SUSTAINABLE ENERGY ANALYSIS OF NIGERIAN ROAD TRANSPORTATION SECTOR: EFFECTS OF INFLUENCED FUEL DEMAND PATTERNS

Badmus I.[1], Alao W. A.[2], Ajala M. T. [2], Olalere N. A.[2], Akinleye A. O.[2]
[1]Department of Mechanical Engineering
[2]Department of Industrial Maintenance Engineering
Yaba College of Technology, Yaba, Lagos, Nigeria
Email: ismaila.badmus@yabatech.edu.ng

ABSTRACT

Petrol and diesel utilisations in the Nigerian road transportation sector have been assessed, using exergy efficiency and improvement potential as parameters. The mean petrol engine exergy efficiency was 13.05%, while that of diesel engines was 10.79%. The average improvement potential of petrol engines was 2.07×10^{11} MJ, which was 75.6% of average input exergy. Diesel engines had an average improvement potential of 5.15×10^{10} MJ, which was 69.2% of average input exergy. Practical constancy of the exergy efficiencies of the engines left input exergy values as the sole determining factors of improvement potentials of the systems. Petrol fuel was found to be utilised, away from sustainable path, more than diesel fuel. This observation was found attributable to subsidisation of petrol downstream sector and simultaneous deregulation of the diesel downstream sector as well as the preponderance of petrol engines in the road transportation sector. In conclusion, it was recommended that a mechanism be put in place to check the unsustainable petrol fuel utilisation in the transport sector.

Keywords: *Improvement Potential, Exergy Efficiency, Road Transportation, Fuel Demand, Fuel Subsidy, Sustainable Energy*

1. Introduction

Road transport is the main mode of transportation in many developing countries. In Nigeria, road transportation alone consumes an average of 90% of the total energy used by the transport sector. Besides, 77% of total petrol consumed in the country is used in the transport sector [ECN, 2016]. However, energy utilisation efficiencies are generally low, and the information in Table 1, by Maduekwe et al [2020], is instructive:

Table 1: Nigerian Road Fuel Economy

Vehicle Type	Fuel Type	Vehicle Fleet Size (%)	Fuel economy (km/litre)
Saloon and Station Wagons	Petrol	99	11
	Diesel	1	11
Motorcycles	Petrol	100	30.7
Vans and Pickups	Petrol	75	7.6
	Diesel	25	7.6
Tankers, Trailers, Tractors, Tippers	Diesel	100	3.5
Lorries, Trucks	Diesel	100	3.5
Minibuses, Omnibuses	Petrol	50	3.9
	Diesel	50	3.5

Badmus et al [2012] also worked on analysis of Nigerian transportation system energy consumption, but only energy and exergy analyses were made, and the time scope was from 1980 to 2010. There are several ways of assessing a system's energy utilisation sustainability. Some of the parameters commonly used are exergy efficiency, depletion number, sustainability index and improvement potential [Dincer and Zamfirescu, 2018]. While depletion number and sustainability index are separate functions of a single variable, the exergy efficiency, the improvement potential is a function of both the exergy efficiency and the exergy input rate.

Ordinarily, and as it is elsewhere, demands for petrol and diesel as transportation fuels are different [Nwachukwu and Mba, 2016]. However, in Nigeria, due to public pressures, successive governments have always subsidised the pump prices of petrol as well as household kerosene, leaving diesel fuel, otherwise known as automotive gas oil, to market forces [Onyekwena et al, 2017; Adeoti et al, 2016]. This has resulted in the pump prices of the former always being lower than those of the latter, with one sometimes doubling the other. Expectedly, this has also skewed the demand for transportation fuel in favour of petrol. In fact, Adegoriola and Suleiman [2020] flatly asserted that the present transportation fuel consumption pattern in Nigeria had been largely influenced by the government policy through partial deregulation of downstream sector of the petroleum industry. Indeed, on the average, Gujba et al [2013] posited not long ago that over 61% of travel was by petrol vehicles and the rest by diesel. The effects of this transportation fuels demand pattern on energy utilisation sustainability in the sector are examined in this paper.

2. Methodology

2.1 Exergy efficiency

$\psi = \frac{Ex_{out}}{Ex_{in}}$ . . . (1)

The relationship between energy efficiency and its exergy efficiency is given by [Badmus, 2021]:

$\psi = \eta/\varphi_f$ . . . (2)

In Eq. (2), φ_f is the exergy factor of Szargut and Styrylska as enunciated in Szargut et al. [1988]. The fuel exergy factor used for both petrol and diesel fuels in this work is 1.07 [Szargut, 2005]. The heating values have been taken from Garg et al. [2006], and they are 44150 MJ/tonne for petrol, and 42910 MJ/tonne for diesel.

When analysing a system of vehicles, as in our case, the system efficiency (ψ_m) is given by:

$\psi_m = \frac{\sum \psi_i \epsilon_i}{\sum \epsilon_i}$ . . . (3)

The subscript 'i' in Eq. (3) is for the ith vehicle in the system, 'ψ_i' is the exergy efficiency and 'ϵ' is its exergy input.

In this paper, vehicle energy efficiencies in Table 2, adapted from Badmus [2021] will be used:

Table 2: Thermal Efficiencies of Road Vehicles in Nigeria (%)

Vehicle	Petrol Engine	Diesel Engine
Cars	13.33	15.47
Light Duty Vehicles	8.44	16.88
Heavy Duty Vehicles	11.78	9.12
Motorcycles	32	-------

2.2 Improvement Potential

Obviously, maximum improvement in the exergy efficiency of a process or a system is attained when exergy loss is least. Consequently, van Gool [1992] in Dincer and Zamfirescu [2018] suggested the concept of an exergetic 'improvement potential', P, when analysing different processes or systems:

$P = (1-\psi)(Ex_{in} - Ex_{out}) = (1-\psi)(1-\psi)Ex_{in} = (1-\psi)^2 Ex_{in}$ . . . (5)

The Improvement Potential is a function of two variables, the exergy efficiency, ψ, and input Exergy, Ex_{in}. The function varies quadratically with ψ and linearly with Ex_{in}. When ψ attains a maximum value of 1 or 100%, the Improvement Potential vanishes. This means that, at this maximum attainable efficiency, there is no room for further improvement as the entire input exergy has been fully utilized. Conversely, when ψ is nil, the entire input exergy is fully degraded. Then, the improvement potential is at climax, being equal to the entire exergy input. Between these two extremes, the improvement potential is a fraction of the input exergy.

An overall change in improvement potential, P(φ, E), is given by:

$\Delta P = \frac{\partial P}{\partial E}\Delta E + \frac{\partial P}{\partial \varphi}\Delta\varphi$ . . . (6)

But $\frac{\partial P}{\partial E} = (1-\varphi)^2$ . . . (7)

And $\frac{\partial P}{\partial \varphi} = 2E(\varphi - 1)$ . . . (8)

While the partial change in improvement potential with respect to input exergy is a positive function of exergy efficiency only (Eq. 7), the one with respect to exergy efficiency is a negative function of both input exergy and the system exergy efficiency (Eq. 8). This is because, in practice, φ is always less than unity (100%).

For sustainability, improvement potential should be decreasing. Its maximum value for any combination of exergy input and exergy efficiency is attained when the value of ΔP is zero. Then,

$\Delta E_{max} = \frac{2E\Delta\varphi}{1-\varphi}$

$\frac{\Delta E_{max}}{E} = \frac{2\Delta\varphi}{1-\varphi}$ . . . (9)

Hence, when the actual input energy change, ΔE, is less than ΔE_{max}, improvement potential will decrease. When it is more, the improvement potential will increase. In other words, when relative input exergy change, $\Delta E_{relative}$ ($= \Delta E - \Delta E_{max}$) < 0, improvement potential will decrease. Both the value and algebraic sign of relative input exergy change are very important in determining direction of improvement potential change.

For any given efficiency change, relative to a particular initial efficiency, the right hand side of Eq. (9) gives the maximum fractional change in input energy that should take place. Energy utilisation is sustainable if the actual fractional input exergy is less than the right hand side of Eq. (9). However, it is not sustainable if it is more. The equation expects no input exergy change, following an unchanging system exergy efficiency.

3. Results and Discussion

Table 3: Road Transportation Fuel Consumption from 1990 to 2019 in Metric Tonnes

Year	Cars Petrol	LDV Petrol	HDV Petrol	Motorcycles Petrol	Total Petrol	Cars Diesel	LDV Diesel	HDV Diesel	Total Diesel	Petrol Consumed (%)
1990	3287824	711706.9	17465.2	349304	4366300	71483.7	691009.1	1620297	2382790	64.69
1991	3289639	712099.7	17474.84	349496.8	4368710	71514	691302	1620984	2383800	64.70
1992	3313238	717208.2	17600.2	352004	4400050	56046	541778	1270376	1868200	70.20
1993	4018272	869825.1	21345.4	426908	5336351	101031.9	976641.7	2290056	3367730	61.31
1994	4246928	919321.6	22560.04	451200.8	5640010	69310.5	670001.5	1571038	2310350	70.94
1995	3109416	673087.3	16517.48	330349.6	4129370	67992	657256	1541152	2266400	64.56
1996	3000810	649577.8	15940.56	318811.2	3985140	67953.3	656881.9	1540275	2265110	63.76
1997	3293887	713019.4	17497.41	349948.2	4374352	63624.81	615039.8	1442162	2120827	67.35
1998	2658232	575420.6	14120.75	282415	3530188	54297.48	524875.6	1230743	1809916	66.11
1999	2374655	514035.5	12614.37	252287.4	3153592	47740.11	461487.7	1082109	1591337	66.46
2000	1957500	423730	10400	207970	2599600	61550	590880	1399230	2051660	55.89
2001	2936700	635700	15600	312000	3900000	63730	611830	1448840	2124400	64.74
2002	3571870	773190	18970	379480	4743510	66880	642040	1520380	2229300	68.03
2003	3587630	776610	19060	381160	4764460	63650	611010	1446900	2121560	69.19
2004	3373480	730250	17920	358400	4480050	45830	439950	1041820	1527600	74.57
2005	3554050	769340	18880	377590	4719860	56640	543760	1287660	1888060	71.43
2006	3415380	739320	18140	362860	4535700	27600	264910	627330	919840	83.14
2007	3642670	788520	19350	387000	4837540	23170	222390	526640	772200	86.23
2008	3906040	845530	20750	414980	5187300	25380	243680	577050	846110	85.97
2009	3980190	846000	20760	415210	5262160	18910	181520	429860	630290	89.30
2010	4469520	565460	13880	277530	5326390	14710	141210	334380	490300	91.57
2011	4696940	506270	12420	248480	5464110	16360	157030	371850	545240	90.93
2012	4924360	446560	10960	219170	5601050	11320	108670	257330	377320	93.69
2013	6534950	1414600	34710	694280	8678540	47350	454560	1076410	1578320	84.61
2014	7153720	1548550	38000	760020	9500290	53850	516920	1224110	1794880	84.11

2015	6534950	1414600	34710	694280	8678540	47350	454560	1076410	1578320	84.61
2016	7157340	1549330	38020	760410	9505100	65270	626600	1483830	2175700	81.37
2017	7428196	1607963	39459.21	789184.2	9864802	32940.15	318421.5	746643	1098005	89.98
2018	11104090	2403674	58985.87	1179717	14746467	26108.31	252380.3	591788	870276.6	94.43
2019	5987527	1296105	31806.25	636125	7951563	25781.04	249216.7	584370	859367.7	90.25

From Table 3, average percentage of petrol fuel consumed during the period was 76.47%. Minimum was 55.89% in the year 2000, and the maximum was 94.43% in 2018. Hence, even the minimum percentage petrol fuel consumption during the period covered by this work was more than 50%. 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 two categories of carriers also recorded highest and lowest mean values of 1.95011×10^{11} MJ and 9.80009×10^{8} MJ respectively. Mean energy utilisation of motorcycles during the period was 1.96005×10^{10} MJ, which was more than each of similar values for petrol HDVs and diesel cars. This suggests that use of motorcycles was more rampant than use of petrol HDVs and diesel cars and diesel LDVs in the country. While cars consumed most petrol, HDVs consumed most diesel fuels.

Throughout the period covered by this work, the exergy efficiencies of petrol engines system were consistently higher than those of the diesel engines. Secondly, both systems have practically constant efficiencies (Fig. 2). The implication of this is that change in exergy efficiency ($\Delta\varphi$) is always zero within each system, from year to year. Hence, exergy efficiencies could not contribute to improvement potential changes. Invariably under this circumstance, the improvement potential becomes a linear function of exergy input only, as shown in Fig. 4 for petrol engines. The only exception is for petrol engines between 2008 and 2013. During this period, the petrol engines system efficiencies went down, before picking up again. Based on the exergy efficiencies alone, diesel engines should have higher improvement potentials. However, throughout the period, exergy utilisations by the petrol engines were consistently higher than those by diesel engines, being close only once, in the year 2000 (Fig. 1).

Petrol engines exergy utilisations ranged from a minimum of 1.22806×10^{11} MJ (2,599,600 metric tonnes) in the year 2000 to a maximum of 6.9663×10^{11} MJ (14,746,467 metric tonnes) in 2018. The corresponding (minimum and maximum) values for diesel engines were 1.73242×10^{10} MJ (377,320 metric tonnes) in 2012, and 1.54625×10^{11} MJ (3,367,730 metric tonnes) in 1993 (Table 3). During the periods when the exergy efficiencies were constant in Fig. 2, Eq. 9 expected an exergy input of, at most, zero value for sustainability. However, Fig. 1 shows that this was not the case, as exergy was consumed indiscriminately. The result of uncontrolled, unsustainable energy utilisation is shown in Fig. 3. The total exergy input in the year 2000 is the lowest, resulting in the lowest exergy improvement potential (Fig. 3).

In terms of changes of input exergy values with changes in exergy efficiencies along sustainable energy utilisation path (Eq. 9), Fig. 5 indicates that petrol engines have greater deviations than diesel engines. Indeed, petrol engines have a total deviation of 1.69268×10^{11} MJ, average deviation of 5642265734 MJ, minimum deviation of -3.2099×10^{11} MJ and a maximum deviation of 2.30612×10^{11} MJ, resulting in a deviation range of 5.51607×10^{11} MJ. The corresponding values for diesel engines are -7×10^{10} MJ, -2.3×10^{09} MJ, -4.9×10^{10} MJ, 6.88×10^{10} MJ and 1.18×10^{11} MJ. The average improvement potential of petrol engines is 2.07×10^{11} MJ , which is 75.6% of average input exergy. Diesel engines have an average improvement potential of 5.15×10^{10} MJ, which is 69.2% of average input exergy. This indicates that petrol engines have a higher improvement potential than diesel engines.

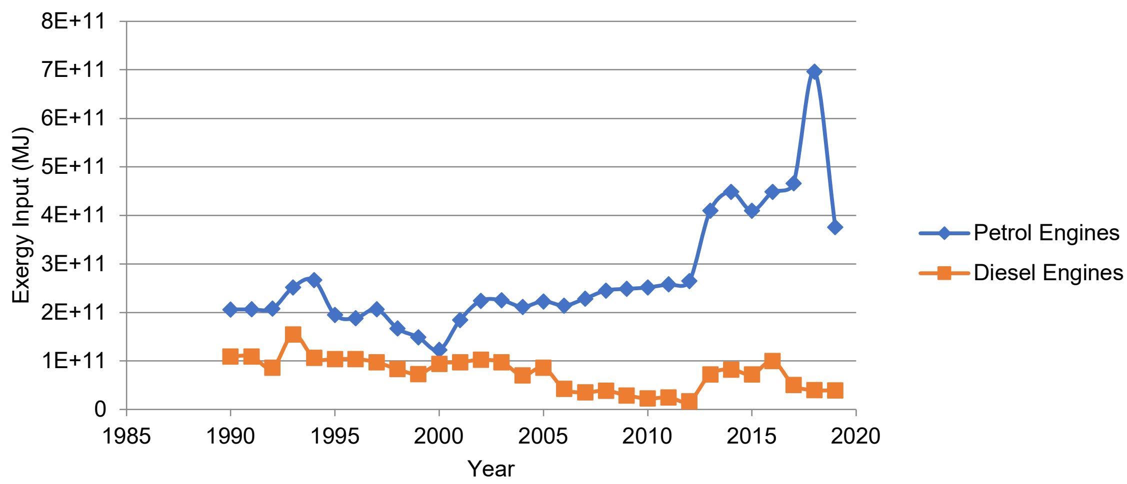

Fig. 1: Engines Annual Exergy Inputs

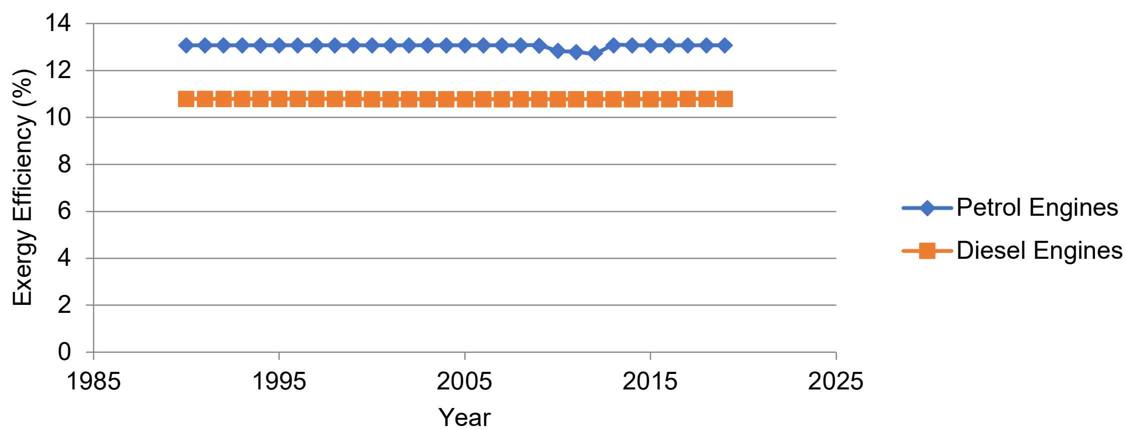

Fig. 2: Engines Annual Exergy Efficiencies

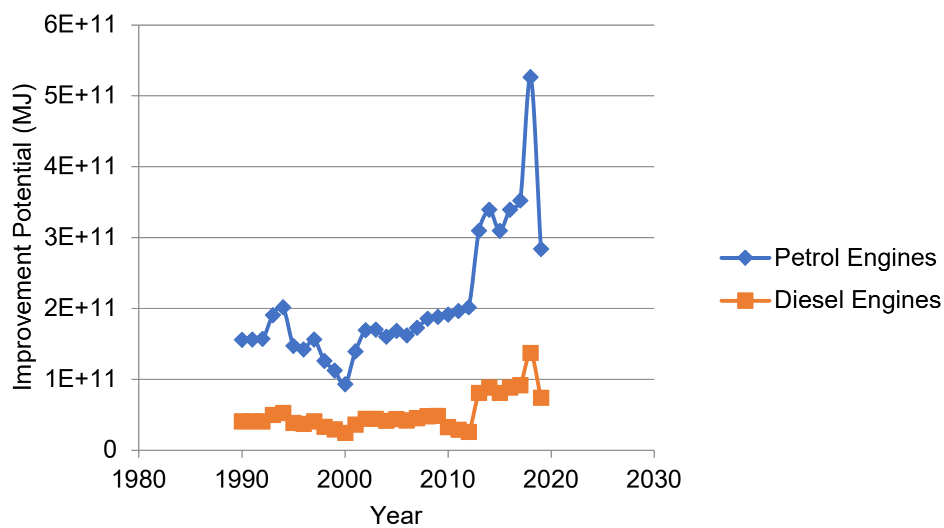

Fig. 3: Engines Annual Improvement Potentials

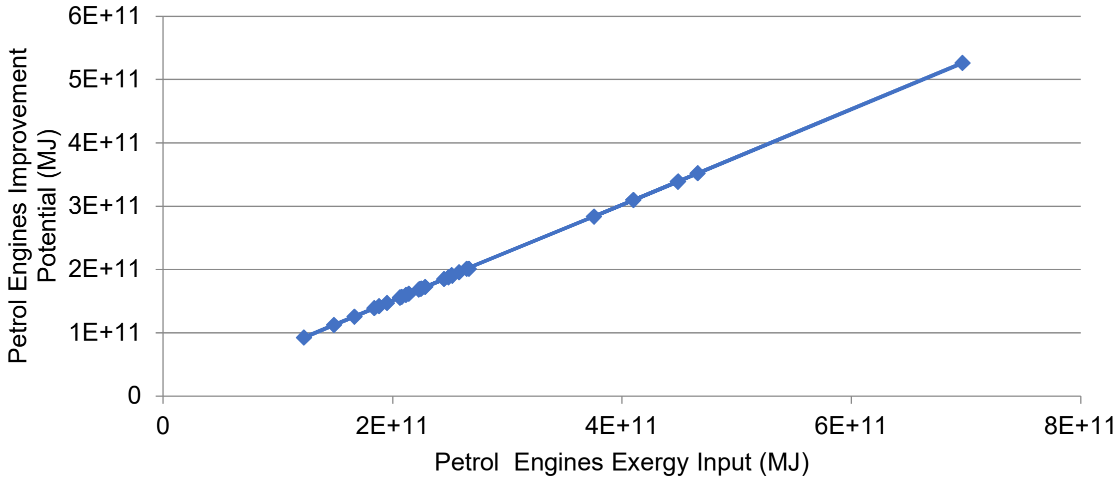

Fig. 4: Petrol Engines Improvement Potentials variation with Input Exergy

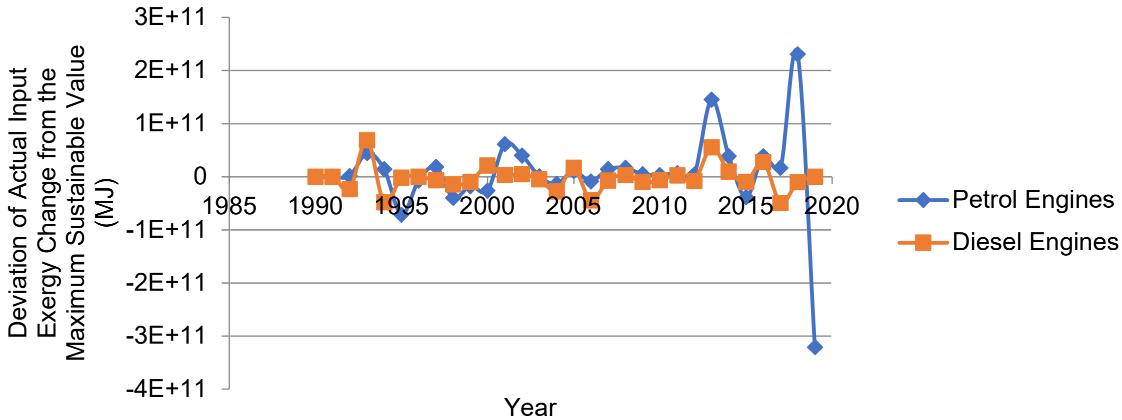

Fig. 5: Deviations of Actual Input Exergy Changes from the Maximum Allowable Values

4. Conclusion

Petrol and diesel engines sustainable fuel utilisations have been assessed using exergy improvement potential as the main parameter. Exergy efficiencies were practically constant throughout the period of the assessment. Improvement potential depended on the exergy inputs of the engines, with petrol engines having larger potentials than the diesel engines. Petrol fuel was also found to be more utilised (with a total change deviation of 1.69268×10^{11} MJ from the maximum for sustainability) than diesel fuel (with a total change deviation of -7×10^{10} MJ). This is largely attributable to government subsidies on petrol retail prices and deregulation of the downstream sale of diesel as well as preponderance of petrol engines in the sector. It is necessary to put a mechanism in place to check the unsustainable petrol fuel utilisation in the transport sector. This may be in terms of reducing customs import duties on efficient motor vehicles and outright ban of importation of old, inefficient vehicles. Foreign direct investments in the area of establishing vehicle assembly plants in the country could also be encouraged.

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