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Mathematical Modeling of Tractor Fuel Consumption for Ridging Operation in Sandy Loamy Soil

[1]Ekemube, R.A., *[2]Atta, A.T., [1]Nkakini, S.O. and [3]Amgbara, T.O.

[1]Department of Agricultural and Environmental Engineering, Rivers State University, Port Harcourt City, Nigeria.
[2]Kenaf and Jute Improvement Program, Institute of Agricultural Research and Training, Obafemi Awolowo University, Moore Plantation, Ibadan, Nigeria.
[3]Department of Industrial Safety and Environmental Engineering, Kenule Beeson Saro-Wiwa Polytechnic, Bori, Rivers State, Nigeria.
*adekunleatta@gmail.com; raymond.ekemube@ust.edu.ng

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ABSTRACT

The need to use selected soil-implement-machine parameters as factors affecting fuel consumption is essential. A mathematical model for predicting tractor fuel consumption per working area for ridging operation has been developed using Buckingham's pi theorem in dimensional analysis. Generalized reduced gradient (GRG), a nonlinear method of Excel solver was used for the establishment of the model's constant. The model was validated by simulating the experimental results using the equation, graphical comparison, and assessing the coefficient determination (r^2), root mean square error, and paired t-Test. The field experiment was performed at Rivers Institute of Agricultural Research and Training (RIART) Farm in Rivers State University, Port Harcourt, Nigeria. The group balanced block design (GBBD) was adopted. The design consisted of 9 experimental treatments with three replicates. The experimental fuel consumption per working area was determined by quantity of fuel used per working area with the aid of fuel flow meter. The field test parameters (speed, height, forward speed, cone index, bulk density) were measured accordingly with their specific standards procedures. The field test parameters (speed, height, forward speed, cone index, bulk density) results were simulated with fuel consumption to obtain the constant in the predictive mathematical model. The developed model displayed good agreement between measured and predicted results with high coefficient of determination and low root mean square error. The paired t-Test results also showed no significant difference at 95 and 99 % confidence levels. It is thus, suggested that the model be used for predicting tractor fuel consumption during ridging operation.

1. INTRODUCTION

Ridging is a tillage operation performed after ploughing and harrowing operations that involves the use of implement such as ridger for preparing seedbed conducive for crop production. This can be done to raise the soil up to 30 to 60 cm with different forms or shape . A study by Ikpo and Ifem (2005) reported that tractors used more energy at the lowest work rate during ridging operation. Researchers such as Fathollahzadeh et al. (2010), Ajav and Adewoyin (2012), Adewoyin (2013) and Adewoyin and Ajav (2013) reported that a tractor's fuel consumption is affected by many parameters during tillage operation. These include type and structure of soil, climate, tractor type, tractor size and tractor-implement relationship. Other fundamental factors that affect fuel consumption in tillage operation include power consumption increment by increasing the working speed, actual width of cut, soil strength, moisture content and the working depth (Cortez et al., 2008; Kichler et al., 2011; Silveira et al., 2013; Moitzi et al., 2014; Leghari, et al., 2016; Nasr et al., 2016).

The prediction of tractor fuel consumption during ridging operation can be determined by different approaches. These approaches are usually focused on supplies of power and individual engines, which call for extensive engine testing to validate the amount of fuel consumed (ASAE, 2002a, b; Grisso et al., 2004; 2010; 2011). Much models have not been developed by various researcher to predicted tractor fuel consumption per working area during ridging operation. Igoni et al. (2019) used dimensional analysis to develop a tractor fuel consumption model for ridging operation. But, in literature there is a dearth of information on tractor fuel consumption model for predicting fuel consumption for ridging operation. Hence, there is need to develop a mathematical model to predict fuel consumption in terms of working area using dimensional analysis. This will be as a guide to farmer before field work. The aim of this study is to develop a mathematical model for predicting tractor fuel consumption per working area for ridging operation.

2. MATERIALS AND METHODS

2.1. Experimental Site Description

This experiment was performed at the Rivers Institute of Agricultural Research and Training (RIART) farm at Rivers State University, Port Harcourt, Nigeria (latitude of 4° 49′ 27″ N, and longitude of 7° 2′ 1″ E). The experimental design used in this study is group balanced block design (GBBD). A farm size of 138 m by 50 m (6900 m^2) was divided into three plots of 9 sub-plots each. Each sub-plot of 50 m by 2 m was marked with a 1 m alley. The sub-plot was provided for different treatment options and with a space of 2 m between each block and 1 m at the sides of the outer blocks.

2.2. Tractor and Implement Specifications

The tractor used to perform the ploughing operation was A two-wheel drive tractor Swaraj 978 FE (Swaraj, India) was used for this study (Plate 1). The tractor has a total weight of 3015kg, engine horsepower of 72 hp and lifting power of 2200 kg. Front and the rear tyres were 7.5–16, 8 ply and 16.9 – 28, 12 radial respectively. A 1180 mm frame width mounted-type disc plough with disc diameter of 300 mm of disc plough (Baldan Implementos Agricolas, Brazil) with 3-disc bottom mounted on a gauge wheel was used for the experiments (Plate 2).

Plate 1: Swaraj 978 FE tractor

Plate 2: Disc ridger

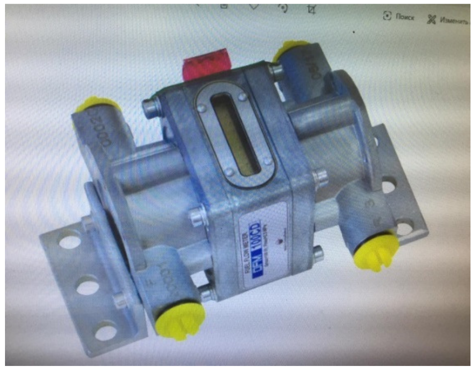
Plate 3: DFM 100CD fuel flow meter

2.3. Fuel Flow Meter Specification

The DFM 100CD fuel flow meter (Technoton Engineering, Belarus) used for the purpose of this research has nominal fuel pressure 0.2 MPa, maximum fuel pressure 2.5 MPa, minimum kinematic viscosity 1.5mm^2/s, maximum kinematic viscosity 6.0 mm^2/s, minimum supply voltage 10 V and maximum supply voltage 45 V (Plate 3).

2.4. Model Derivation

The significance of accurate prediction in any field of engineering cannot be overemphasized. Therefore, the mathematical tool that was employed in this work is dimensional analysis using the Buckingham pi theorem. Hence, in this research fuel consumption model development was done using the method of fuel consumption per working area (FC_{wa}, L/ha). Some of the factors affecting tractor fuel consumption were presented in Table 1 and the dimensional matrix in Table 2.

Table 1: Dimensions of some variables influencing fuel consumption

Variables	Symbol	Unit	Dimensions
Fuel consumption	FCw_a	L/ha	$L^3 L^{-2}$ (L)
Forward speed	V	Km/h	LT^{-1}
Ridge height	h	m	L
Cone index	CI	N/cm^2	$ML^{-1}T^{-2}$
Bulk density	P	g/cm^3	ML^{-3}
Width of cut	W	m	L

Table 2: Dimensional matrix of the variables

Dimensions	Parameters					
	FC_{wa}	V	h	CI	ρ_b	W
M	0	0	0	1	1	0
L	1	1	1	-1	-3	1
T	0	-1	0	-2	0	0

Fuel consumption, FC_{wa} is a function of (h, W, V, CI, ρ_b)
Mathematically:

$$FC_{ta} = f(h, W, V, CI, \rho_b) \quad (1)$$

The dependent variable = FC_{wa}
Total number of variables, n = 6
Total number of fundamental dimensions, m = 3
Therefore, number of dimensionless groups (π- terms) to be formed = n – m = 6 – 3 = 3

Equation 2 can be written as:

$$f\left(\pi_{1,}\ \pi_2, \pi_3\right) \quad (2)$$

Each π- term contains (m + 1) variables, where m = 3 and is also equal to repeating variable choosing from ρ_b, h, V as repeating variables, then five π- terms is given as:

$$\pi_1 = \rho_b{}^{a_1}. \quad {}^{b_1}. V^{c_1}. FC_{wa} \quad (3)$$
$$\pi_2 = \rho_b{}^{a_2}. h^{b_2}, V^{c_2}. W \quad (4)$$
$$\pi_3 = \rho_b{}^{a_4}. h^{b_4}, V^{c_4}. CI \quad (5)$$

Where ρ_b = Bulk density (g/cm^3), h = Ridge height (m), W = Width of cut (m), V = Tractor forward speed (km/h) and CI = Cone index (N/cm^3)

2.4.1. Transformation to dimensionless parameters

A new set of π terms can be generated by multiplication or division with each other. In addition, the present π terms can be reversed to make a new π term. This is to ensure simplicity in the experimentation process. The present π terms($\pi_{1,}\ \pi_2$, and π_3) can be adjusted to generate a new π term (Langhaar, 1980; Tarham and Carman, 2004; Nkakini et al., 2019a, b; Igoni et al., 2019).

π_1 terms:

$$M^0L^0T^0 = \rho_b^{a_1}. h^{b_1}V^{c_1}. FC_{wa}$$
$$(ML^{-3})^{a_3}. (L)^{b_3}. (LT^{-1})^{c_3}. L^3T^{-1}$$

Equating the exponents of M, L and T:

For M: $0 = (1)a_1 + (0)b_1 + (0)c_1 + 0$

$a_3 = 0$

For L: $0 = (-3)a_1 + (1)b_1 + (1)c_1 + 3$

Substituting $a_1 = 0$

$$b_1 + c_1 + 3 = 0$$
$$b_1 + c_1 = -3$$

For T: $0 = (0)a_1 + (0)b_1 + (-1)c_1 + (-1)$

Substituting $a_1 = 0$

$$-c_1 - 1 = 0$$
$$c_1 = -1$$

Recall, $b_1 + c_1 = -3$

Substituting $c_1 = -1$

$$b_1 - 1 = -3$$
$$b_1 = -3 + 1$$
$$b_1 = -2$$

Substituting the values of $a_{1,} b_1$ *and* c_1 *in* π_3:

$$\pi_1 = \rho_b^0. d^{-2}. V^{-1}. FC_h$$

$$\pi_1 = \frac{FC_{wa}}{h^2V} \quad (6)$$

π_2 – terms:

$$M^0L^0T^0 = \rho_b^{a_2}. h^{b_2}V^{c_2}. W$$
$$(ML^{-3})^{a_2}. (L)^{b_2}. (LT^{-1})^{c_2}. L$$

Equating the exponents of M, L and T:

For M: $0 = (1)a_2 + (0)b_2 + (0)c_2 + 0$

$$a_2 = 0$$

For L: $0 = (-3)a_2 + (1)b_2 + (1)c_2 + 1$

Substituting $a_2 = 0$

$$b_2 + c_2 + 1 = 0$$
$$b_2 + c_2 = -1$$

For T: $0 = (0)a_2 + (0)b_2 + (-1)c_2 + 0$

Substituting $a_2 = 0$

$$-c_2 + 0 = 0$$
$$c_2 = 0$$

Recall, $b_2 + c_2 = -1$

Substituting $c_2 = 0$

$$b_2 = -1$$

Substituting the values of a_2, b_2 and c_2 π_2:

$$\pi_2 = \rho_b^0 . h^{-1} . V^0 . W$$
$$\pi_2 = \frac{W}{h} \quad (7)$$

π_3 – terms:

$$M^0 L^0 T^0 = \rho_b^{a_3} . h^{b_3} V^{c_3} . CI$$
$$(ML^{-3})^{a_3} . (L)^{b_3} . (LT^{-1})^{c_3} . ML^{-1}T^{-2}$$

Equating the exponents of M, L and T:

For M: $0 = (1)a_3 + (0)b_3 + (0)c_3 + 1$

$$a_3 + 1 = 0$$
$$a_3 = -1$$

For L: $0 = (-3)a_3 + (1)b_3 + (1)c_3 + (-1)$

Substituting $a_3 = -1$

$$3 + b_3 + c_3 - 1 = 0$$
$$b_3 + c_3 = -2$$

For T: $0 = (0)a_3 + (0)b_3 + (-1)c_3 + (-2)$

Substituting $a_3 = -1$

$$-c_3 - 2 = 0$$
$$c_3 = -2$$

Recall, $b_3 + c_3 = -2$

Substituting $c_3 = -2$

$$b_3 - 2 = -2$$
$$b_3 = 0$$

Substituting the values of $a_3, b_3,$ and c_3 in π_3:

$$\pi_3 = \rho_b^{-1} . h^0 . V^{-2} . CI$$
$$\pi_3 = \frac{CI}{\rho_b V^2} \quad (8)$$

Substituting the values of $\pi_1, \pi_2, \pi_3, \pi_4$ and π_5 in Equation (2):

$$f\left(\frac{FC_{wa}}{W}, \ \frac{h}{W}, \ \frac{CI}{\rho_b V^2}\right) = 0 \quad (9)$$

Where f = functional notation for fuel consumption

2.4.2. Formulation of the fuel consumption model

The method of product and quotient component functions were adopted for development of the fuel consumption model. This prognostic model was developed by simple multiplication and division of the component equations. The validity of combining the equation components by multiplication and division were tested by assuming that the general prediction model is obtained by simple multiplication and division of the pi terms (Equations 10 and 11).

π_1^1 was established by dividing Equation 7 by Equation 8:

$$\pi_1^1 = \frac{\pi_2}{\pi_3} = \frac{\frac{h}{W}}{\frac{CI}{\rho_b V^2}} \quad (10)$$

$$\pi_1^1 = \frac{\rho_b s^2 h}{CIW} \quad (11)$$

Hence, the relationship becomes:

$$\pi_1 = K_{FC} f(\pi_1^1) \quad (12)$$

$$\frac{\pi_1}{\pi_1^1} = K_{FC} \quad (13)$$

Substituting the values of π_1 and π_1^1 into Equation (12):

$$\frac{FC_{wa}}{W} = K_{FC}\left[\frac{\rho_b V^2 h}{CIW}\right] \quad (14)$$

K_{FC} can be calculated using method of GRG in excel solver and the constant obtained becomes the K_{FC} value

$$\therefore K_{FC} = \frac{FC_{wa} CI}{\rho_b V^2 h} \quad (15)$$

On rearranging Equation (15), it becomes:

$$FC_{wa} = K_{FC}\left[\frac{\rho_b V^2 h}{CI}\right] \quad (16)$$

Equation (16) expresses the tractor fuel consumption per working area during ridging operation.

Where K_{FC} = Fuel consumption constant

2.4.3. Model validation

The developed model was validated by simulating the experimental data and then comparing the experimental with the prediction data. The parameters (ridge height, forward speed, cone index and bulk density) were determined experimentally and substituted into the formulated model to compute the predicted fuel consumption per working area. Also, the root mean square error (RMSE) was used to check the prediction error as represented in Equation (17).

$$RMSE = \sqrt{\frac{\sum_{i-1}^{i-N}\left(FC_{wa(m)} - FC_{wa(P)}\right)^2}{N}} \quad (17)$$

Where N = number of samples, $FC_{wa(m)}$ = measured fuel consumption (L/ha), and $FC_{wa(P)}$ = predicted fuel consumption (L/ha).

Furthermore, the developed model was validated with regression curve and coefficient of determination (r^2). These were used to check if the measured and predicted results have good agreement. Also, graphical comparison of measured and predicted results as well the paired t- test as presented in Equation (18) was considered as significant at $t_{computed} > t_{table}$ (95 and 99 % confidence) levels.

$$t = \frac{\sum D/N}{\sqrt{\frac{\sum D^2 - \left(\frac{(\sum D)^2}{N}\right)}{(N-1)(N)}}} \quad (18)$$

Where $\sum D$ = summation of the differences, $\sum D^2$ = summation of the squared differences, and $(\sum D)^2$ = summation of the differences squared.

2.5. Experimental Procedures

Preceding ridging operation, soil core was used for obtaining the soil sample from the depth of 0 – 10, 10 – 20 and 20 - 30 cm at random in the field to determined textural classification of the soil and the bulk density. The collected soil samples were taken to the laboratory for analysis. The bulk density was determined using core method (Walter et al., 2016). The disc ridger was attached to the tractor and levelled using the top links of the tractor in order to reduce parasitic forces. The level control of the lifting mechanism (three-point linkage height) was set to lower the disc ridger to the desired ridging depth. The tractor forward speeds were determined by selecting a particular gear that gave the desired speed. This was done in a practice area in advance for each test plot to maintain the desired treatment. The ridge height measurement was done by placing a meter rule from furrow bottom to the surface of the ridged land, while the width of cut was measured by placing a steel tape from one side of the furrow wall to the other end. Time was determined with a stopwatch set at zero before each operation. The cone index was also determined using a cone penetrometer. The digital method of measuring the quantity of fuel used was adopted to determine tractor fuel consumption. During this process, the use of the DFM fuel flow meter was employed to measure fuel consumption. The metre was mounted on the fuel line between the tractor's fuel tank and the pump. At the end of each test operation the data was taken from the fuel flow meter as display information, switching is performed by light touch to the top cover of fuel flow meter by iButton key. Mathematically, fuel consumption per working area was calculated by expression in Equation 19.

$$FC_{wa} = \frac{10 \times T_{fc}}{V \times W \times E \times h} \quad (19)$$

Where FC_{wa} = Fuel consumption per working area (L/ha), T_{fc} = Tractor fuel consumption (L), V = Forward speed (km/h), W = Implement width (m), E = Implement field efficiency (%) and h = Working hour (h).

3. Results and Discussion

3.1. Establishment of Constant for Fuel Consumption per Working Area

From Equation 16, K_{FC} was constant for the fuel consumption per working area model formulated using fuel flow meter. The generalized reduced gradient method of excel solver was used to compute the constants by simulating measured field test results d, S, CI, W, measured FC_{wa}, estimated FC_{wa} and error squared and the values for the constants (K_{FC}) were established for ridging operation (Table 3). It was obtained as $K_{FC} = 105.5392$. The computed constant (K_{FC}) of the model formulated was fitted into the fuel consumption per working area model established. Table 3 showed acceptable agreement with minimum error, revealing the reliability and acceptability of the model. Therefore, the fuel consumption per working area model established for ridging operation at tractor forward speed, ridge height, width of cut, bulk density and cone index is given in Equation 20.

$$FC_{ta} = 105.5392\ K_{FC} \left[\frac{\rho_b V^2 h}{CI}\right] \tag{20}$$

This model is similar to that of Kumar and Pandey (2015) that used multiple linear regression analysis with excel spread sheet and fitted to the model structure formulae to calculate the coefficient. Also, Equation 20 is similar to fuel consumption equations developed by Nkakini et al. (2019a, b), and Igoni et al. (2019) that used linear regression to fit in their fuel consumption equations to determined constants.

Table 3: Fuel consumption per working area and operating conditions for ridging

Treatment	Parameters						(Error)^2
	ρ_b (g/cm^3)	V (km/h)	CI (N/cm^2)	h (m)	Measured FC_{wa} (L/ha)	Predicted FC_{wa} (L/ha)	
1	4533.75	5.00	156.25	0.10	2.27	2.3979	0.016346
2	4904.25	7.00	156.25	0.10	4.8	4.6998	0.010043
3	5274.75	9.00	156.25	0.10	6.9	7.7690	0.755222
4	9067.5	5.00	195.31	0.20	4.03	4.2149	0.034176
5	9808.5	7.00	195.31	0.20	9.72	8.2611	2.128274
6	10549.5	9.00	195.31	0.20	13.99	13.6562	0.111443
7	13601.3	5.00	226.56	0.30	5.46	5.9394	0.2298
8	14712.8	7.00	226.56	0.30	11.61	11.6412	0.000972
9	15824.3	9.00	226.56	0.30	18.93	19.2436	0.098328

K_{FC} = 105.5392 and SS_E = 3.384604

3.2. Model Validation

The reality of a formulated model for solving a particular problem depends on its estimates and validation. Results of the formulated fuel consumption per working area model for ridging operation was by substitution of the values of a number of measured data which was compared with the predicted fuel consumption per working area as shown in Table 3. Figures 1 and 2 showed the graphical comparison between measured and predicted fuel consumption per working area values using fuel flow meter. It was observed that the model has a high relationship with measured data from the ridging operation with coefficient of determination (r^2) value of 0.9856. Considering the means of predicted and measured data statistically, it was revealed that the root mean square error (RMSE) analysis which illustrated the error differences between the measured and predicted results is 0.72. Furthermore, the t-test was used to determine the level of significance between the means of measured and predicted fuel consumption per working area at 0.05 and 0.01 significance levels. The value of the paired t-test ($t_{calculated}$) was 0.19 which was less than the t_{table} values (2.306 and 3.355) (i.e., $t_{cal} < t_{tab}$). This pointed out that there is no significant difference between the measured and the predicted data. This was comparable to the finding of Karpavarfard and Rahmanian-Koushkaki (2015) that developed fuel consumption model of a chisel plough using dimensional analysis. Also, ASAE (2000a) referenced ASAE EP496 that the fuel consumption equations developed was 15 % higher than the Nebraska tractor test performance under field condition. As well, Nkakini et al. (2019a, b); and Igoni et al. (2019) used dimensional analysis in Buckingham pi theorem to develop fuel consumption model for ploughing, harrowing and ridging, respectively.

R.A. Ekemube et al. / Nigerian Research Journal of Engineering and Environmental Sciences
7(1) 2022 pp. 309-318

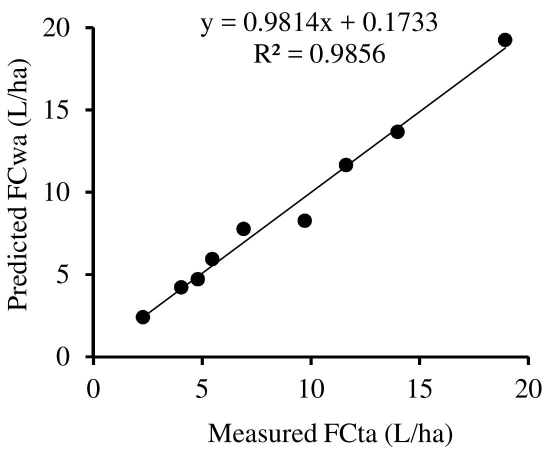

Figure 1: Predicted vs measured FC_{wa} for ridging

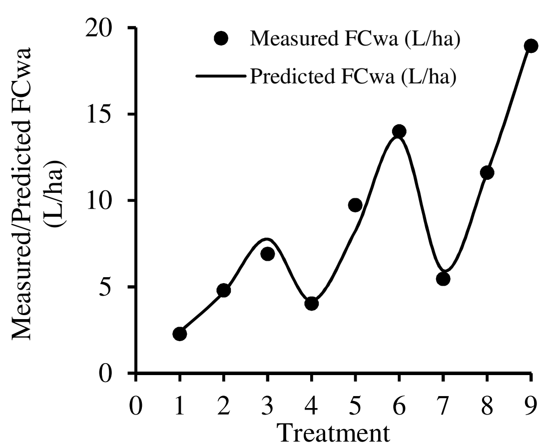

Figure 2: Measured and predicted tilled FC_{wa} vs treatment for ridging

4. CONCLUSION

This study had developed a tractor fuel consumption model for ridging operation to ensure prediction of fuel consumption per working area usage. The following conclusions were drawn from the obtained results:

i. A mathematical model for predicting tractor fuel consumption per working area in course of ridging operation has been developed.
ii. The developed model constant (K_{FC}) for ridging operation with respect to the equipment used was obtained as 105.5392.
iii. Model prediction achieved in this study can be categorized as good for high coefficient of determination (r^2), low root mean square error, and paired t-test calculated was less than the table value.
iv. The results showed acceptable agreement with measured and predicted model results showing that the model can predict experimental data precisely.

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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