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A Mathematical Model for Predicting the Effects of Tyre Pressure on Fuel Consumption

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Abstract: This study studies the relationship between tyre pressure and fuel consumption of vehicles using experimental methods and mathematical model to predict vehicle fuel consumption. The model obtained was $F = 0.6272- 2.5941p+3.3428p^2 \pm 0.018$ where F is the fuel consumed and p is the tyre pressure of a vehicle, which can also be used to predict the amount of fuel consumed by other vehicles. The model was validated with its own data which showed a deviation of ±5% which is within experimental error. Using the recommended tyre pressures the model reduces the fuel consumption by 17.6% thus reducing cost of fuel. From the experiment, it was observed that the relationship between the fuel consumption and the tyre pressures of various vehicles is in the form of $F = B_2p^2 - B_1p+B_0 \pm e$, where B_0, B_1, B_2 and 'e' depends on other factors of the vehicle such as the age of the vehicle and the conditions under which the measurements were taken. This equation can be used to predict fuel consumptions for vehicles when their tyre pressures are known. In all, it was seen from the research that any deviation in tyre pressure of vehicles resulted in an additional fuel consumed by vehicles. It is recommend that, there should be a massive public education or awareness about the need to keep recommended tyre pressure at all times because when tyre pressure falls below the recommended value, the decrease in the pressure invariably leads to an increase in fuel consumption.

Keywords: Fuel consumption, model, tyre, tyre pressure

INTRODUCTION

In the world today, due to the high cost of running a vehicle, there have been many research works to see ways of minimizing this cost. Some of this cost comes from the tyre of the vehicle, amount of fuel needed to run the vehicle smoothly, buying spare parts of vehicles and ensuring safety of the vehicle. As an automobile travel, the surface of the tyre and the road come into contact and must be continually peeled apart. In addition, each surface (both the tyre and the road) is deformed slightly so that in effect, the wheel rolls uphill. These effects combine to produce a rolling resistance. A ratio of 1:5.3 or more than a two percent is found for the effect on fuel economy for every ten percent change in rolling resistance for highway driving and a ratio of 1:9.6, or about a one percent fuel economy change for every ten percent change in rolling resistance for urban driving, Calwell *et al*. (2003). Consistent with these findings, the study of Friedrich (2002) reports a thirty percent reduction in a tyre's rolling resistance can reduce a vehicle's fuel consumption from two percent to six percent, depending on driving conditions and other factors.

According to the Rubber Manufacturer's Association, when a tyre is under inflated by one pound per square inch (psi), the tyre's rolling resistance is increased by approximately 1.1% and that a five to eight percent deterioration in rolling resistance performance, which equates to roughly one percent reduction in fuel efficiency (Calwell *et al*., 2003). This is similar to the review study done by Schuring and Futamura (1990) which found for each ten percent reduction in the rolling resistance coefficient the fuel efficiency increased by (1.2-2.5%) for city and (0.9-2.1%) for highway driving. This is because inflation pressure determines tyre stiffness, which has a significant influence on the contact area of the tyre and pressure distribution over the contact surface. Thus, as pressure in the vehicles tyres is reduced, the rolling resistance increases over the road because the surface contact area and virtual hill height is increased. When the rolling resistance is increased, it takes more energy (fuel) to get the automobile to go the same distance.

The relationship between tyre pressure, rolling resistance and fuel economy is complex and dynamic and is dependent on several other factors, including

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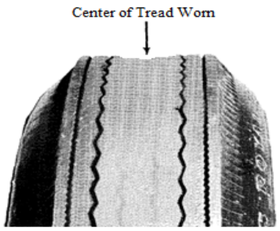

Fig. 1a: Over inflation

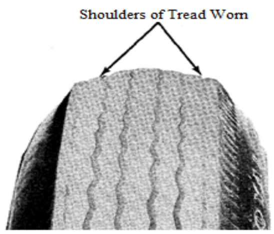

Fig. 1b: Under inflation

vehicle type and load, road and environmental conditions.

Overall, rolling resistance makes up a relatively small percentage of the losses in a typical vehicle; it accounts for about four percent of a vehicle's energy expenditure at low speeds and about 7% at highway speeds (Stein, 2006). However, these modest losses are substantial when in the context of automobile travel accounts for the largest source of energy use and greenhouse emissions, with petroleum combustion causing 2438 Tg (106 tons) Carbon dioxide (CO_2) or forty three percent of the emissions. Globally the situation is similar, where in 1990 the transportation sector was responsible for some twenty five percent of the world's energy use and twenty two percent of the global CO_2 emissions (Stein, 2006).

Tyres are specified by the vehicle manufacturer with a recommended inflation pressure, which permits safe operation within the specified load rating and vehicle loading. Most tyres are stamped with a maximum pressure rating. For passenger vehicles and light trucks, the tyres should be inflated to what the vehicle manufacturer recommends, which is usually located on a decal just inside the driver's door, or in the vehicle owners handbook. Tyres should not be inflated to the pressure on the sidewall; this is the maximum pressure, rather than the recommended pressure.

If tyre pressure is too high, the tyre contact patch is reduced, which decreases rolling resistance. However, ride comfort is reduced, but traction is not always reduced, stopping distance is not always increased (Han, 2007). Also, going above maximum sidewall pressure rarely results in the center of the tyre wearing more than the shoulders as shown in Fig. 1a. If tyre pressure is too low, the tyre contact patch is increased, increasing rolling resistance, tyre flexing and friction between the road and tyre. This "under inflation" as shown in Fig. 1b can lead to tyre overheating, premature tread wear and tread separation in severe cases. Braking distance does not statistically change as tyre pressure increases, suggesting that a larger contact patch from under inflation may not be a significant contributor for the conditions explored in these specific tests.From the above information it is seen that the inflation pressure or tyre pressure of a vehicle affects rolling resistance, tyre heating, tread wear and tread separation which result in vehicle fuel consumption.

The facts are that, tires with proper inflated pressure can safe its life up to 20% which is nine months more of its life span. Inflating correct tire pressure can also prevent tires from overheating, explosion and on the other hand, ease motoring and reduce maintenance cost (Hillier, 1991). The main problem therefore is, what is the effect of incorrect tyre pressure on the on the performance of vehicle and the relationship between the tyre pressure and fuel consumption. This study seeks to find the effect that tyre pressures of vehicles have on the fuel consumption and develop a model for predicting the fuel consumption.

Importance of tyres: Tyres are part of the backbone of a car, truck, piece of construction equipment or bicycle. Tyres add traction, braking, steering and load support to vehicles while also absorbing shock and creating a smooth and comfortable ride. There are o-shaped parts that can be pneumatic or solid and fit around the wheels of the vehicle to protect the wheels and add to their effect. A solid tyre consists of rubber, metals and plastic parts (Williams, 2008).Vehicle tyres can affect not only the way cars are handled, but also affect the overall performance and fuel economy of a vehicle. One of the most important things to do is a regular schedule to check air pressure in tyres. Incorrect air pressure in tyre causes the tyre failure. Tyre failure while driving can lead to crush and possibly injure the driver and the passengers (Gibson, 2006).

Rolling resistance: According to Friedrich (2002) rolling resistance is the resistance to rolling caused by deformation of the tyre in contact with the road surface. As the tyre rolls, tread enters the contact area and is deformed to conform to the roadway. The energy required to make the deformation depends on the inflation pressure, rotating speed and numerous physical properties of the tyre structure, such as spring force and stiffness. Friedrich (2002) stated that, tyre makers sought lower rolling resistance tyre constructions in order to improve fuel economy in cars and especially trucks, where rolling resistance accounts for a high amount of fuel consumption. The pneumatic tyre also has the more important effect of vastly reducing rolling resistance compared to a solid tyre. Because the internal air pressure acts in all directions, a pneumatic tyre is able to "absorb" bumps in the road as it rolls over them without experiencing a reaction force opposite to the direction of travel, as in the case with a solid (or foam-filled) tyre. Overall,

Table 1: Reading taken for the first two days for Vehicle No.1

				Tyre Pressure (N/mm^2)			
Day	Time	Odometer reading (km)	Fuel reading (L)	Right front	Left front	Right rear	Left rear
1	8:00	39947	39.75	0.2758	0.2758	0.3447	0.3241
	11:00	39991	32.18	0.2758	0.2758	0.3447	0.3241
	14:00	40025	28.39	0.2758	0.2758	0.3447	0.3241
	17:00	40055	24.61	0.2758	0.2758	0.3447	0.3241
2	8:00	40080	75.71	0.2758	0.2758	0.3378	0.3172
	11:00	40111	71.92	0.2758	0.2758	0.3378	0.3172
	14:00	40141	68.14	0.2758	0.2758	0.3378	0.3172
	17:00	40206	60.57	0.2758	0.2758	0.3378	0.3172

rolling resistance makes up a relatively small percentage of the losses in a typical vehicle; it accounts for about 4% of a vehicle's energy expenditure at low speeds and about 7% at highway speeds (Stein, 2006).

Tread wear: Friction between the tyre and the road surface causes the tread rubber to wear away over time. The legal standards prescribe the minimum allowable tread depth for safe operation. Hillier (1991) suggest several types of abnormal tread wear as poor wheel alignment, excessive wear of the innermost or outermost rims, gravel roads, rocky terrain and other rough terrain will cause accelerated wear. Over inflation above the sidewall maximum can cause excessive wear to the center of the tread. However, inflating up to the sidewall limit will not cause excessive wear in the center of the tread. Modern tyres have steel belts built in to prevent this. Under inflation causes excessive wear to the outer ribs. Quite often, the placard pressure is too low and most tyres are underinflated as a result. Unbalanced wheels can cause uneven tyre wear, as the rotation may not be perfectly circular. Tyre manufacturers and car companies have mutually established standards for tread wear testing that includes measurement parameters for tread loss profile, lug count and heel-toe wear. also known as tyre wear. Tyre wear rates reported in the literature range between 0.006 and 0.09 g/km per tyre (Rogge *et al*., 1993). The actual wear rate is, however, dependent on a range of factors such as driving style, weather and tyre and road characteristics (Johnson, 2005). According to Stalnaker *et al*. (1996), the wear rate has been shown to be several times higher during urban driving than during motorway driving, due to increased acceleration, braking and cornering in cities. Thus, a significant part of the worn tread rubber may be emitted in cities, even though city driving only accounts for a small part of the tyre mileage.

MATERIALS AND METHODS

The design used for this study was experiment which sought to find out the effect of tyre pressure on fuel consumed by vehicle. Kwame Nkrumah University of Science and Technology (KNUST) campus shuttle buse terminal was selected for the study. The experiment was carried out for a period of 3 months using five of the shuttle buses.

Table 2: Average tyre pressures and the corresponding fuel consumptions for Vehicle No.1

Average pressure (N/mm^2)	Fuel consumption (L/km)
0.3051	0.1721
0.3051	0.1114
0.3051	0.1261
0.3017	0.3030
0.3017	0.1221
0.3017	0.1261
0.3017	0.1164

In each day, the 5selected vehicle tyre pressures, odometer reading and the fuel reading were recorded for each vehicle. Records were taken at intervals of 3 h. The results for vehicle with vehicle No.1 readings for the first two days were tabulated and presented in Table 1.

From Table 1 the average pressure was found and the fuel flow, that is, the fuel was divided by the distance covered and the results were presented in Table 2.

Readings were taken for three months period of the experiment for each of the five vehicles and the results were tabulated and presented in a graphical form. From Table 2 the pressures were arranged from 0.3017 N/mm^2 upwards with intervals of 0.0055. With the same pressure, different fuel consumptions were attained. For instance, at the pressure of 0.3051 N/mm^2, the recorded fuel consumptions were, 0.1721, 0.1114 and 0.1261litres/km. Average fuel consumption was used to represent the corresponding tyre pressure; thus for 0.3051 N/mm^2, an average of 0.1365±0.0258 litres/km was obtained. This was done for the other four vehicles namely Vehicle No.2, Vehicle No.3, Vehicle No. 4 and Vehicle No.5 and the results were tabulated and presented in a graphical form in Fig. 4 and 5.

Model suitability for the data: This research concentrates on mathematical models using statistical method of modelling. According to Stachowiak (1973) a statistical method of model is a formalization of relationships between variables in the form of mathematical equations. A statistical model describes how one or more random variables are related to one or more random variables. The model is statistical as the variables are not deterministically but stochastically related. In this study, a mathematical

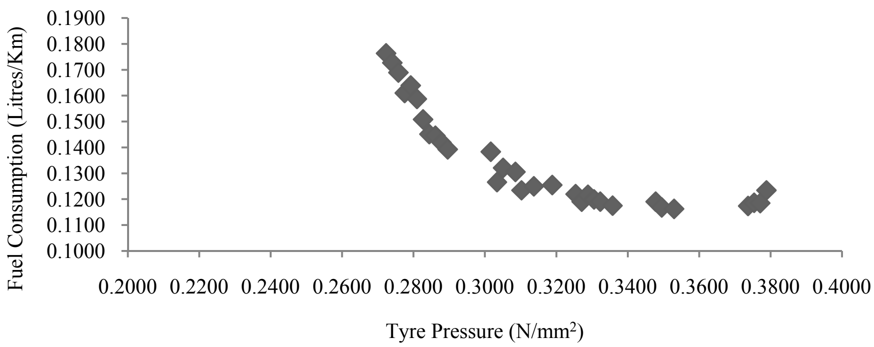

Fig. 2: A scatter diagram for Vehicle No.1 showing fuel consumption verses tyre pressure

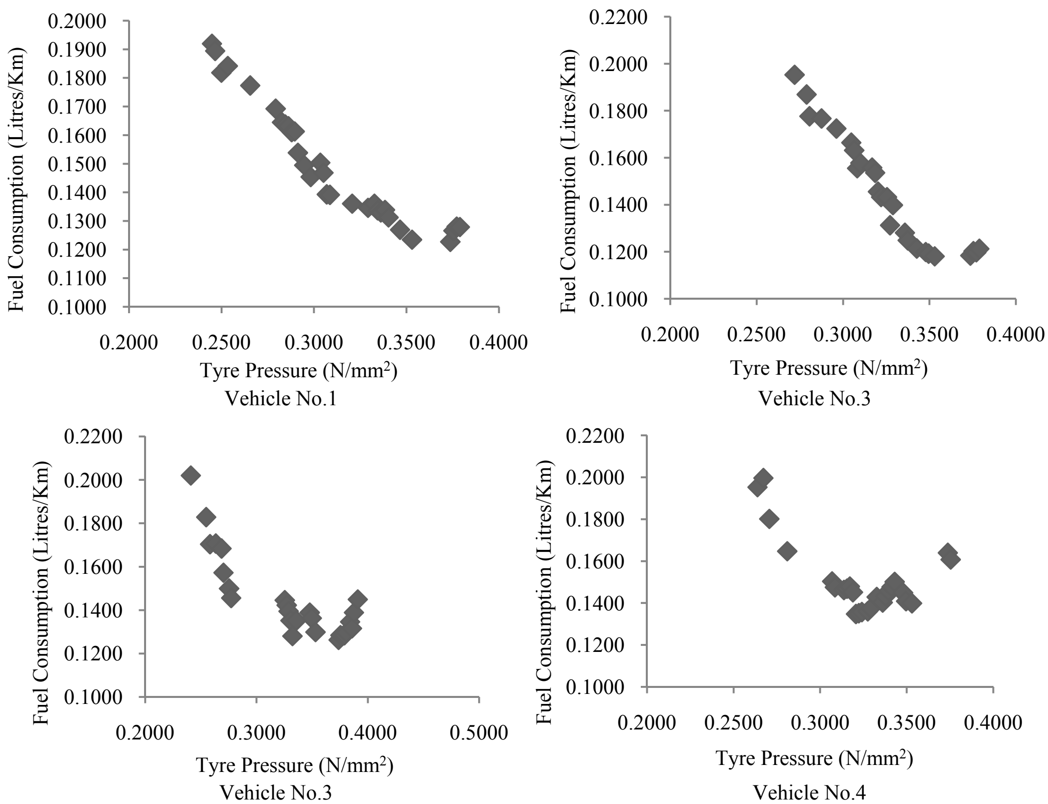

Fig. 3: A scatter diagrams for Vehicles No. 2, 3, 4 and 5 showing fuel consumption against tyre pressure

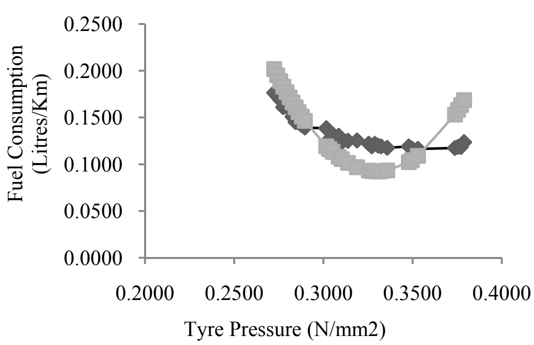

Fig. 4: Model values of Vehicle No.1 compared to the measured value

terms, a statistical model is frequently thought of as a pair (Y,P) where Y is the set of possible observations and P the set of possible probability distributions on Y. It is assumed that there is a distinct element of P which generates the observed data. Statistical inference enables us to make statements about which element(s) of this set are likely to be the true one. For this research least squares method of estimation for regression was used to estimate the model. Least squares method is the simplest and thus very common estimator. It is conceptually simple and computationally straightforward. Least squares estimates are commonly used to analyze both experimental and observational data.

Table 3: Substituted values and their summation for Vehicle No. 1 for solving the equation

Tyre pressure (N/mm^2) (p)	Fuel consumption N (L/km) (F)	p^2	p^3	p^4	pf	p^2f
0.2723	0.1764	0.0742	0.0202	0.0055	0.0480	0.0131
0.2741	0.1727	0.0751	0.0206	0.0056	0.0473	0.0130
0.2758	0.1689	0.0761	0.0210	0.0058	0.0466	0.0128
0.2775	0.1610	0.0770	0.0214	0.0059	0.0447	0.0124
0.2792	0.1639	0.0780	0.0218	0.0061	0.0458	0.0128
0.2810	0.1587	0.0789	0.0222	0.0062	0.0446	0.0125
0.2827	0.1508	0.0799	0.0226	0.0064	0.0426	0.0121
0.2844	0.1451	0.0809	0.0230	0.0065	0.0413	0.0117
0.2861	0.1445	0.0819	0.0234	0.0067	0.0413	0.0118
0.2879	0.1418	0.0829	0.0239	0.0069	0.0408	0.0118
0.2896	0.1393	0.0839	0.0243	0.0070	0.0403	0.0117
0.3017	0.1383	0.0910	0.0274	0.0083	0.0417	0.0126
0.3034	0.1266	0.0920	0.0279	0.0085	0.0384	0.0116
0.3051	0.1321	0.0931	0.0284	0.0087	0.0403	0.0123
0.3085	0.1305	0.0952	0.0294	0.0091	0.0403	0.0124
0.3103	0.1235	0.0963	0.0299	0.0093	0.0383	0.0119
0.3137	0.1250	0.0984	0.0309	0.0097	0.0392	0.0123
0.3189	0.1255	0.1017	0.0324	0.0103	0.0400	0.0128
0.3254	0.1220	0.1059	0.0345	0.0112	0.0397	0.0129
0.3271	0.1190	0.1070	0.0350	0.0115	0.0389	0.0127
0.3289	0.1218	0.1081	0.0356	0.0117	0.0401	0.0132
0.3306	0.1199	0.1093	0.0361	0.0119	0.0396	0.0131
0.3323	0.1190	0.1104	0.0367	0.0122	0.0396	0.0131
0.3358	0.1175	0.1127	0.0378	0.0127	0.0395	0.0132
0.3478	0.1190	0.1210	0.0421	0.0146	0.0414	0.0144
0.3495	0.1168	0.1222	0.0427	0.0149	0.0408	0.0143
0.3530	0.1163	0.1246	0.0440	0.0155	0.0410	0.0145
0.3737	0.1174	0.1396	0.0522	0.0195	0.0439	0.0164
0.3754	0.1186	0.1409	0.0529	0.0199	0.0445	0.0167
0.3771	0.1185	0.1422	0.0536	0.0202	0.0447	0.0169
0.3788	0.1235	0.1435	0.0544	0.0206	0.0468	0.0177
Summation = 9.7875	4.1741	3.1239	1.0081	0.3289	1.3021	0.4107

RESULTS AND DISCUSSION

Development of a model using least squares method: The scatter diagrams for the various collected data for Vehicle No. 1, 2, 3, 4 and 5 which were collected and tabulated were plotted as shown in Fig. 3, 4 and 5. From the scatter diagrams, it could be inferred that the correlation between the fuel consumption and the tyre pressures are in the form of a polynomial function of a second degree. Hence a model can be developed using the least square method of modeling (Fig. 2).

The least square method of regression and correlation was used to develop the models for the five vehicles. In the least square method, the equation for the model is given by $F = B_0+B_1p+B_2p^2+e$, where F represent the fuel consumption, p represent tyre pressure, B_0, B_1 and B_2 are constants for the polynomial which must be derived from the data obtained and e represent the error in the data. This equation can be written into three equations as:

$$\sum_{i=1}^{n} F_i = B_0 n + B_1 \sum_{i=1}^{n} p_i + B_2 \sum_{i=1}^{n} p_i^2 \quad (1)$$

$$\sum_{i=1}^{n} p_i F_i = B_0 \sum_{i=1}^{n} p_i + B_1 \sum_{i=1}^{n} p_i^2 + B_2 \sum_{i=1}^{n} p_i^3 \quad (2)$$

$$\sum_{i=1}^{n} p_i^2 F_i = B_0 \sum_{i=1}^{n} p_i^2 + B_1 \sum_{i=1}^{n} p_i^3 + B_2 \sum_{i=1}^{n} p_i^4 \quad (3)$$

Putting the various values for the different vehicles into these equations and solving for various constants, B_0, B_1 and B_2 give the equation for each vehicle. For instance, for Vehicle No. 1, the tyre pressure values were tabulated and the summations found as shown in Table 3. Substituting these values in to the equations gives:

$$4.1741=31B_0+9.7875B_1+3.1239B_2 \quad (4)$$

$$1.3021=9.7875B_0+3.1239B_1+1.0081B_2 \quad (5)$$

$$0.4107=3.1239B_0+1.0081B_1+0.3289B_2 \quad (6)$$

Solving these equations simultaneously gives B_0 = 3.6285, B_1 = -21.4049 and B_2 = 32.3927. Substituting the main equation gives $F = 3.6285 - 21.4049p + 32.3927p^2$ as the equation for Vehicle No.1. This procedure was repeated four the other four vehicles and the equations obtained were tabulated and presented in Table 4.

Table 4: Various vehicles' equations for the five vehicles

Vehicle no.	Vehicles' equations
1	$F = 3.6285 - 21.4049p + 32.3927p^2$
2	$F = 0.6272 - 2.5941p + 3.3428p^2$
3	$F = 0.5568 -1.7946p + 1.618p^2$
4	$F = 1.4454 - 7.9701p + 11.7484p^2$
5	$F = 0.6402 - 2.7463p + 3.7853p^2$

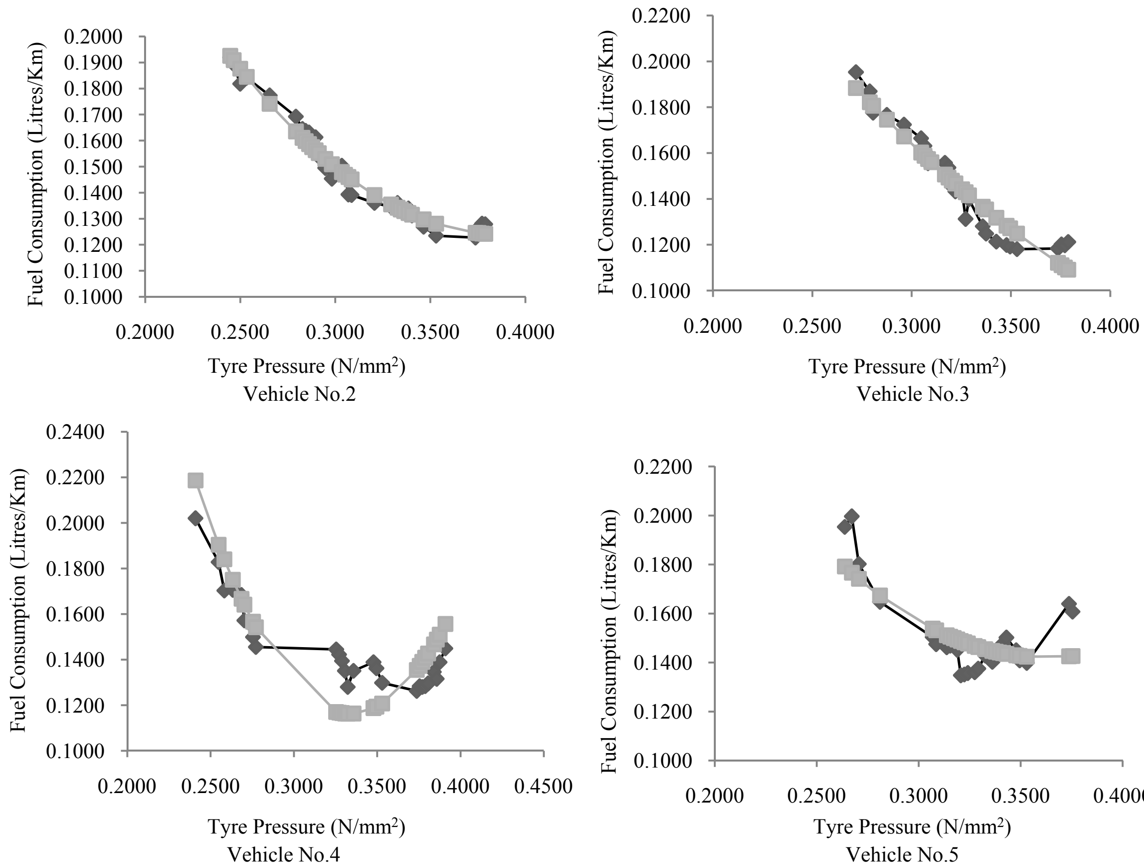

Fig. 5: Model values of Vehicles No. 2, 3, 4, and 5 compared to the measured values respectively

With these equations obtained, the various model graphs were drawn as shown in Fig. 4 and 5 for Vehicle No. 1 to 5. In all the graph plotted in Fig. 4 and 5 a general trend were observed as the tyre inflation pressure reduces the fuel consumption increased, perhaps this might be due to a higher rolling resistance which required much greater force to propelled the vehicle.

VERIFICATION OF THE MODEL

To verify the model, two steps were carried out. First of all, the R^2 values were found for all the five vehicles using the least squares method for correlation. R^2 values represent the correlation, that is, how closely the variables are associated, were found using this equation:

$$R^2 = \frac{\left(B_1 \sum_i (p_i - \bar{p})(F_i - \bar{F}) + B_2 \sum_i (p_i^2 - \bar{p}^2)(F_i - \bar{F})\right)}{\sum_i (F_i - \bar{F})^2} \tag{7}$$

The values found were substituted into the equation and the R^2 values were found and the results obtained were tabulated and presented in Table 5.

Comparing the R^2 values with the model values of the five vehicles, it could be seen that, the equation for vehicle No.2 was the better and could be used as the model. This vehicle has R^2 value of 0.93 and the fuel consumption model values deviate by ±5 which is within experimental error. So, the equation F = 0.6272-

Table 5: The various correlations or R^2 values for the five vehicles

Vehicle	Vehicles' equations	R^2	$/1 - R^2/$
1	$F = 3.6285 - 21.4049p + 32.3927p^2$	1.54	0.54
2	$F = 0.6272 - 2.5941p + 3.3428p^2$	0.93	0.07
3	$F = 0.5568 - 1.7946p + 1.618p^2$	0.90	0.10
4	$F = 1.4454 - 7.9701p + 11.7484p^2$	1.39	0.39
5	$F = 0.6402 - 2.7463p + 3.7853p^2$	0.53	0.47

Table 6: Comparing the R^2 values when using the vehicles own equation and when using the model

	Using vehicles own equation		Using the model	
Vehicle	R^2	$/1 - R^2/$	R^2	$/1 - R^2/$
1	1.54	0.54	0.73	0.27
2	0.93	0.07	0.93	0.07
3	0.90	0.10	0.46	0.54
4	1.39	0.39	1.12	0.12
5	0.53	0.47	0.64	0.36

Table 7: Error values for the other four vehicles when using the model

Vehicle	Error values
1	±0.025
3	±0.025
4	±0.018
5	±0.0295

2.5941p+ 3.3428p^{2}withR^2 = 0.93can be accepted as the model for predicting vehicle fuel consumption. Using this model with the recommended tyre pressure will reduce the fuel consumption by 17.6% and this will safe cost of fuel.

Secondly, this model was tested using the data for the other four vehicles and the results obtained for the R^2 values were presented in Table 6.

From Table 6, it could be inferred that using the model gives better R^2 than using the vehicles own equation. Which means that the model gives better fuel consumption values compared with using the vehicles own equation. Only Vehicle No.3 has better R^2 value when using its own equation than using the model but the rest shows the opposite. This means that, the model can be used for all the five vehicles and by extension all vehicles if possible. But from the general equation using least square method, there is an error value 'e' which has to be found when error values exceed ±5. Using the general model equation for the other four vehicles it could be seen that the error values exceed that value and so the error value 'e' of the equation has to be found for the four vehicles and the least value taken. Using 95% confidence, the equation gives:

$$F = 0.6272 - 2.5941p + 3.3428p^2 \pm 1.96\sigma_e \quad (8)$$

where, σ_e represent standard deviation of the error values:

$$\sigma_e \text{ is given by } \sigma_e = \sqrt{\frac{\sum(e-\bar{e})^2}{N}} \quad (9)$$

where,
N = The number of values taken

These summations were substituted into the equation and errors found were tabulated and presented in Table 7. Taken the least gives the final general equation of $F = 3.3428p^2 - 2.5941p + 0.6272 \pm 0.018$. Since ±0.018 is the least it can be used, because using the largest error value will mean that the error for the other vehicles will be increased.

CONCLUSION

An experiment was conducted to develop a model for the relationship between the tyre pressure and its corresponding fuel consumed. The model obtained was $F = 0.6272 - 2.5941p + 3.3428p^2 \pm 0.018$ which can also be used to predict the amount of fuel consumed. The model was validated with its own data which showed a deviation of ±5% which is within experimental error. Using the recommended tyre pressures reduce the fuel consumption by 17.6% thus reducing cost. It also minimized emissions thereby making movement safe and desirable. It is recommend that there should be a massive public education or awareness about the need to keep recommended tyre pressure at all times because when tyre pressure falls below the recommended value, the decrease in the pressure invariably leads to an increase in fuel consumption. Also underscoring this need is the fact that most drivers or car owners fail to regularly check the level of their tyre pressure.

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