Chapter

Vehicles Power Consumption: Case Study of Dar Rapid Transit Agency (DART) in Tanzania

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Abstract

Energy consumption and its environmental impact are now among the most challenging problems in most developing cities. The common sources of energy used as the fuel in transportation sector include gasoline, diesel, natural gas, propane, biofuels, electricity, coal, and hydrogen. However, in Tanzania, diesel and gasoline are still the dominant source of energy used by public and private vehicles. We have experienced significant efforts of converting conventional vehicles (gasoline engines) to operate on Compressed Natural Gas (CNG) or on hybrid system (gasoline and natural gas) as an alternative source of energy in Tanzania. The CNG is considered as cleaner combustion energy used as a vehicular fuel alternative to gasoline or diesel. In this chapter, the amount of energy consumption from the fuel combustion, the impact of environmental health (toxicity gas emission), the cost of fuel used by the transit buses in terms of fuel energy consumption, and driving profile are discussed. The scope of this work is based on the total energy contained in the fuel only. The ability of the engine to transform the available energy from the fuel into useful work power (efficiency) is left to the designers and manufacturers.

Keywords: CNG, consumption, cost, diesel, emission, energy, gasoline

1. Introduction

The Tanzania strategic plans to increase economy are focused on industrialization agenda. The implementation of this agenda will increase the energy demand, hence the heavy fuel consumptions in industries and transportations sector. Energy consumption and its environmental impact are now among the most challenging problems in the most cities. Dar es Salaam is one of those fastest growing cities in Tanzania with the population over 5 million and expected to be a mega city with more than 10 million by 2030. Traffic congestion is one of the most prevalent transport challenges in Dar es Salaam. Due to the traffic congestion there is an increase of fuel consumption and likely potential harmful emissions. Moreover, the high fuel consumption (the imported commodity) significantly affects the national economy. The strategies are to reduce the harmful emissions by using fuel with less emission such as Compressed Natural Gas (CNG) and to develop electric powertrain systems. The chapter concludes with a brief look at fuel consumption and carbon dioxide (CO_2) emissions in public transport vehicles and other modes of transport.

The Government of Tanzania through Dar es Salaam Rapid Transit (DART) agency operates a Bus Rapid Transit (BRT) system in Dar es Salaam. BRT system aimed to be a cost effective sustainable transportation system for the city of Dar es Salaam to ensure fast and orderly flow of traffic on urban streets and roads. It is reported by DART agency that, in phase one project each trunk bus and feeder bus daily operate nearly 297 km and 245 km, respectively. However, BRT's bus fare is still higher than other operators (daladala) due to the high operation costs. DART projects are implemented in phases. According the DART Agency [1], the phase one of DART corridor mainly involved 20.9 km of roads: Kimara to Kivukoni (15.8 km), Magomeni to Morocco (3.4 km) and Fire to Kariakoo (1.7 km). Other facilities include 27 bus stations and 5 terminals. The phase two is along Kilwa Road from city centre to Mbagala Rangi Tatu; other parts of the corridor start from South Kawawa road at Morogoro Road junction to Mgulani JKT round with 20.3 km. The implementation of the phase three DART project goes through the Nyerere highways from Gongolamboto to the City Center and some area of the Uhuru Road from Tazara to Kariakoo to Gerezani, which covers a total of 23.6 km.

Motor vehicles have been powered by gasoline, diesel, steam, gas turbine, and electric. [2]. The common Internal Combustion (IC) engines are gasoline spark-ignition and diesel compression-ignition engines involving the combustion of a fuel inside a chamber that results in the expansion of the air/fuel mixture to produce mechanical work. In Tanzania, gasoline is the most common ground-transportation fuel, mostly used by private vehicles, followed by diesel used by most public vehicles and heavy duty trucks. As it is for the most public buses, BRT buses also use diesel as a fossil fuel. Diesel fuel in compression ignition engines produces a high level of toxicity in emission gases which leads to a health and environmental hazard [3]. The emitted gases associated with diesel fuel include nitrous oxides (NO_x), carbon monoxide (CO), and carbon dioxide (CO_2).

Tanzania has huge reserves of Natural Gas that city buses, especially the BRT systems, can use so as to minimize the harmful emissions. The development of gas supply infrastructures in Dar es Salam, Mtwara, and Coast Region are the examples of the ongoing initiatives. Recently, the natural gas, CNG in particular, has been considered to be a potential replacement and alternative to diesel and petrol fuels in vehicles due to its lower hazardous emission of gases in the environment. Applications of natural gas have been given much attention among stakeholders and researchers due to the remarkable attributes towards greener transportation. Studies on the use of natural gas in trains, buses, trucks, motorcycles, scooters and bicycles have been presented in various research reports. Since Tanzania has huge reserves of natural gas, this market growth increases with the users in various sectors including transportation.

Natural gas is used in transportation sector (public and private vehicles), industries, and domestic. If the use of natural gas resource is adopted effectively, the life of the people will improve both economically and environmentally. Therefore, a well-designed plan for the use of the natural gas in transmission and distribution is important. The objective is to optimize the utilization of gas resource as the alternative fuel energy in various sectors and the environmental safety. The strategy is to emphasize on the supply of CNG for transport sector use, and Piped Natural Gas (PNG) for domestic, commercial and industrial sectors in Tanzania. The CNG is mostly used in a public transit transportation fuel in other countries. CNG is a processed fluid gas into a high-pressure natural gas compression in a tube [4]. Compared to gasoline and diesel, vehicles powered by CNG emit less carbon monoxide, nitrogen oxides (NO_x), and particulate matter [5]. Apart from the government initiatives of using CNG in transportation, there are strategic plans to supply

CNG to the industries outside the downstream pipeline, and to other customers for heating and cooking purposes.

Since both the gas and petrol engines run according to the Otto principle with a spark plug ignition, there are several centers in Tanzania converting petrol engines to work in hybrid systems. Dar es Salaam Institute of Technology (DIT) and University of Dar es Salaam (UDSM) are among these centers. It is therefore very important that the plans for the natural gases infrastructure expansions get real so that suppliers and operators can invest in proper natural gases products to be used effectively in transportation, industry and domestic sectors. Currently, at CNG stations, gas flow to the vehicle is measured by mass for sale with dispensers designed with compensation for temperature variations to ensure accurate quantities are delivered to the tank [6].

Since, transit buses are among the cost effective forms of mass transit; most cities consider transit buses as the backbone of the transport system. However, the environmental health impact and running cost must be closed managed. In this chapter we investigate the current situation of BRT system buses using diesel, CNG and gasoline engines. The fuel consumption which is mentioned as the factor that affects the running costs, the cost of the fuel and the amount of fuel per distance, driving profile, and the emitted gases (mainly carbon dioxide) are discussed.

2. Propulsion energy

In this section, we briefly consider the main energy sources; gasoline, diesel and CNG as the input power to the IC engine vehicles. The fuel consumption, and overall efficiency, on the baseline scenario are discussed. Although urban driving is characterized by lower driving speeds and presumably more frequent stops which lead to higher consumption values [7, 8], this study is characterized by the special lanes (that is, not shared by other vehicles) for DART's buses. In this section, the energy from the CNG, gasoline and diesel fuels are analyzed where the difference in (potential) energy of reactants (exothermic reaction) and products are presented.

2.1 Natural gas

The heat is given off when a specified amount (say, one mole) of a methane (reactant) burns in oxygen gas (heat of combustion) during the reaction. The general bond dissociation energy equation (enthalpy change) for the reaction at a specified temperature through the reaction is converted into a motive force for the vehicle is in shown in Eq. (1) [9]. The heating of the fossil fuel results in CO_2 emission.

$$C_xH_y + \left(x + \frac{y}{4}\right)O_2 \rightarrow xCO_2 + \frac{y}{2}H_2O + \text{Energy} \tag{1}$$

where C_xH_y is the generic chemical formula for the fossil fuel, and O_2, the oxygen in the input, and the output of the reaction are the emitted carbon dioxide (CO_2), water (H_2O) and the released energy.

Methane (natural gas), which is a fossil fuel burns in oxygen to release energy as shown in Eq. (2). From **Table 1**, the combustion of methane gas will release 802.3 KJ/mol which is equivalent to calorific values of 50.1 KJ/g. The energy content of different fuels is made up of different chemical compounds, that is, bond breaking energies and bond forming energies reaction.

$$CH_4{}^{(g)} + 2O_2{}^{(g)} \rightarrow CO_2{}^{(g)} + 2H_2O^{(g)} + \text{Energy} \tag{2}$$

Bond Type	Energy (kJ/mole)
C–H	414
C–C	347
C=C	615
O–H	463
C–O	360
C=O	728
H–H	436
O=O	498

Table 1.
Average bond energies of common bonds.

2.2 Gasoline

Energy from the gasoline (petrol) released during the reaction is as shown in Eq. (1). From the general reaction, the octane (reactant) burns in oxygen gas to release energy from the reaction. The bond dissociation energy (enthalpy change) for the reaction at a specified temperature through the gasoline chemical reaction is shown in Eq. (3).

$$2C_8H_{18}{}^{(l)} + 25O_2{}^{(g)} \rightarrow 16CO_2{}^{(g)} + 18H_2O^{(g)} + \text{Energy} \tag{3}$$

The calculation reveals that the calorific value of the gasoline (petrol) is approximately 42 KJ/g.

2.3 Diesel

Energy from diesel is released during the reaction shown in Eq. (1) where the dodecane reactant, in the case of diesel, burns in oxygen gas to release energy from the reaction. The bond breaking energies and bond forming energies reaction is shown in Eq. (4).

$$4C_{12}H_{23}{}^{(l)} + 71O_2{}^{(g)} \rightarrow 12CO_2{}^{(g)} + 46H_2O^{(g)} + \text{Energy} \tag{4}$$

The calculation reveals that the calorific value of the diesel is approximately 43 KJ/g.

3. Longitudinal dynamics of the vehicle

Vehicle dynamics depend on tire and road contact forces and torques, mass of the vehicle, road profile (road grade angles), ambient conditions, and driving profile. These parameters contribute into the total fuel consumption. The total power consumption is defines by the vehicle dynamics and distance travelled by the vehicle. The IC engine vehicles transform the chemical energy (from gasoline/petrol, diesel, or CNG) into useful work (power consumed). The energy released by the gasoline, diesel, and CNG driven vehicles is discussed here. In fact, there are various factors affecting energy consumption when using IC engines. The ratio of power transmitted in a rotating shaft, referred to as brake power, and engine input

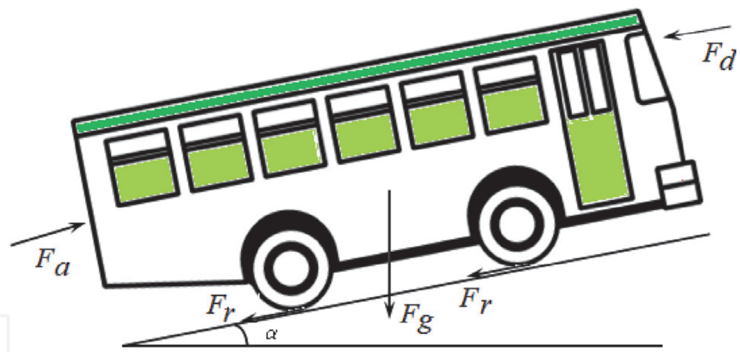

Figure 1.
Forces acting on a moving BRT bus.

power provides the overall efficiency of the IC engine. It should be noted that, modern engines (petrol and diesel) have better efficiency. **Figure 1** shows the forces acting on the moving bus. Therefore, the discussion assumes the better performance of engines.

3.1 Internal combustion engine power

It has been mentioned that BRT buses utilizes diesel as a fossil fuel. In analyzing the power consumed by the BRT bus, we need to understand the components of forces and resistance (opposing forces) that act on it. These forces and resistance on the bus are; rolling resistance due to tire and road interaction, aerodynamic drag resistance, grade resistance depends on motion towards the up-hill or the down-hill, and accelerating force due to the motion of the vehicle mass as shown in Eq. (5)-(8) [10–13].

$$F_r = c_r mg \cos\alpha \tag{5}$$

$$F_d = \frac{1}{2}\rho c_d A v^2 \tag{6}$$

$$F_g = mg \sin\alpha \tag{7}$$

$$F_a = ma \tag{8}$$

where,
F_r is the rolling resistance,
F_d is the aerodynamic drag resistance,
F_g is the grade resistance,
F_a is accelerating force,
c_r is the rolling resistance coefficient,
m is the vehicle mass (N),
α is the road grade angle (radian),
c_d is the wind resistance coefficient (N/(m^2/s)^2),
A is the vehicle frontal area (m^2),
v is the vehicle speed (m/s),
a is the vehicle acceleration (m/s^2),
ρ density of air, and.
g is the gravitational constant (nominally 9.81 m/s^2).

By definition, the rolling resistance is the combination of all frictional load forces of the tire on the road surface and the friction within the BRT bus. Aerodynamic drag is the resistance of air to the movement of the vehicle. The gradability of the vehicle load power can increase or decrease depending on whether the car is ascending or descending an incline. Therefore, the vehicle power needed are typically based on vehicle acceleration requirements, usually specified as the time to accelerate and depends on the maximum available torque and maximum available power of the propulsion system. Then, the prime mover force which is the total tractive force, F_T *for* the vehicle is given in Eq. (9).

$$F_T = F_r + F_d + F_a + F_g \tag{9}$$

The tractive power and total tractive energy are given in (10) and (11), respectively.

$$P = F_T v \tag{10}$$

$$E = Pt = P\frac{s}{v} \tag{11}$$

where,
t is the time spent,
s is the distance travelled,
P is the tractive power, and.
E is the tractive energy.

4. BRT bus power consumption

The BRT system scenario and power consumption are presented in this section. The type of buses and routes are depicted in **Figures 2** and **3**, respectively. Our discussion of the vehicle's engine performance will consider the DART phase one network (route), from Kivukoni terminal to Kimara terminal with 21 stations and 3 terminals. The DART's buses in this route start from Kivukoni station to Kimara in Dar es Salaam as a one-segment of the route. For analysis purpose, diesel fuel, gasoline fuel, and CNG fuel are considered in the discussion section. Technically, the speed of the vehicle, v (km/h) is obtained to estimate the speed of the engine, ω (rpm) and torque, τ (Nm).

Table 2 presents the route codes and destinations of the BRT buses in DART project phase one. The route code 001, from Kivukoni to Kimara, is used in this discussion. Other routes can be analyzed in the approach. Distances between

Figure 2.
BRT bus at the station.

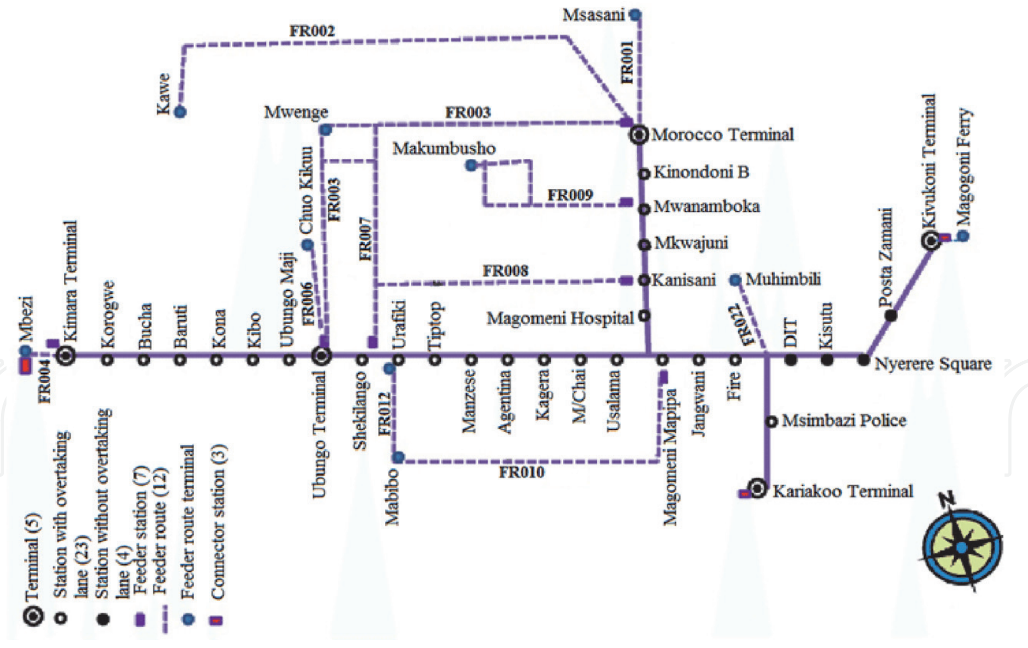

Figure 3.
DART phase one network Source: DART agency [1].

SN	Route Code	Source	Destination
1	001	Kimara	Kivukoni
2	002	Ubungo	Kivukoni
3	003	Morocco	Kivukoni
4	004	Kimara	Gerezani
5	005	Ubungo	Gerezani
6	006	Morocco	Gerezani
7	007	Kimara	Morocco
8	008	Ubungo	Morocco
9	080	Muhimbili	Gerezani
10	090	Kimara	Mbezi

Table 2.
DART project phase one route codes and destinations.

stations and terminals are presented in **Table 3**. The total distance covered by the route code 001 is 15.6 km. The estimated energy consumption is calculated by using Eq. (11) based on the road profiles (grade angles at each sample) and driving profiles (speed, stops, accelerating, and braking). Then, the estimated energy consumption is converted into kWh to be compared with the available energy in the fossil fuels [14]. This consumption depends on the motion of the vehicle and how it behaves in motion. Due to the fact that, these dynamic parameters are complex and varies from different inputs, the discussion is focused only on the energy released from the fuel as the input of the engines.

4.1 Driving profile measurements

Measurement of the driving profile can be done in different ways. The rotation vector sensor and the gravity sensor are the most frequently used sensors for motion detection and monitoring. Speed, orientation and position of the DART's

SN	Name	Category	Distance (km)
1	Kivukoni	Terminal	0.0
2	Posta Zamani	Station	1.14
3	Nyerere Square	Station	1.52
4	Kisutu	Station	2.25
5	DIT	Station	2.62
6	Fire	Station	3.18
7	Jangwani	Station	3.85
8	Magomeni Mapipa	Station	4.88
9	Usalama	Station	5.6
10	Mwembe chai	Station	6.12
11	Kagera	Station	6.6
12	Argentina	Station	7.25
13	Bakrhesa	Station	7.77
14	Manzese	Station	8.4
15	Urafiki	Station	9.0
26	Shekilango	Station	9.8
17	Ubungo	Terminal	10.5
18	Ubungo Maji	Station	11.2
19	Kibo	Station	12.2
20	Kona	Station	12.8
21	Baruti	Station	13.38
22	Bucha	Station	13.86
23	Korogwe	Station	14.5
24	Kimara	Terminal	15.8

Table 3.
DART Route 001 distances between stations/terminals.

bus were recorded by the use of the Global Positioning System (GPS) and Inertial Navigation System (INS) where integration of Inertia Measurement Unit (IMU) and GPS (GPS/IMU) are used [15].

There are several techniques to obtain the speed of the moving vehicles. For example, algorithm to estimate vehicle speed from accelerometer data generated by an onboard smart-phone [16] has been proposed in various literatures. However, according to authors in [16], speed estimation by the integration of the mobile-phone accelerometer data will not yield accurate results, since the accelerometer data in the direction of motion is not pure acceleration, but involves white noise, phone sensor bias, vibration, gravity component, and other effects. Similarly, the use of GPS to measure vehicle speed, on the other hand, depends on the number of visible GPS satellites at the recording time. Other factors include model of the mobile phone, whether condition, radio noise, concurrent usage, location and type of terrain, mobile network triangulation, Wi-Fi network location, and magnetic fields. [17] depending on the algorithm used. The speed of the vehicle can be estimated after analyzing the acceleration characteristic values in advancing direction and vertical direction as explained in [18].

4.2 Road profile measurements

The road profile and vehicle's speed (discussed earlier) are measured to determine power consumed by the vehicle. The quality of the road profile defines comfort ride, quality of load and passenger transportation as well as external excitation of the ground vehicle [19]. This subsection presents the road condition monitoring where rotation vector sensor and the gravity sensor are used.

The road grade angle (even vehicle speed) can be obtained by this method. The algorithm using KALMAN filters combines the use of accelerometer sensor and gyroscope (also known as gyro) sensor readings to obtain the speed and road profile. The readings in all orientations (x, y, z) are modeled as shown in Eqs. (12)-(14) where x_{xi} is the reading along x dimension, x_{yi} is the reading along y dimension, and x_{zi} is the reading along z dimension of the respective sensor (accelerometer and gyroscope). The t is the time of reading at k sample.

$$g_x^{(k+1)} = g_x^{(k)} + \nu_x^{(k)} t \tag{12}$$

$$g_y^{(k+1)} = g_y^{(k)} + v_y^{(k)} t \tag{13}$$

$$g_{y1}^{(k+1)} = g_{y1}^{(k)} + v_{y2}^{(k)} t \tag{14}$$

where,

v_x, v_y and v_z are sensor readings in *x, y,* and *z* orientations at t interval of time, and g_x, g_y and g_z are the road grade or speed in *x, y,* and *z* orientations at k sample time and updated at $k + 1$ sample.

Finally, the readings at each sample are utilized to compute the road profile.

5. Results discussions

The engine torque is created on the crankshaft by the cylinder pressure pushing on the piston during the power stroke. Therefore, the maximum torque depends on the pressure pushed during the power stroke. However, in practice, the torque versus speed characteristic of an IC engines are not as linear as electric machines.

The typical gasoline engine operates at no more than 10:1 compression ratio while the typical diesel engine may operate with a compression ratio as high as 25:1. It is obvious that, the higher the compression ratio, the better the overall engine efficiency. However, the scope of this work is based on the total energy contained in the fuel only. The great deal of the energy produced by a combustion engine is wasted. In this work, it is assumed that the speed of the vehicle along the route is the same regardless of the engine used.

The driving profile (time/speed) of the BRT bus for route 001 obtained is shown in **Figure 4**. The distance of 15.8 km was travelled in about 37 minutes. The average speed of this BRT bus is 26 kilometer per hour (kph). Despite the 23 expected stops at the stations and terminals, there are other stops at the road junctions, and zebra crossings. Moreover, the drivers try to observe the speed limit of 50 kph and 60 kph along the route 001 road. The power consumption is proportional to the modes of the vehicle: traction (when the prime mover force, $F_t > 0$), braking ($F_t < 0$), and coasting ($F_t = 0$). **Figure 5** shows the average power consumption for the BRT bus on route 001. The energy used to brake or slow down a vehicle in a conventional vehicle is dissipated as heat in the braking system and lost to the vehicle. An electric vehicle can be designed to regenerate the energy and store it on the vehicle for auxiliary usage.

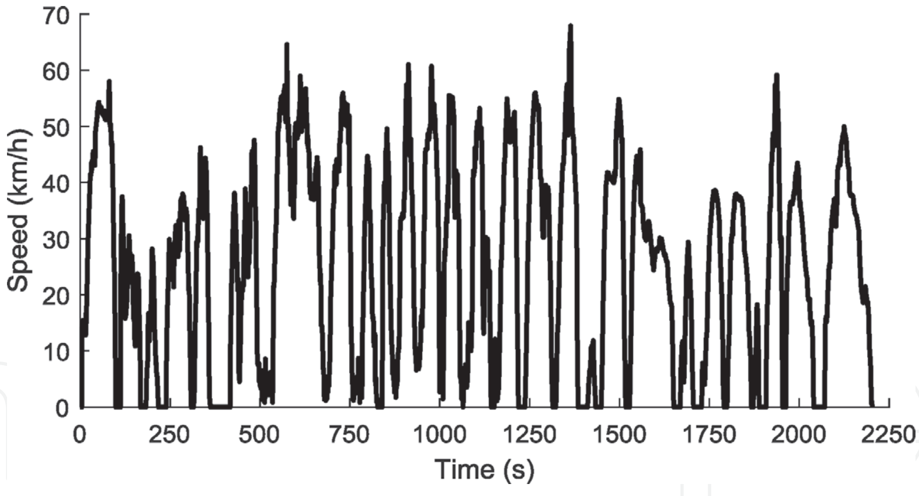

Figure 4.
Driving profile of the BRT bus on route 001.

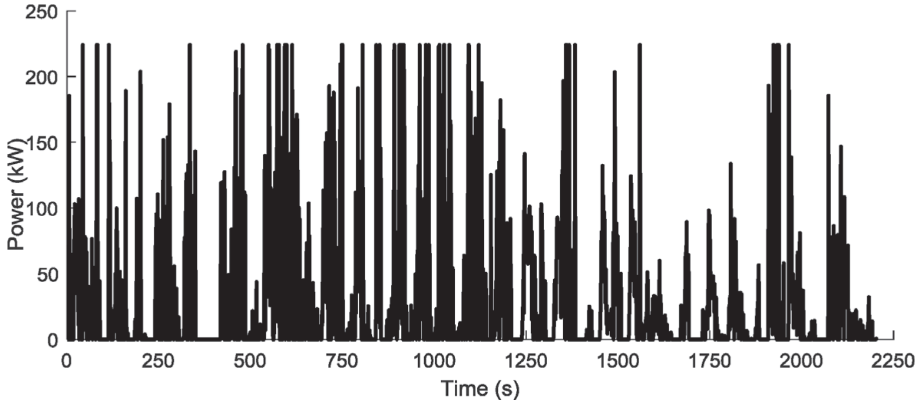

Figure 5.
Average power consumption for the BRT bus on route 001.

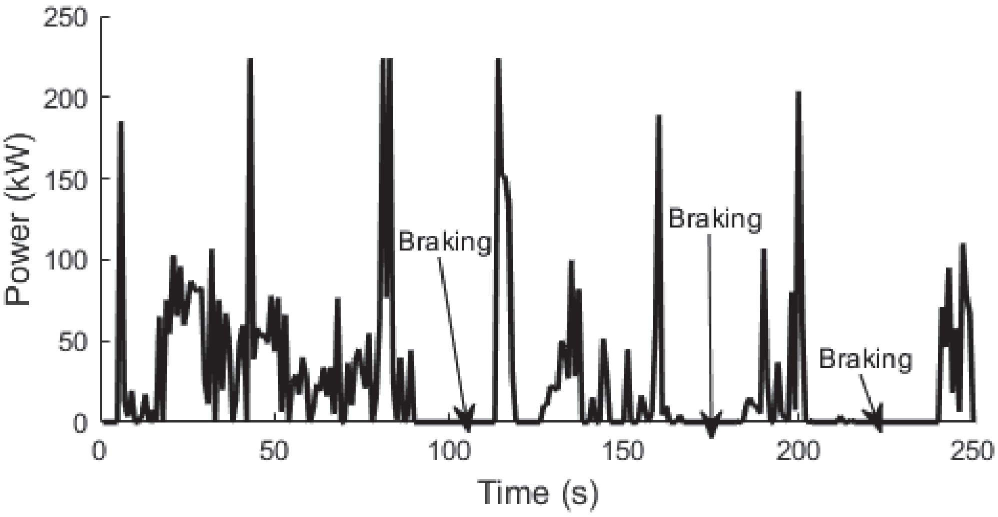

Figure 6.
Section of power consumption (0–250 second).

Figure 6 depicts the section of power consumption (0–250 seconds), showing the stopping (or braking) periods. The more power is consumed when the bus is in accelerating mode. As discussed earlier, the power consumption (and emission) depends on the vehicle design parameters, auxiliary devices, driving profiles, road profiles and conditions. **Figure 7** shows the amount of energy consumption for the BRT bus on route 001 obtained by using Eq. (11).

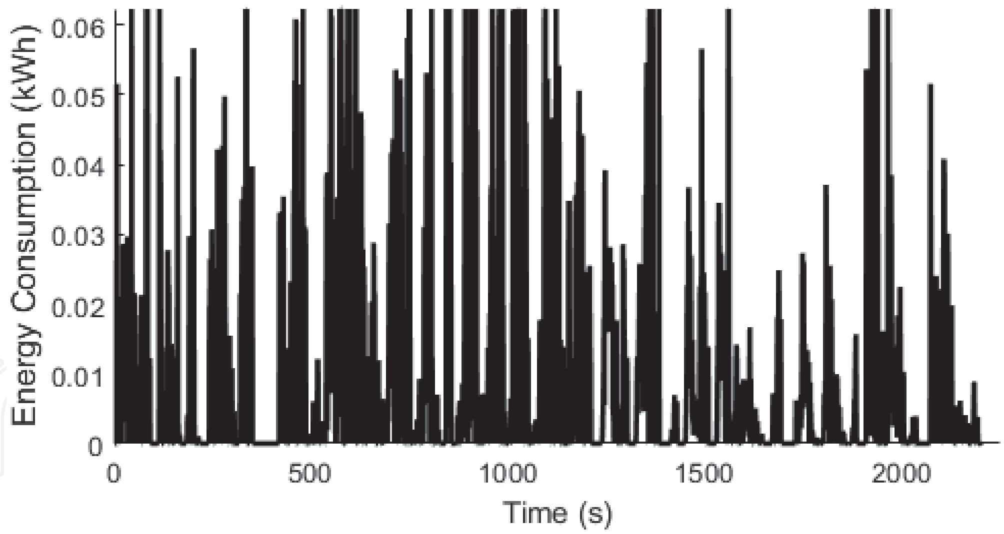

Figure 7.
Energy consumption for the BRT bus on route 001.

Parameter	Unit	Value
Wind resistance coefficient	$N/(m^2/s)^2$	0.599
Rolling Resistance Coefficient, C_r	—	0.01
Vehicle mass, m	kg	11750
Passenger mass	kg	5590
Vehicle total mass	kg	17340
Frontal area, A	m2	6.93
Acceleration due to gravity, g	m/s^2	9.8
Final-drive ratio, r_f	—	3.37
4-speed transmission ratios, r_t	—	[2.393 1.450 1.000 0.677]
Wheel radius, r_r	m	0.381
Engine efficiency	—	0.92
Tank capacity is about	liter	475
Maximum engine torque	—	1200 Nm
Maximum engine power	—	284 kW

Table 4.
Transit bus parameters.

The total energy consumed when the given vehicle (parameters in **Table 4**) on route 001has been computed to be approximately 19.952 kWh. In fossil fuel environment, this energy can be obtained from gasoline, diesel, or CNG. The calorific values of these fuels (Energy/mass) can be in KJ/g or kWh/Kg. In converting calorific value, energy/mass, in KJ/g of the fuel into calorific value in kWh/ Kg, we divide the energy/mass (KJ/g) value by 3.6. Gasoline and diesel densities are presented in **Table 5** [20]. Using information from **Table 5**, other conversions (kWh/Kg and kWh/L) are presented in **Table 6**.

In Tanzania mainland, the Energy and Water Utilities Regulatory Authority (EWURA) is responsible to publish cap prices for petroleum products. The wholesale and retail prices vary from time to time depending on price of the imported petroleum product imported. For example, According to the released wholesale and retail prices released by EWURA on Wednesday, 3rd February 2021, the retail

Fuel	Kg/liter
Gasoline	0.737
Diesel	0.850

Table 5.
Specific gravity of motor fuel (Kg/L).

Fuel	KJ/g	kWh/Kg	kWh/L
Gasoline	42	11.67	8.6
Diesel	43	11.94	10.15
CNG	50.1	13.92	—

Table 6.
Other units for energy mass of the fuel.

Fuel	Required energy (kWh) route 001		Fuel Cost*
	Kg	Liters	
Gasoline	—	2.32	4,377.84
Diesel	—	1.9	3,475.10

**Gasoline (petrol): 1887.00 TZS/Liter; Diesel 1829.00 TZS/Liter; CNG: 1550.00 TZS/kg.*

Table 7.
Energy consumed and cost of fuel used in route 001.

Fuel	CO_2 Emission (Kg)
Gasoline	5.336
Diesel	5.073
CNG	3.257*

**Emission when high calorific gas is used.*

Table 8.
CO_2 emission in one segment of Kivukoni-Kimara route.

prices were as indicated in the underneath of **Table 7**. From Eq. (11) the average required energy for the BRT bus on route 001 approximately 19.952 kWh. This energy can be delivered by the gasoline, diesel or CNG as shown in **Table 7**. Therefore, with other factors assumed the same and perfect, gasoline IC engine bus would consume 2.32 liters of gasoline to cover the route while diesel IC engine would consume 1.9 liter of diesel in the same route. CNG engine bus, on the other hand, would 1.22 Kg of CNG gas. The total fuel cost required is shown in the extreme column of **Table 7**.

The emission of carbon dioxide (CO_2) for an internal combustion engine to move a vehicle down the road depends on the type of fuel used. While 1 L of gasoline produces approximately 2.3 Kg of CO_2, burning 1 L of diesel produces approximately 2.67 Kg of CO_2. For the case of CNG, CO_2 emission depends on the calorific gas (i.e. low calorific gas and high calorific gas). This emission ranges from 2.25 Kg of CO_2 (low calorific gas) to 2.67 Kg of CO_2 (high calorific gas) when burning 1 Kg of CNG. Hence, the total CO_2 emission in route 001 is shown in **Table 8**. The CNG emission is still low compared to gasoline and diesel.

6. Conclusion

The concerns of the global warming and environmental pollution have led to more severe regulations on CO_2 and other pollutant emissions. Therefore, converting conventional vehicles to operate on natural gas is a good option for BRT system. The operating cost is low due the low cost of CNG and the CO_2 gas emission is low compared to other fuel types (diesel and gasoline). Since CNG is available locally, (not imported), the national agenda of industrialization is supported by the use of CNG as an alternative source of energy.

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