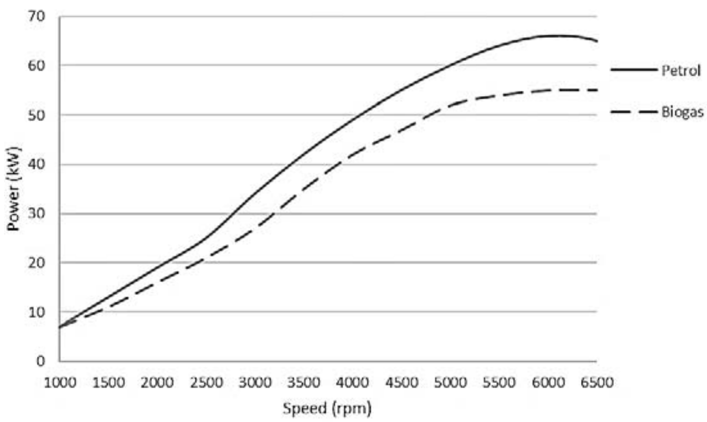

Fig. 6. Chassis dynamometer peak power output plot

The drop observed in maximum torque and power outputs are functions of different factors. The engine of the vehicle with a compression ratio of 10.5:1 would certainly favour the combustion of petrol and not biogas which functions optimally in engines with a compression ratio of 13:1. Another factor responsible for the power decrease is the lower density of biomethane which indicates that a larger volume of the fuel must be inducted into the cylinders to produce similar power levels as petrol. This is difficult to achieve in a retrofitted system because the engine cylinders of the vehicle were designed with respect to the combustive properties of petrol; closely related is that the cylinder capacities remain constant irrespective of the fuel employed thus limiting the amount of biogas that can be involved in combustion under normal conditions.

Also, volumetric efficiency is reduced in the system since the gaseous fuel displaces a similar volume of air from reaching the combustion chamber causing a corresponding reduction in power.

Another reason for the reduction in power is the gas mixer (a component of the conversion kit) which restricts airflow into the engine while the homogenization process takes place. This slight restriction accounts for a reduction in power output and may be improved by the use of a multiport injection conversion kit where the fuel delivery is facilitated by gaseous injectors directly in the intake manifold or in the cylinders.

VIII. Conclusion

Comparative assessment of both fuels on the test vehicle not only showed that biogas can be easily accommodated for use as a replacement fuel for petrol but also validated claims of the efficiency of biogas in SI systems, although a compromise of a reasonable percentage reduction in power output was experienced with the use of the fuel which may be compensated for by the lower cost of biogas.

Furthermore, apart from increasing compression ratio and the use of multiport injection systems, the addition of hydrogen to biogas (to improve burning properties), turbo-charging, spark advance, inclusion of a high energy ignition system, re-designing the combustion chamber to improve turbulence and knock-resistance, inter-cooling and the use stratified charge or pre-chamber ignition system will further increase the system performance when running on biogas [3], [40]; some of these variables will be included in subsequent phases of this study to ascertain the effects not only on the performance of the vehicle on biogas but also the influence of these variables on exhaust emissions.

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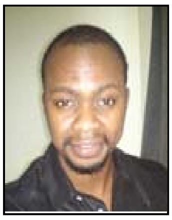

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