Original Research Article

Sustainable Energy Analysis of Nigerian Road Transportation Sector: Benchmarking against Global Trends

Abstract

Sustainability of road transportation sector fuel exergy utilisation in Nigeria between 1990 and 2019 was examined and compared with the global trends in the same sector. Parameters used were exergy efficiency, depletion number, sustainability index and improvement potential. Petrol engines had the highest mean efficiency of 13.05% and heavy duty vehicles the lowest of 8.57%. Their respective mean depletion numbers were 0.8695 and 0.9143, while their mean sustainability index values were 1.1501 and 1.0937 respectively. However, petrol engines had the highest mean improvement potential of 2.07×10^{11} MJ and cars had the lowest value of 1.86×10^{10} MJ. When benchmarked against global values, petrol engines still had the highest mean potential difference value of 5.93×10^{10} MJ while cars have the lowest value of 6.02×10^{9} MJ. Improvement Potential values were largely influenced by exergy utilisation rates, the influence of which outweighed that of exergy efficiencies, of the different carriers.

Keywords: Exergy, Sustainability Index, Road transportation, Automobiles, Depletion number, Improvement Potential, Global Trends

Introduction

Transportation is a very important sector of world economy. In Nigeria, road transportation alone consumes an average of 90% of the total energy used by the transport sector. Besides, 77% of total petrol or Premium Motor Spirit (PMS) consumed in the country is used in the transport sector of which 4.2% and 95.8% are allocated to the domestic water navigation and road transport sub-categories respectively [ECN, 2016]. Furthermore, 75.3%, 8%, 16.3% and 0.4% of the total PMS used for road transport are used in passenger cars, motorcycles, Light-Duty Trucks/buses and Heavy Duty-Trucks/buses respectively. This is in addition to 1.7%, 0.7% and 64.9% of the country's Diesel or Automotive Gas Oil (AGO) consumption used for domestic water navigation, rail and road transport respectively [Cervigni, 2017]. Passenger transportation accounts for about 60% to 70% of energy consumption from transportation activities, and more than 70% of the country total energy consumption is in the transport sector [Chukwu et al, 2015]. Nigeria is the largest vehicle market of the Economic Community of West African States (ECOWAS) and accounts for roughly two-thirds of the region's vehicle fleet.

The average vehicle fuel efficiency in Nigeria in the early 1990s was 13.07 mpg (18 litres per 100 km) [Obih, 2001], at a time when the average fuel efficiency in the US was 24.09 mpg (9.76 litres per 100 km) for light duty vehicles [RITA/BTS, 2012]. Adegbulugbe [1991] also got the same estimate of about 18 litres of gasoline per 100 km. Besides, the average new car in 2005 worldwide had a fuel economy level of about 29.4 mpg (8 litres per 100 km) [Elzinga et al, 2011; Cuenot and Fulton, 2011]. Okafor et al [2014] estimated average energy efficiency of public passenger transport vehicles in Nigeria, and obtained 18.12 litres of gasoline per 100 km for petrol engines and 36.89 litres per 100 km for diesel engines. This is likely due to the observation of Johnson and Hossain [2017] that for vehicle models older than those of the year 2000, average rates of fuel consumption are significantly higher for diesel engines than for petrol engines. This is the situation with our case study in Nigeria.

Table 1 [Akumu, 2013] is instructive about how critical the road transport fuel economy in Nigeria (18 Litres/100 km) is, if we benchmark it against those from some African countries.

Table 1: Fuel Economy Values in Kenya and Ethiopia

Ethiopia	2005	2008	2010
Average Fuel Economy (Litres/100 km)	8.4	8.4	7.9
Diesel	9.3	9.4	9.0
Petrol	7.8	7.4	6.9
Kenya			

Average Fuel Economy (Litres/100 km)	7.69	7.6	NA
Diesel	8.67	9.09	NA
Petrol	7.52	7.2	NA

Although Nigeria, Ethiopia and Kenya all have preponderance of used vehicles in their fleets, one factor that stands Nigeria out is lack of maintenance culture: people drive their cars until they break down, and fix them [Deloitte, 2016]. Fuel efficiency is low in Nigeria because the vehicle fleet is old and poorly maintained, there is traffic congestion in most urban centres and driving habits are bad [Jochem, 2000; Cervigni et al, 2013]. About a decade ago, more than 85% of motor vehicles being imported into the country annually were used vehicles [Agbo, 2011]. Right about now, approximately 90% of vehicles entering Nigeria are second-hand vehicles. Imported passenger cars are permitted to be up to 15 years old, and no age limits are applied to imported commercial vehicles [Miller, 2019]. This is an increase of 5% within a decade period. In a most recent report [Human Environment and Transport Inspectorate, 2020], ECOWAS countries decided that, as from 1st January 2021, only used vehicles with a minimum of Euro 4/IV standard would be imported, cutting away more than 80% of the used vehicles hitherto imported in the region. It is noteworthy that there were no records of importation of used vehicles into the country prior to 1988 [Ajayi and Dosunmu, 2002].

According to Ntziachristos and Dilara [2012], a typical Compression-Ignition (CI) engine has a real life efficiency of 25% to 35%, dropping to around 25% to 30% for cars while heavy duty trucks efficiencies are in the range of 35% to 40%. From Forster and Gaus [2003], Spark Ignition (SI) engine cars have efficiencies in the range of 24% to 36% while SI heavy duty vehicles have theirs in the range of 22% to 31%. Generally, Ntziachristos and Dilara [2012] report 18% to 20% for SI engines, and it is believed this range is applicable to SI light duty vehicles. It is also believed [Kobayashi et. al, 2009] that diesel engines are more efficient than current gasoline engines. However, the Australian case study by Johnson and Hussain [2017] is more applicable to Nigeria Besides, according to Yamamoto [1999], a typical motorcycle thermal efficiency is 32%. In Nigeria, rather than being brought in used, motorcycles are imported in completely knocked-down (CKD) form to be assembled.

Hence, from 1980 to 1987, any analysis similar to this work should be based on the assumptions of 19% typical average engine thermal efficiency for SI engines, 28% for CI cars, 30% for CI light duty trucks and 38% for CI heavy duty trucks

Nigeria's vehicle market is dominated by demand for gasoline, which accounts for 80% of combined gasoline and diesel demand [International Organization of Motor Vehicle Manufacturers, 2015] quoted in Miller [2019]. However, the proportion of private vehicles that run on diesel is negligible. Majority of small and medium-sized minibuses also run on petrol. About a half of the large buses run on petrol as well. The higher price of diesel has resulted in far fewer heavy trucks and buses running on the more efficient diesel than would be expected if both fuels were similarly priced [Cervigni et al, 2013].

In the famed Brundtland report, sustainable development was to "ensure that humanity meets the needs of the present without compromising the ability of future generations to meet their own needs"[World Commission on Environment and Development, 1987]. The International Chamber of Commerce gave a clearer definition that "sustainable development combines environmental protection with economic growth and development" [Welford, 1997]. Closely related to sustainability and industrial ecology is the concept of exergy. This is because it relates resource utilisation with environmental parameters. Hence, it is normally used by energy professionals in sustainable energy utilisation analyses. The main objective of this work is to assess sustainability of road transportation sector fuel utilisation in Nigeria from 1990 to 2019, using exergy efficiency, depletion number, sustainability index and improvement potential as parameters, and comparing the results with the global trends in the same sector.

Methodology

. Since the data used in this work is post-1987, thermal efficiencies, η,, , will be evaluated for Nigeria in a way similar to that of Badmus et al [2012] in Equation 1, and based on the findings of Adegbulugbe [1991], Obih [2001] as well as Okafor et al [2014], in order to take care of the findings of Ajayi and Dosunmu [2002]::

$$\eta_{th,Nigeria} = \frac{\eta_{fuel,\ Nigeria}}{\eta_{fuel,\ global\ trend}} \times \eta_{th} \cdots (1)$$

In particular, the efficiency values in Table 2 was used accordingly.

Table 2: Thermal Efficiencies of Different Carriers

SI Engines		CI Engines	
Cars			
Global Trend	Nigeria	Global Trend	Nigeria
30% [Forster and Gaus, 2003]	13.33%	27.5% [Ntziachristos and Dilara, 2012]	15.47%
Light Duty Vehicles (LDVs)			
Global Trend	Nigeria	Global Trend	Nigeria
19% [Ntziachristos and Dilara, 2012]	8.44%	30% [Ntziachristos and Dilara, 2012]	16.88%
Heavy Duty Vehicles (HDVs)			
Global Trend	Nigeria	Global Trend	Nigeria
26.5% [Forster and Gaus, 2003]	11.78%	37.5% [Ntziachristos and Dilara, 2012]	9.12%
Motorcycles (SI, Global Trend)			
32% [Yamamoto, 1999]			

The global trend of SI values have been multiplied by a factor of 4/9, based on Elzinga et al [2011] as well as Cuenot and Fulton [2011] on one hand and on Adegbulugbe [1991], Obih [2001] as well as Okafor et al [2014] on the other. However, the global trend of CI values for cars and Light Duty Vehicles have been multiplied by a factor of 9/16, based on Akumu [2013] and the equivalent diesel value obtained from Adegbululgbe [1991], Obih [2001] as well as Okafor et al [2014] . The global CI value for Heavy Duty Vehicles is multiplied by a factor of 9/37 based on Akumu [2013] and Okafor et al [2014] on the other, since the diesel engine part of the work of Okafor et al [2014] concentrated on heavy duty vehicles. The efficiency value for motorcycles is a typical global value, since they are normally imported into the country as CKDs.

Many authors, like Rosen et al. (2008), define exergy efficiency (ψ) thus:

$\psi = \frac{Ex_{out}}{Ex_{in}}$ . . . (2)

In Equation (2), Ex_{in} is the input exergy, while Ex_{out} is the utilised exergy.

Also, according to Connelly and Koshland (1997), assessment of fossil fuel consumption can be characterised by a depletion number, D_p, given by:

$D_p = \frac{Ex_D}{Ex_{in}}$ . . . (3)

Ex_D is the exergy destruction or exergy destroyed in the process.

But, $Ex_{in} - Ex_{out} = Ex_D$ . . . (4)

Hence, relationship between depletion number and exergy efficiency is:

$\psi = 1 - D_p$, or,

$D_p = 1 - \psi$ . . . (5)

Importance of the depletion number is that it indicates the fraction of input energy resources that is degraded through entropy creation, turning them into states of no useful energy values. Also, Rosen et. al (2008) as well as Dincer and Zamfirescu (2014) suggested assessing sustainability of a fuel or any energy resource using a sustainability index, SI, expressed as the inverse, or reciprocal, of the depletion number:

$SI = 1/D_p = \frac{1}{1-\psi}$ . . . (6)

In addition, van Gool [1992] in Hammond [2007], as well as in Dincer and Zamfirescu [2018] noted that the maximum improvement in the exergy efficiency of a process or a system is attained when exergy loss is least. Consequently, he suggested that it is useful to employ the concept of an exergetic 'improvement potential', IP, when analysing different processes or sectors of the economy:

$IP = (1-\psi)(Ex_{in} - Ex_{out}) = (1-\psi)(1-\psi)Ex_{in} = (1-\psi)^2 Ex_{in}$ . . . (7)

When an analysis indicates that the improvement potential is high, it means the exergy losses are too high and there is a big room for exergy efficiency improvement. On the other hand, when the improvement potential is low, there is little that can be done to the process or system in order to improve its exergy efficiency. It is then expected that, in exergy analyses of processes and systems, attention is paid to those with high improvement potentials in order to optimise their exergy efficiencies.
The specific exergy of the fuel (ε_f) at environmental conditions reduces to its chemical exergy, and can be written as follows:
$\varepsilon_f = \phi_f$ LHV . . . (8)
LHV is the lower heating value of the fuel and ϕ_f is the exergy factor of Szargut and Styrylska as enunciated in Szargut et al. [1988]. The fuel exergy factor used for both gasoline and diesel fuels in this work is 1.07 [Szargut, 2005]. The heating values have been taken from Garg et al. [2006]. They are 44150 MJ/tonne for petrol, and 42910 MJ/tonne for diesel.
From the definition of exergy, mechanical work, W, is identical to the physical work exergy, E^W. Hence,
$E^W = W$ . . . (9)
From the foregoing, the energy efficiency η_m and exergy efficiency, ψ_m for the fossil fuel-driven kinetic energy production process which produces shaft work, W, from fuel mass m_f, can be expressed as follows:
$\eta_m = W/m_f LHV$
$\psi_m = E^W/m_f \phi_f LHV$
Hence,
$\psi_m = \eta_m/\phi_f$ . . . (10)
Equation (2) was used to determine the energy efficiency, η_m, while Equation (10) was used to determine values of exergy efficiency, using Equation (2) of various carriers in this work.

Mode Exergy Efficiency

In this paper, engines are sometimes grouped together into a mode in order to evaluate their common parameters like efficiency, depletion number, sustainability index and improvement potential. Examples of modes are petrol engines, diesel engines, LDVs, HDVs and cars. Using exergy efficiency as an example, since exergy efficiency is ratio of output to input, as in equation (2), the mode exergy efficiency is given by:
$\varphi_m = \frac{\sum \varphi_i \epsilon_i}{\sum \epsilon_i}$ . . . (11)
The subscript 'i' is for the ith carrier in the mode, 'ψ' is the exergy efficiency and 'ϵ' is its exergy input. If we linearise the expression by dividing numerator and denominator by '$\Sigma\epsilon_i$', the total exergy input (Ex_{in}), we have:
$\varphi_m = \sum \varphi_i \epsilon_i'$ . . . (12), where

$\epsilon_i' = \frac{\epsilon_i}{\sum \epsilon_i}$ . . . (13)
In equation (13), ϵ_i' is the fractional exergy utilised by carrier 'i'.

For instance, in the case of petrol engines with cars, LDVs, HDVs and motorcycles, the petrol engines exergy efficiency is given by:

$\varphi_m = \varphi_c\epsilon'_c + \varphi_L\epsilon'_L + \varphi_H\epsilon'_H + \varphi_y\epsilon'_y \ldots (14)$

A small, finite change in φ_m is given by:

$\Delta\varphi_m = \frac{\partial}{\partial\epsilon'_i}(\sum\varphi_i\epsilon'_i)\Delta\epsilon'_i \ldots (15)$

Since the φ_is are constant in our case, equation (15) becomes:

$\Delta\varphi_m = \sum\varphi_i\,\Delta\epsilon'_i \ldots (16)$

In equation (14), subscripts 'c', 'L', 'H' and 'y' are for cars, LDVs, HDVs and motorcycles respectively.

As a benchmark, and having observed that the main challenge of the Nigerian transportation sector is poor carrier exergy utilisation efficiency, the parameters used in this work were also evaluated for global trends. Values of the parameters, obtainable outside Nigeria boundary, are regarded as global trends.

Results and Discussion

Energy consumptions in MJ, by different carriers, are shown Table 3.

Table 3: Road Transportation Energy Consumption in Nigeria from 1990 to 2019

Year	Cars Petrol	LDV Petrol	HDV Petrol	Motorcycles Petrol	Cars Diesel	LDV Diesel	HDV Diesel
1990	1.45157×10^{11}	31421859635	771088580	15421771600	3067365567	29651200481	69526952852
1991	1.45238×10^{11}	31439203080	771514186	15430283720	3068665740	29663768820	69556423440
1992	1.46279×10^{11}	31664739823	777048830	15540976600	2404933860	23247693980	54511834160
1993	1.77407×10^{11}	38402775958	942399410	18847988200	4335278829	41907695347	98266320124
1994	1.87502×10^{11}	40588049965	996025766	19920515320	2974113555	28749764365	67413240580
1995	1.37281×10^{11}	29716804737	729246742	14584934840	2917536720	28202854960	66130832320
1996	1.32486×10^{11}	28678860753	703775724	14075514480	2915876103	28186802329	66093191668
1997	1.45425×10^{11}	31479805450	772510563	15450211264	2730140597	26391359105	61883186868
1998	1.17361×10^{11}	25404821433	623431201	12468624016	2329904867	22522413712	52811176981
1999	1.04841×10^{11}	22694667148	556924347	11138486944	2048528120	19802438494	46433304056
2000	8.64236×10^{10}	18707679500	459160000	9181875500	2641110500	25354660800	60040959300
2001	1.29655×10^{11}	28066155000	688740000	13774800000	2734654300	26253625300	62169724400
2002	1.57698×10^{11}	34136338500	837525500	16754042000	2869820800	27549936400	65239505800
2003	1.58394×10^{11}	34287331500	841499000	16828214000	2731221500	26218439100	62086479000
2004	1.48939×10^{11}	32240537500	791168000	15823360000	1966565300	18878254500	44704496200
2005	1.56911×10^{11}	33966361000	833552000	16670598500	2430422400	23332741600	55253490600
2006	1.50789×10^{11}	32640978000	800881000	16020269000	1184316000	11367288100	26918730300
2007	1.60824×10^{11}	34813158000	854302500	17086050000	994224700	9542754900	22598122400
2008	1.72452×10^{11}	37330149500	916112500	18321367000	1089055800	10456308800	24761215500
2009	1.75725×10^{11}	37350900000	916554000	18331521500	811428100	7789023200	18445292600
2010	1.97329×10^{11}	24965059000	612802000	12252949500	631206100	6059321100	14348245800
2011	2.0737×10^{11}	22351820500	548343000	10970392000	702007600	6738157300	15956083500
2012	2.1741×10^{11}	19715624000	483884000	9676355500	485741200	4663029700	11042030300
2013	2.88518×10^{11}	62454590000	1532446500	30652462000	2031788500	19505169600	46188753100
2014	3.15837×10^{11}	68368482500	1677700000	33554883000	2310703500	22181037200	52526560100
2015	2.88518×10^{11}	62454590000	1532446500	30652462000	2031788500	19505169600	46188753100
2016	3.15997×10^{11}	68402919500	1678583000	33572101500	2800735700	26887406000	63671145300

2017	3.27955×10^{11}	70991554353	1742124033	34842480664	1413461837	13663464420	32038468294
2018	4.90246×10^{11}	1.06122×10^{11}	2604226249	52084524976	1120307582	10829639960	25393638528
2019	2.64349×10^{11}	57223025551	1404246026	28084920516	1106264426	10693889455	25075326998

Sources: NNPC [1997, 2008, 2019]; Fed. Min. of Environment [2020]

Energy Consumption

Table 3 presents energy consumption in the sector during the period covered by this work. Out of all the categories of carriers, petrol cars recorded the absolutely highest energy consumption of 4.90246×10^{11} MJ (2018) during the period considered in this paper, while petrol HDV recorded the absolutely lowest of 4.5916×10^{8} MJ (2000). The minimum annual energy use of motorcycles (9.18188×10^{9} MJ), which was in the year 2000 was more than similar values for each of petrol HDVs, diesel cars and diesel LDVs. Maximum energy utilisation in the motorcycles subsector was also 5.20845×10^{10} MJ (in the year 2018) during the period, and this was more than similar values for petrol HDVs, diesel cars and diesel LDVs. This suggests that use of motorcycles was more rampant than use of petrol HDVs, diesel cars and diesel LDVs in the country. These energy consumption values are particularly influential on the exergy improvement potentials of the various carriers, subsectors and the sector in general, when considered along with the carriers' energy utilisation efficiencies.

Exergy Efficiencies

As shown in Table 4, the analysis of the Nigerian transportation sector within the period covered by this work indicates that petrol engines have the highest mean efficiency of 0.1305, with minimum and maximum values of 0.1275 and 0.1308 respectively. Cars follow petrol engines with a mean value of 0.1246 along with minimum and maximum efficiency values of 0.1243 and 0.1249 respectively. Diesel engines have exergy efficiencies ranging from 0.1078 to 0.1080 and a mean value of 0.1079, coming third, after petrol engines and cars. LDV exergy efficiencies are from 0.0859 to 0.1242 with a mean value of 0.1058. HDV are the least efficient, having an average value of 0.0857, with minimum and maximum values of 0.0852 and 0.0874 respectively.

Within the global trend, however, HDV have the highest mean efficiency of 0.3478, followed by diesel engines with 0.3274, cars (0.2801) and petrol engines (0.2657). LDV have the lowest mean exergy efficiency globally, with a value of 0.2129. The corresponding minimum and maximum values are 0.3409 and 0.3497; 0.3273 and 0.3275; 0.2800 and 0.2803; 0.2650 and 0.2728 as well as 0.1871 and 0.2367.

This trend is not surprising, considering the fact, as observed by Johnson and Hossain [2017], that for vehicle models older than those of the year 2000, average rates of fuel consumption are significantly higher for diesel engines than for petrol engines. This is also corroborated by Okafor et al [2014].

Petrol engines exergy efficiencies are the highest. They are practically constant at 0.1308, except between years 2008 and 2013, when it goes down from 0.1308 to 0.1275 in 2012 before coming up to 0.1308 again in 2013. This is largely due to the reduced exergy consumption of the most efficient petrol engine in the country, during the period, the motorcycles. The petrol engines considered in this paper consist of LDVs with a carrier thermal efficiency of 0.084, HDVs with a carrier thermal efficiency of 0.118, cars, with a carrier thermal efficiency of 0.133 and motorcycles with an efficiency of 0.32. Applying equations (14) and (15) between 2009 and 2012 on petrol engines:

$\varphi_c = 0.133$

$\Delta\epsilon'_c = 0.8792 - 0.7564 = 0.1228$

$\varphi_L = 0.084$

$\Delta\epsilon'_L = 0.0797 - 0.1608 = -0.0811$

$\varphi_H = 0.118$

$\Delta\epsilon'_H = 0.0020 - 0.0039 = -0.0019$

$\varphi_y = 0.32$

$\Delta\epsilon'_y = 0.0391 - 0.0789 = -0.0398$

Hence, $\Delta\varphi_m = 0.133\times0.1228 - 0.084\times0.0811 - 0.118\times0.0019 - 0.32\times0.0398 = -0.00344$.

This is why there is a depression between 2008 and 2013 in the petrol engines exergy efficiency curve (Figure 1).

In particular, the motorcycle thermal efficiency is about quadruple that of LDVs, approximately triple that of HDVs and more than double that of cars. Hence, its exergy utilisation dropping from 7.89% of total petrol utilisation in 2009 to 3.91% in 2012 before rising to 8% in 2013 (Figure 2) has a negative impact on the overall exergy efficiency of petrol engines during the period. Cars (both petrol and diesel engines), diesel engines (of all categories) and HDVs all have practically constant exergy efficiencies, due to relatively constant proportions of their exergy inputs. However, LDVs have variable efficiencies throughout the period under consideration, mainly due varying proportions of their exergy inputs. Practically, the overall LDV exergy efficiency varies directly with diesel exergy utilisation (Figure 3). This is because diesel engine LDV has a thermal efficiency which is double that of the petrol engine. Hence, it has more influence on the overall exergy efficiency of the LDVs. This is despite the fact that average utilisation of petrol throughout the period by LDVs is 65.61% of total, while that of diesel is 34.39%.

There are both petrol and diesel engines under the HDV category. Petrol engines have a thermal efficiency of 11.78%, while that of diesel engines is 9.12%. Both are very low and very close. However, (the lower efficiency) diesel engines dominate the exergy utilisation (Figure 4), with an average utilisation rate of 97.4%, leaving petrol engines with only 2.6% during the period covered by this work. This has resulted in the HDVs having the lowest exergy efficiency during the period.

Depletion Number

For Nigeria case (Table 4), HDV has the highest mean value of 0.9143, followed by LDV (0.8942), diesel engines (0.8921) and cars (0.8754). The least value is that of petrol engines, and it is 0.8695. Their respective minimum and maximum values are 0.9126 and 0.9148; 0.8758 and 0.9141; 0.8920 and 0.8922; 0.8751 and 0.8757 as well as 0.8692 and 0.8725.

In the global trend series (Table 5), HDV has the lowest depletion number, with values ranging from 0.6503 to 0.6591 and an average value of 0.6522. This is followed by diesel engines, with values ranging from 0.6725 to 0.6727 and an average value of 0.6726. The third lowest values are of cars, with values ranging from 0.7197 to 0.7203 and an average value of 0.7199. LDV and petrol engines have highest depletion numbers with values ranging from 0.7633 to 0.8129, and an average value of 0.7871 as well as values ranging from 0.7272 to 0.7350 and an average value of 0.7343 respectively.

From equation (5), depletion number is complementary to exergy efficiency. This is because when the two parameters are added together for a particular system or process, the result is 100%. Hence, whenever one is high, the other is low, and vice versa for any system or process. Indeed, while exergy efficiency measures degree of exergy utilisation or energy availability, depletion number measures degree of exergy destruction, energy degradation or entropy creation. Hence, it is expected that depletion numbers corresponding to exergy efficiencies discussed earlier are just complementary to them. This is exactly what we have in Figure 5. A comparison of Figures 1 and 5 reveals this fact graphically.

Sustainability Index

In the Nigerian sector analysis, petrol engines have the highest mean sustainability index value of 1.1501. This is followed by cars with 1.1423 and diesel engines with 1.1209. In the fourth category, in decreasing order, is LDV with a value of 1.1185. HDV have the lowest value of 1.0937. Their minimum and maximum values are 1.1461 and 1.1504; 1.1420 and 1.1427; 1.1209 and 1.1211; 1.0939 and 1.1418 as well as 1.0932 and 1.0958.

For the global trend, HDV have the highest mean sustainability index. Its value is 1.5333. Diesel engines are next, with a value 1.4868. Cars are next, with a value of 1.3890. Petrol engines value follows that of cars. It is 1.3618. LDV have the least value of 1.2709. Respective minimum and maximum values are 1.5172 and 1.5377; 1.4866 and 1.4869; 1.3883 and 1.3895; 1.3605 and 1.3752 as well as 1.2301 and 1.3101.

Also, from equation (6), Sustainability Index is the reciprocal of Depletion Number. This is because energy degradation or exergy destruction is inimical to sustainability. Hence, for energy utilisation to be sustainable, the depletion number must be low. A corollary of this is that high exergy utilisation efficiency is also a good indication of sustainability. Indeed, apart from the ranges of values, Figure 1 and Figure 6 are very similar. Hence, the analysis in this segment of the paper is similar to that of the exergy efficiency analysis.

Improvement Potentials

Within the time frame of this work in the Nigerian transportation sector, petrol engines have the highest mean improvement potential of 2.07×10^{11} MJ as indicated in Table 4. This is followed by HDV (6.25×10^{10} MJ), diesel engines (5.15×10^{10} MJ), LDV (3.58×10^{10} MJ) and cars (1.86×10^{11} MJ). The respective minimum and maximum values are as shown in Table 4.
On the global trend, the highest is petrol engine (1.47×10^{11} MJ). Others are HDV (3.17×10^{10} MJ), diesel engines (2.93×10^{10} MJ), LDV (2.77×10^{10} MJ) and cars (1.26×10^{10} MJ). The corresponding minimum and maximum values are also shown in Table 5.
Differences between Nigerian and global trends values of improvement potential are highest for petrol engines with a mean value of 5.93×10^{10} MJ. Mean values of differences of other improvement potentials are 3.08×10^{10} MJ for HDV, 2.22×10^{10} MJ for diesel engines, 8.08×10^{9} MJ for LDV and 6.02×10^{9} MJ for cars. The corresponding minimum and maximum values are in Table 6.
Quite unlike other parameters, Improvement potential is an explicit function of both mode efficiency and input exergy. Of course, the mode efficiency itself is a function of both input exergy and carrier exergy efficiency. This is why, as expected, Improvement Potential is a strong function of input exergy. This strong dependence of Improvement Potential on input exergy can be seen graphically when we compare the similarities between Figure 7 and Figure 9. Improvement Potential trends of the transportation sector within the time scope of this work are graphically presented in Figure 7, along with the global trends. The differences are also presented in Figure 8. More importantly, the strong dependence is reflected in the fact that while petrol engines and cars have the highest and lowest improvement potential differences respectively (Table 6), they also have the respective highest and lowest exergy input values (Table 7), despite the fact that their mean exergy efficiencies are the highest (Table 4). Since input exergy is a strong independent variable in determining improvement potentials, reckless utilisation of fossil fuels in this transportation sector could highly deleterious. Besides, a measured and/or controlled decrease in input exergy will also reduce CO2 and other fossil-fuelled emissions due to the sector.

Table 4: Mean, Minimum and Maximum Values of Different Parameters for Nigeria Case

Parameter	Nigeria														
	Mean Value					Minimum Value					Maximum Value				
	Petrol Engine	Diesel Engine	Cars	LDV	HDV	Petrol Engine	Diesel Engine	Cars	LDV	HDV	Petrol Engine	Diesel Engine	Cars	LDV	HDV
ψ_m	0.1305	0.1079	0.1246	0.1058	0.0857	0.1275	0.1078	0.1243	0.0859	0.0852	0.1308	0.1080	0.1249	0.1242	0.0874
D_p	0.8695	0.8921	0.8754	0.8942	0.9143	0.8692	0.8920	0.8751	0.8758	0.9126	0.8725	0.8922	0.8757	0.9141	0.9148
SI	1.1501	1.1209	1.1423	1.1185	1.0937	1.1461	1.1209	1.1420	1.0939	1.0932	1.1504	1.1211	1.1427	1.1418	1.0958
IP (MJ)	2.07×10^{11}	5.15×10^{10}	1.86×10^{10}	3.58×10^{10}	6.25×10^{10}	9.28×10^{10}	2.41×10^{10}	8.73×10^{9}	1.3×10^{10}	1.45×10^{10}	5.26×10^{11}	1.37×10^{11}	4.58×10^{10}	5.73×10^{10}	1.29×10^{11}

Table 5: Mean, Minimum and Maximum Values of Different Parameters in the Global Trend

Parameter	Global Trend														
	Mean Value					Minimum Value					Maximum Value				
	Petrol Engine	Diesel Engine	Cars	LDV	HDV	Petrol Engine	Diesel Engine	Cars	LDV	HDV	Petrol Engine	Diesel Engine	Cars	LDV	HDV
ψ_m	0.2657	0.3274	0.2801	0.2129	0.3478	0.2650	0.3273	0.2800	0.1871	0.3409	0.2728	0.3275	0.2803	0.2367	0.3497
D_p	0.73	0.67	0.71	0.78	0.65	0.72	0.67	0.7	0.76	0.65	0.73	0.67	0.72	0.81	0.65

	43	26	99	71	22	72	25	197	33	03	50	27	03	29	91
SI	1.36 18	1.48 68	1.38 90	1.27 09	1.53 33	1.36 05	1.48 66	1.3 883	1.23 01	1.51 72	1.37 52	1.48 69	1.38 95	1.31 01	1.53 77
IP (MJ)	1.47×10^{11}	2.93×10^{10}	1.26×10^{10}	2.77×10^{10}	3.17×10^{10}	6.63×10^{10}	1.37×10^{10}	5.9×10^{9}	1.02×10^{10}	7.41×10^{9}	3.76×10^{11}	7.79×10^{10}	3.09×10^{10}	4.53×10^{10}	6.54×10^{10}

Table 6: Improvement Potential Differences between Nigeria and Global Trends (MJ)

Improvement Potential Differences	Petrol Engines	Diesel Engines	Cars	LDV	HDV
Mean Value	5.93×10^{10}	2.22×10^{10}	6.02×10^{9}	8.08×10^{9}	3.08×10^{10}
Minimum Value	2.64×10^{10}	1.04×10^{10}	2.83×10^{9}	2.81×10^{9}	7.06×10^{9}
Maximum Value	1.5×10^{11}	5.91×10^{10}	1.49×10^{10}	1.28×10^{10}	6.39×10^{10}

Table 7: Exergy Input Values of Different Modes

	Petrol Engines Exergy Input (MJ)	Diesel Engines Exergy Input (MJ)	Cars Exergy Input (MJ)	LDV Exergy Input (MJ)	HDV Exergy Input (MJ)
Mean Value	2.73×10^{11}	6.48×10^{10}	2.43×10^{10}	4.48×10^{10}	7.48×10^{10}
Minimum Value	1.23×10^{11}	3.03×10^{10}	1.14×10^{10}	1.59×10^{10}	1.731×10^{10}
Maximum Value	6.97×10^{11}	1.72×10^{11}	5.97×10^{10}	6.96×10^{10}	1.55×10^{11}

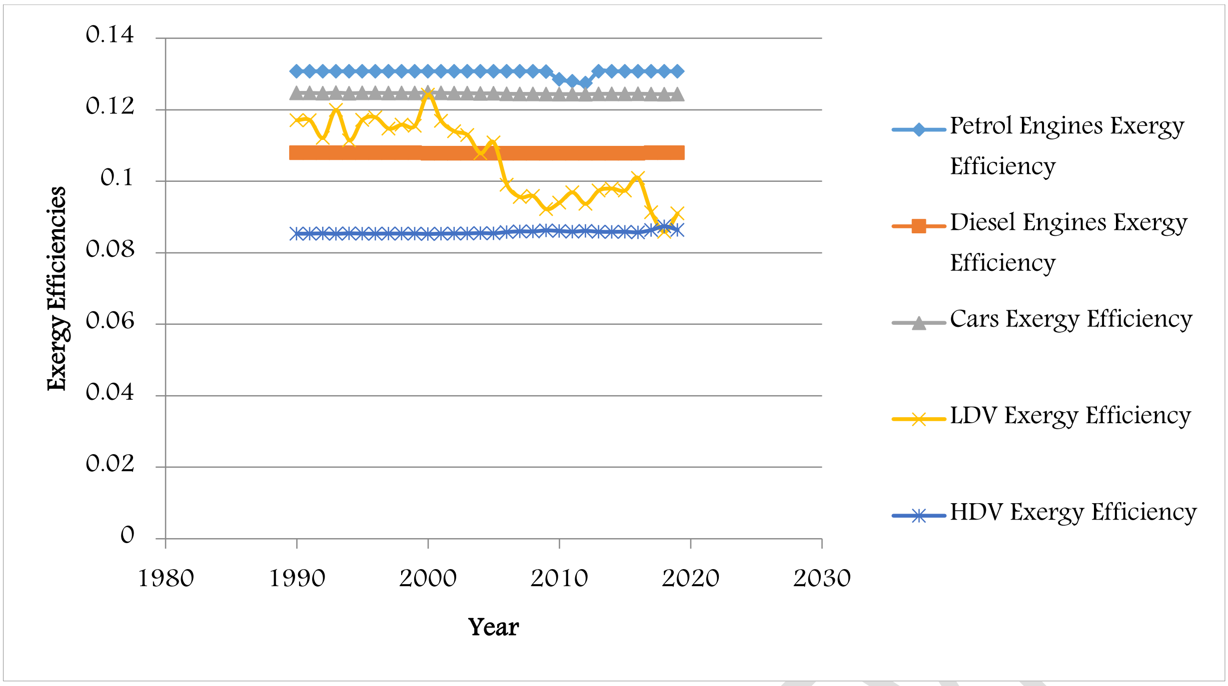

Figure 1: Trends of Exergy Efficiencies over the Years

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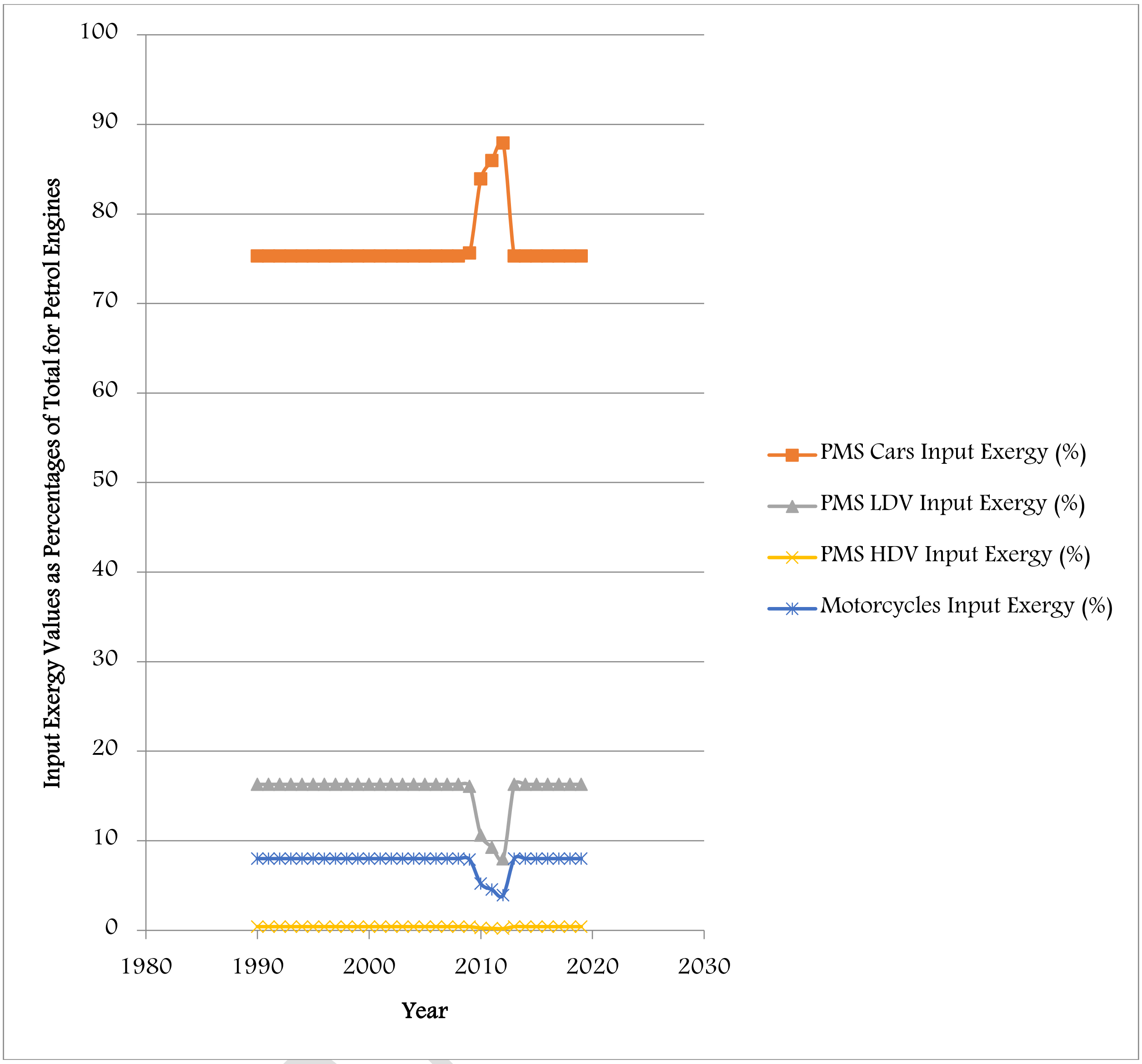

Figure 2: Petrol Engines Percentage Exergy Utilisations

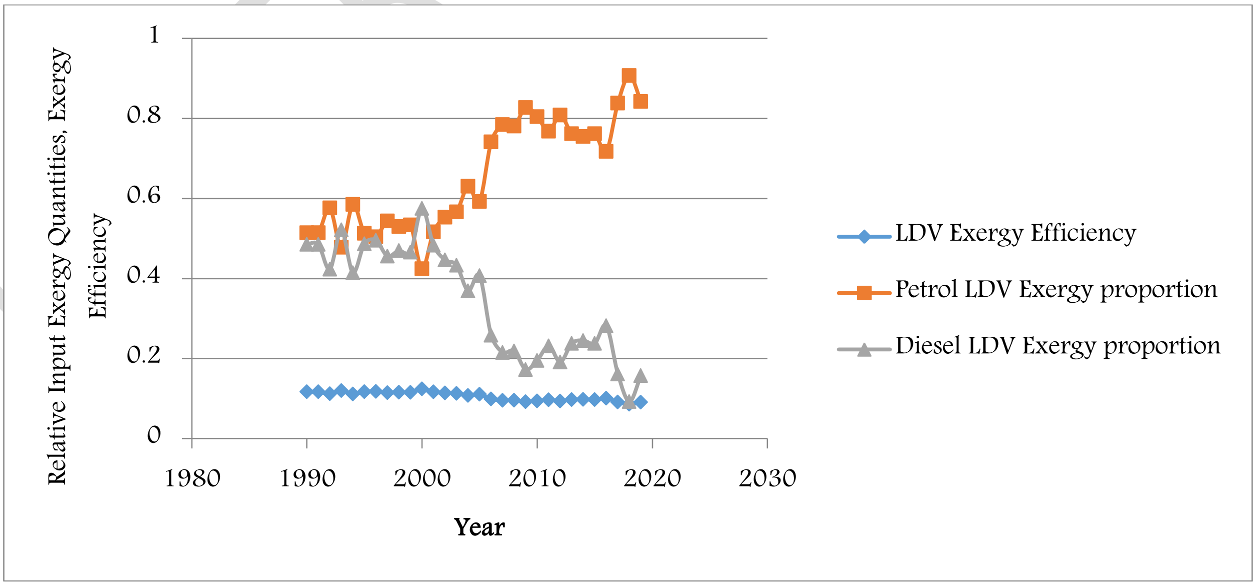

Figure 3: Effects of Relative Input Exergy Quantities on LDV Exergy Efficiency

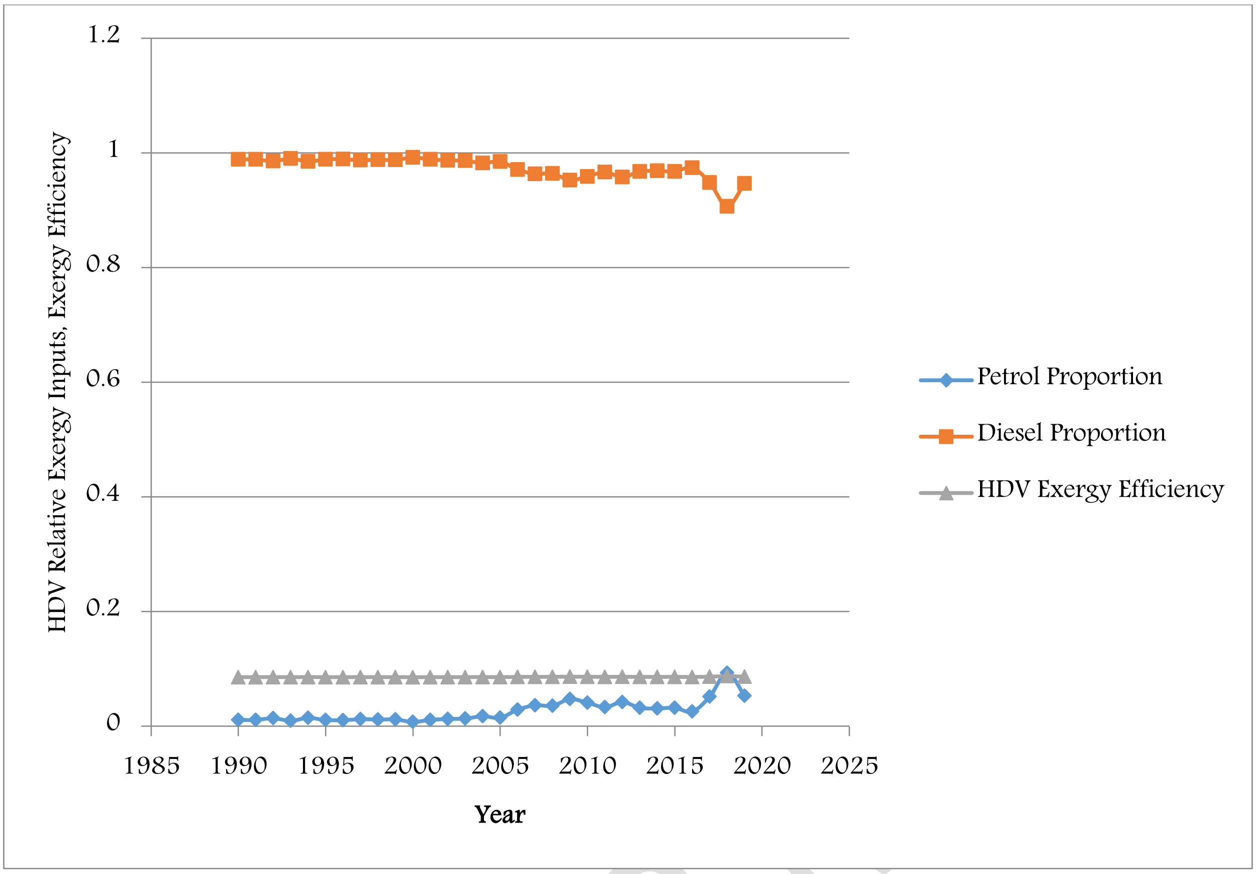

Figure 4: Effects of Relative Input Exergy Quantities on HDV Exergy Efficiency

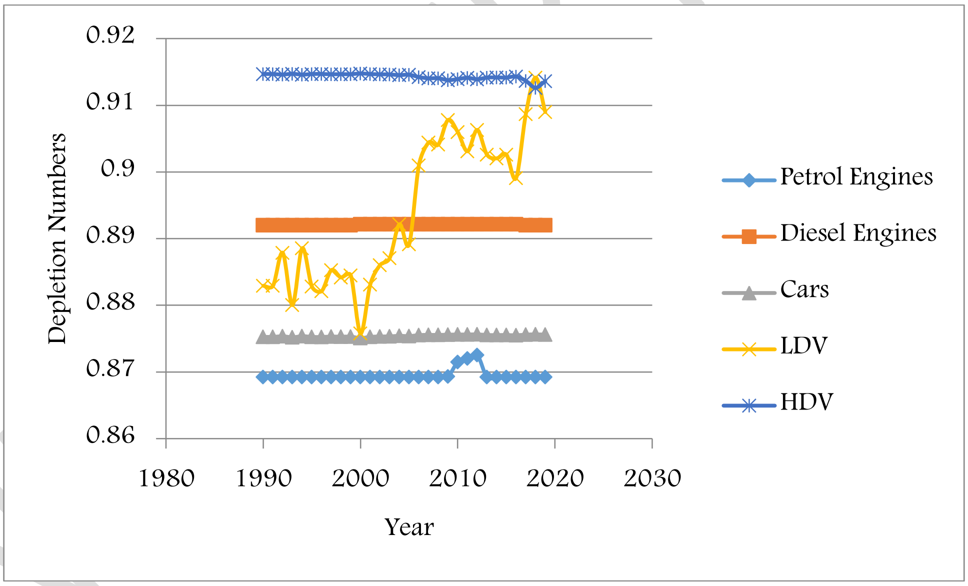

Figure 5: Trends of Depletion Numbers over the Years

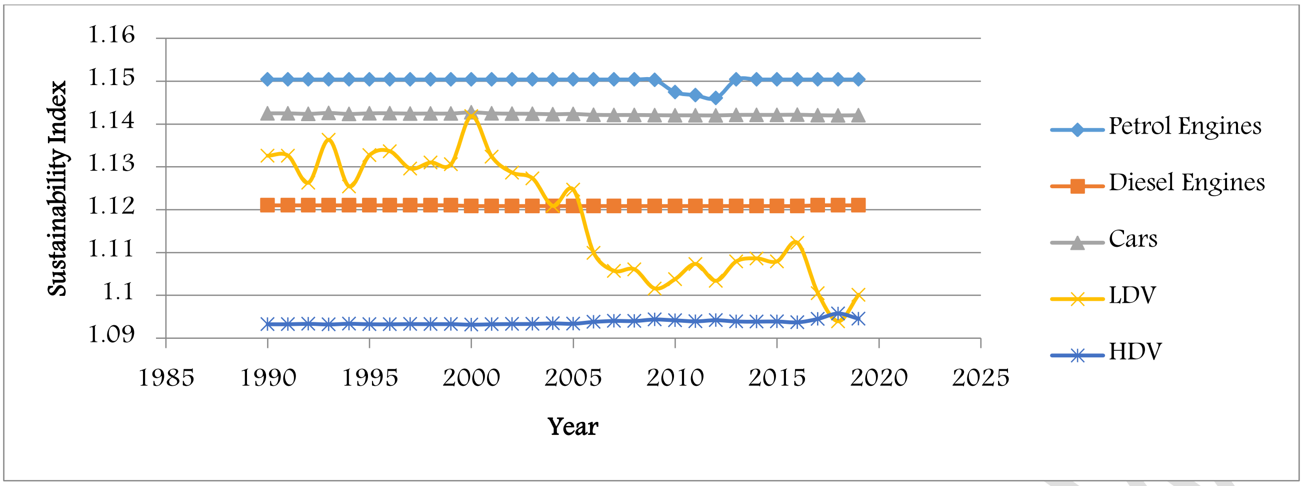

Figure 6: Trends of Sustainability Index Values over the Years

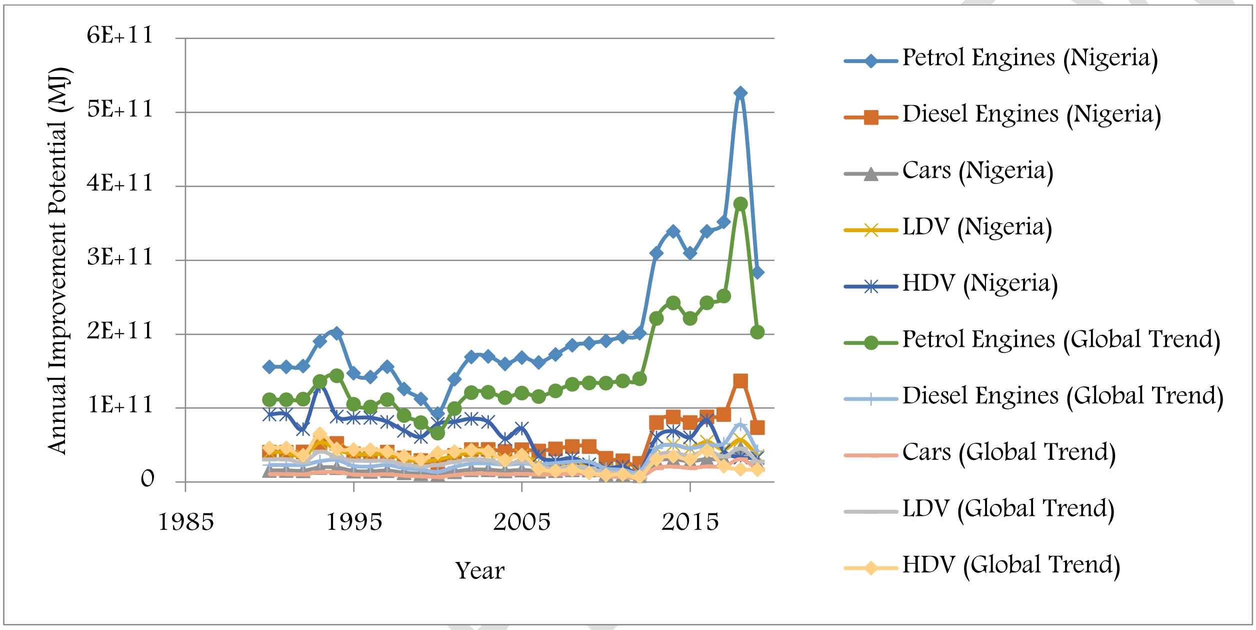

Figure 7: Nigeria and Global Improvement Potential trends

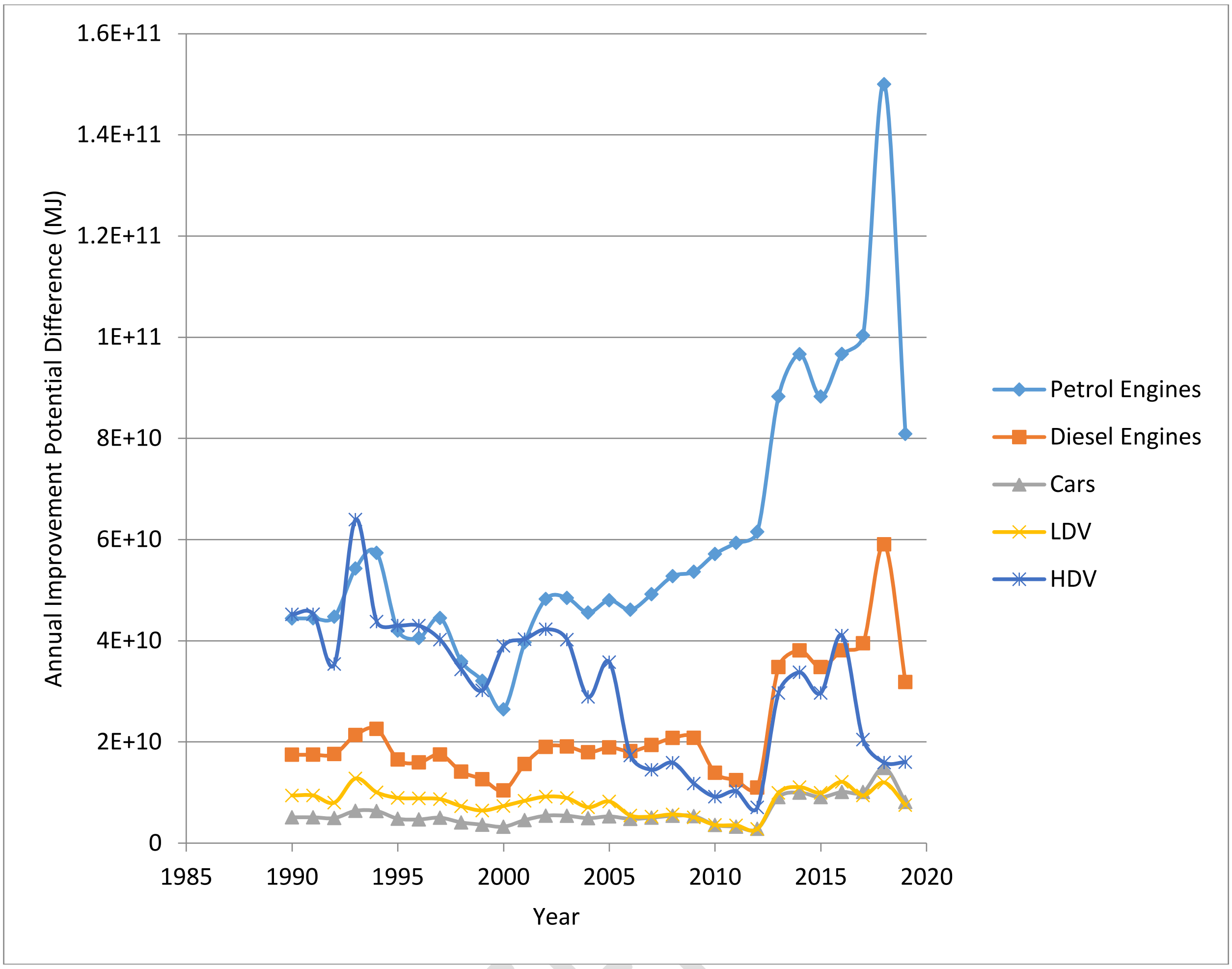

Figure 8: Differences between Nigeria and Global Improvement Potential trends

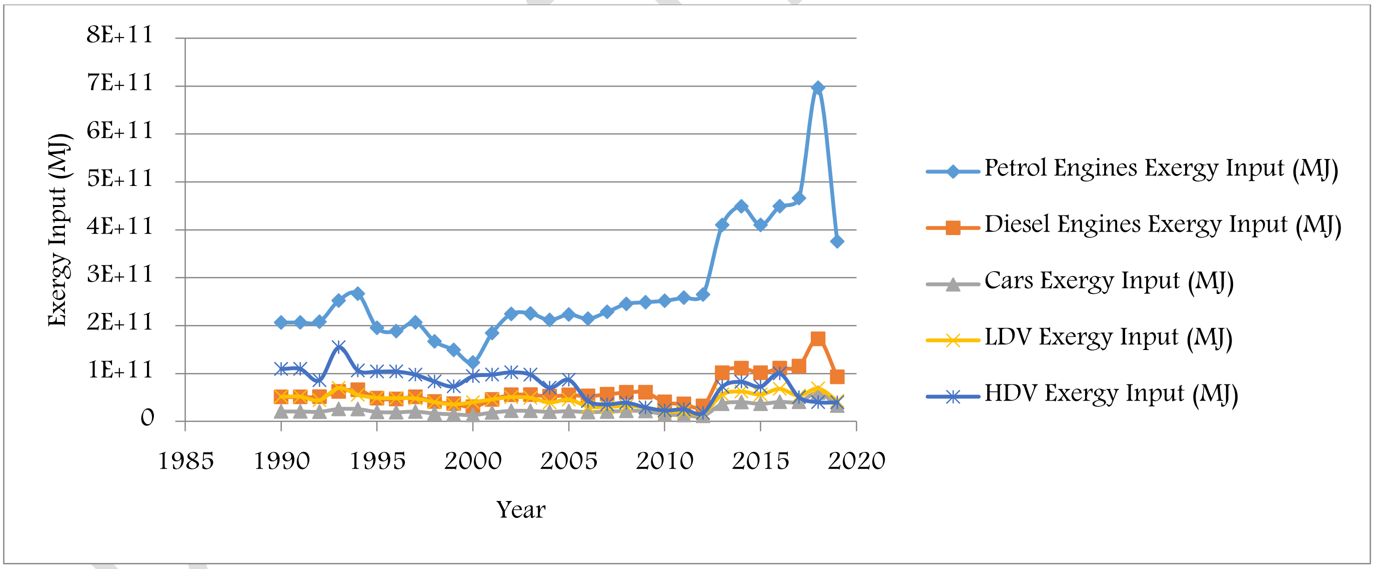

Figure 9: Trends of Exergy Input over the Years for Different Modes

Conclusion

One major factor influencing sustainability of any road transport means is the thermal efficiency of the engine. Besides, due to poor maintenance culture and old vehicle fleets, thermal efficiencies of vehicles plying Nigerian roads are generally low. Another factor is the exergy utilisation rate in the subsector. Sustainability parameters of Nigerian transportation sector are generally low, below the global trends. This is due to non-selective and/or non-informed use of efficient carriers. When compared with the global trends, petrol engines have the highest improvement potential difference of 5.93×10^{10} MJ, while cars have the lowest (6.02×10^{9} MJ), being largely influenced by exergy input rates. Choice of transport means is sustainable when in favour of the ones with high exergy efficiencies.

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