MODELING FUEL CONSUMPTION RATE FOR HARROWING OPERATIONS IN LOAMY SAND SOIL

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Abstract: *A model equation for predicting fuel consumption during harrowing operations using Dimensional analysis with Buckingham pi theorem was developed. The experiment was conducted at the loamy sand soil of Rivers State Agricultural Development Programme Farm in School to Land Authority, Port Harcourt, Nigeria. The experimental design adopted was Factorial Randomized Complete Block Design (RCBD). The field fuel consumption was measured using graduated cylinder and stop watch to note the time taken at the end of each operation. . These field test parameters such as draught, harrowing speed, harrowing depth, moisture content, cone index and width of cut were measured and recorded. The validated developed fuel consumption model equation by graphical comparison showed good treatment between measured and predicted equation results. Furthermore, the RMSE value was low and the t test results showed no significant difference with 95 and 99 % confidence levels. Consequently, suggested that the equation can be used for predicting fuel consumption for harrowing operations.*

Keywords: Predicted Equation, Disc Harrow, Tractor Forward Speed, Dimensional Analysis.

INTRODUCTION

Fuel as an important variable, used by all machinery during farm operation and it is inevitable in farm practices in improving agricultural mechanization. Mechanized tillage has been powered by tractors as the only power source. They are energized by fuel for performance as one of the factors for effective parameters in tillage operations. According to Michalski et al. (2014) fuel consumption is the primary diagnostic parameter in identifying the condition of the vehicle. Moreover, because of the continuous rise in fuel prices, energy consumption has become one of the most important factors in agricultural economy.

LITERATURE/THEORETICAL UNDERPINNING

The factors that fundamentally affect fuel consumption in tillage equipment use is the increase in power consumption 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, 2016). Investigation by Moitzi et al. (2014) revealed that increasing working depth, raises the drawbar pull and the slip and the effect is an increased fuel consumption rate (L h-1) and area-specific fuel consumption (L ha-1). Cortez et al. (2008); Kichler et al. (2011); and Silveira et al. (2013) posited that within the same operating speed and varying the engine speed, there are significant increases in hourly fuel consumption. Researchers have adopted several methods for development of fuel consumption predictive model. In general some of these methods are based on power requirements and others are for individual engines, which call for extensive engine testing to verify the amount of fuel consumption (ASAE 2002a; 2002b; Grisso et al. 2004). They include Persson (1969 given by Huynh and Brown in 1981 as cited by Macmillan 2002).

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Jahns (1883), Hansson et al. (2003), Bowers (2001 as cited in Grisso et al.2004), ASAE Standards (2002a), ASAE (2002a), Kheiralla et al. (2003), Grisso et al.(2004),Kheiralla et al. (2004),Safe et al. (2009), Fathollahzadeh et al. (2010), Rahimi-Ajdadi and Abbaspour-Gilandeh (2011),Adewoyin (2013); Adewoyin and Ajav (2013), Pelletier et al. (2014), Karparvarfard and Rahmanian-Koushkaki (2015), Kumar and Pandy (2015), Lee et al. (2016), Almaliki et al. (2016a),Dahab et al. (2016),Almaliki, et al. (2016b),Shafaeiet al. 2018).

In all-purpose, there have been no published results about application of Dimensional Analysis (Buckingham's pi theorem) for developing model for fuel consumption equation for harrowing operations using disc harrow. The aim of this study was to develop an appropriate predictive model equation for the determination of optimum tractor fuel consumption in harrowing operation.

MATERIALS AND METHODS

Study Area

The experiment was conducted on August 8th, 2018 from 8am to 5pm at the Rivers Agricultural Development Programme farm in School to Land Authority, Port Harcourt, Nigeria (4° 49′ 27″ N, and longitude of 7° 2′ 1″ E). The experimental design adopted was factorial in randomized complete block design (RCBD). A farm location, 160 m by 32.5m (5200 m^2) which was divided into three blocks of 9 plots each. Each plot was marked out 50m by 2 m each along with the alley dimension of 1m in between. The plot was provided for different treatment options and with a space of 4 m between each block and 1 m at the sides of the outer blocks.

Tractor and Implement Specifications

A two wheel drive tractor (Model: 978 FE, manufacturer: Swaraj, country: India) was used for this study. The tractor was one of the commonly used tractors in the area of the country. The tractor total weight 3015 Kg. Front and the rear tyres were 7.5 – 16, 8 ply and 16.9 – 28, 12 radial respectively. A 1390mm cm wide mounted-type with three tandem disc harrow (manufacturer: Swaraj, country: India) with fourteen disc bottom mounted on a guage wheel was used for the experiments. The disc harrow attached to the tractor was levelled using top links of the tractor together in order to minimize parasitic forces.

Experimental Procedure

Figure 1: Harrowing Operation

Figure 2: Measurement of Volume of Fuel Used

Prior to tillage operations, soil auger was used for collecting the soil sample at the depth of 0 - 0.16 m at random in the field to determined textural classification of the soil and moisture content. The composite soil samples were put in well labelled polyethylene bags and were taken to the laboratory immediately. The textural classification of the soil was determined by hydrometer method and the gravimetric (i.e. oven dry method) was used to determine soil moisture content prior to tillage operation. Cone index (CI) was measured with simple measuring device called cone penetrometer having an enclosed angle of 30^o, with a base area of 3.23cm^2 (323mm^2) mounted on a shaft of 45.72cm (457.20 mm). Cone index (soil resistance) to penetration of implements was taken at three different depths, 0.10, 0.13, 0.16 m respectively before any of the tillage operations.

Proceeding to harrowing operation, the harrowing depths were determined by setting the controlling level of the lifting mechanism (three-point linkage height) to lower the disc harrow corresponding to the desired harrowing depth. Harrowing speeds were determined by selecting a particular gear that will give the desired speed. This was done in a practice area in advance entering to each main test plot for maintaining desired treatment. The harrowing depth was measured by placing the meter rule from furrow bottom to the surface of the harrowed 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 stop watch setting at zero before each operation. Draught force was determined using the formula represented below (ASAE 2000a):

$$D = F_i[A + B(S) + C(S)^2]WT \quad (1)$$

Where; D = Draught force, N, F = dimensionless soil texture and adjustment parameter
i = 1 for fine, 2 for medium, 3 for coarse (table), ABC = machine specific parameter (table)
S = speed, W = machine with or number of rows (table), T = depth cm

The topping up the tank method of determining the quantity of fuel used was adopted for determining tractor fuel consumption. This process involved the filling of the tractor fuel tank to the brim before and after each operation test performed. The measurement of fuel consumption was taken using 1000 ml graduated cylinder to top up the fuel level in the tank after each operation test, thereby noting the

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volume of fuel consumed per time taken for the operation. The fuel consumption was determined mathematically by adopting equation (2) given as:

$$FC = \frac{V_{fc}}{T} \qquad (2)$$

Where:

FC = fuel consumption (m^3/s), V_{fc} = volume of fuel consumed, m^3, T = Time, s

Development of Model Equation

The worth of accurate prediction cannot be winded up in any field of engineering. As a result, mathematical tool employed in this work is Dimensional Analysis (Buckingham pi theorem) concerning dimensionally homogeneous equations. Dimensional analysis is a method that helps in determining functional relations providing a technique for combining various parameters that are thought to represent a system into group of dimensionless terms selected as pi terms, which reduces the number of variables in a multifaceted phenomenon to a smaller set of dimensionless ratio. This outcome is in considerable savings in both cost and labour during the experimental determination of the function (Srivastica *et al*., 2006).

Table 1: Some Variables Affecting Fuel Consumption

Variables	**Symbol**	**Unit**	**Dimensions**
Dependent Variable			
Fuel Consumption	Fc	m^3/s	$L^3 T^{-1}$
Independent Variables			
Tractor forward Speed	V	m/s	$LT^{=1}$
Harrowing depth	d	M	L
Width of cut	W	M	L
Cone index	CI	N/m^2	$ML^{-1}T^{-2}$
Bulk density	ρ_b	Kg/m^3	ML^{-3}
Draught force	D	N	MLT^{-2}
Moisture content	Mc	%	$M^0L^0T^0$

Fuel consumption, FC is a function of (d, W, V, CI, $\rho_{b,}$ D, and MC)

Mathematically;

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$$FC = f\left(d, W, V, CI, \rho_{b,} D, MC\right) \quad (3)$$

Or

$$FC = \left(d, W, V, CI, \rho_{b,} D, MC\right) \quad (4)$$

Total number of variables, n = 8, Total number of fundamental dimensions, m = 3

Therefore, number of π- terms = n – m = 5, Equation 3 can be written as:

$$f_1 = \left(\pi_{1,} \pi_2, \pi_{3,} \pi_4, \pi_5\right) \quad (5)$$

Each π- term contains (m + 1) variables, where m = 3 and is also equal to repeating variable choosing from $\rho_{b,}$ d, V as repeating variables, we get five π- terms as:

$$\pi_1 = \rho_b^{a_3}.d^{b_3}V^{c_3}.FC \quad (6)$$

$$\pi_2 = \rho_b^{a_4}.d^{b_4}V^{c_4}.W \quad (7)$$

$$\pi_3 = \rho_b^{a_5}.d^{b_5}V^{c_5}.CI \quad (8)$$

$$\pi_4 = \rho_b^{a_6}.d^{b_6}V^{c_6}.D \quad (9)$$

$$\pi_5 = MC \quad (10)$$

The model fuel consumption equation developed is represented as:

$$\therefore FC = \varphi \frac{DVdMC}{CIW} + C \quad (11)$$

Also, the equation can be written as:

$$Fc = \varphi Z + C \quad (12)$$

Where:

D = Draught force, N, W = Width of cut, m, V = Tractor forward Speed, m/s, d = Harrowing depth, m, CI = Cone index, N/m^2, MC = Moisture content,

Equation Validation

The developed equation was validated with regression curve fitting to check if the measured and predicted results have good agreement. Also, root mean square error (RMSE) was used to check the error difference as represented below:

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$$RMSE = \sqrt{\frac{\frac{1}{N}\sum_{i-1}^{i-N}\left(FC_m - FC_p\right)^2}{N}} \tag{13}$$

Where: N = number of samples, FC_m = measured fuel consumption, FC_p = predicted fuel consumption. Furthermore, the t Test was used to compare the experimental and predicted data to determine significant difference at 0.05 and 0.01 level of significance (95 and 99 % confidence) as given in equation (14).

$$t = \frac{\sum D/N}{\sqrt{\frac{\sum D^2 - \left(\frac{(\sum D)^2}{N}\right)}{(N-1)(N)}}} \tag{14}$$

Where: $\sum D$ = summation of the differences. , $\sum D^2$ = summation of the squared differences,

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

RESULTS/FINDINGS

Table 2: Soil Textural Class

Percentage (%) by Mass		
Clay	**Silt**	**Sand**
14.30	5.30	80.40

Table 3: Mean Results of Field Test Performed during Harrowing Operation

Parameter	Depth of Cut, d_1 (m)			Depth of Cut, d_2 (m)			Depth of Cut, d_3 (m)		
	V_1 (m/s)	V_2 (m/s)	V_3 (m/s)	V_1 (m/s)	V_2 (m/s)	V_3 (m/s)	V_1 (m/s)	V_2 (m/s)	V_3 (m/s)
FC (m^3/s)	2.38E-06	2.60E-06	2.77E-06	2.72E-06	3.22E-06	3.62E-06	3.45E-06	3.76E-06	4.53E-06
W (m)	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
CI (N/m^2)	2900.00	2900.00	2900.00	3000.00	3000.00	3000.00	3100.00	3100.00	3100.00
D (N)	2510.66	2577.45	2645.45	3263.86	3350.68	3439.08	4017.06	4123.92	4232.72
MC (%)	17.50	17.50	17.50	17.50	17.50	17.50	17.50	17.50	17.50

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Table 4: Field Test and Z for Harrowing Operation

Treatment	D (N)	V (m/s)	d (m)	Mc (%)	CI (N/m)	W (m)	Z = $\left(\frac{DVdMc}{CIW}\right)$
d_1V_1	2510.66	1.39	0.10	17.50	2900.00	1.15	1.82E-02
d_1V_2	2577.45	1.94	0.10	17.50	2900.00	1.15	2.62E-02
d_1V_3	2645.45	2.50	0.10	17.50	2900.00	1.15	3.47E-02
d_2V_1	3263.86	1.39	0.13	17.50	3000.00	1.15	2.99E-02
d_2V_2	3350.68	1.94	0.13	17.50	3000.00	1.15	4.29E-02
d_2V_3	3439.08	2.50	0.13	17.50	3000.00	1.15	5.67E-02
d_3V_1	4017.06	1.39	0.16	17.50	3100.00	1.15	4.39E-02
d_3V_2	4123.92	1.94	0.16	17.50	3100.00	1.15	6.80E-02
d_3V_3	4232.72	2.50	0.16	17.50	3100.00	1.15	8.31E-02

Table 5: Validation of the Model Equation for Harrowing Operation

Treatment	D (N)	V (m/s)	R (m)	Mc (%)	CI (N/m)	W (m)	FC = 3.00E-05$\left(\frac{DVdMc}{CIW}\right)$ + 2E-06
d_1V_1	2510.66	1.39	0.10	17.50	2900.00	1.15	2.55E-06
d_1V_2	2577.45	1.94	0.10	17.50	2900.00	1.15	2.79E-06
d_1V_3	2645.45	2.50	0.10	17.50	2900.00	1.15	3.04E-06
d_2V_1	3263.86	1.39	0.13	17.50	3000.00	1.15	2.90E-06
d_2V_2	3350.68	1.94	0.13	17.50	3000.00	1.15	3.29E-06
d_2V_3	3439.08	2.50	0.13	17.50	3000.00	1.15	3.70E-06
d_3V_1	4017.06	1.39	0.16	17.50	3100.00	1.15	3.32E-06
d_3V_2	4123.92	1.94	0.16	17.50	3100.00	1.15	3.88E-06
d_3V_3	4232.72	2.50	0.16	17.50	3100.00	1.15	4.49E-06

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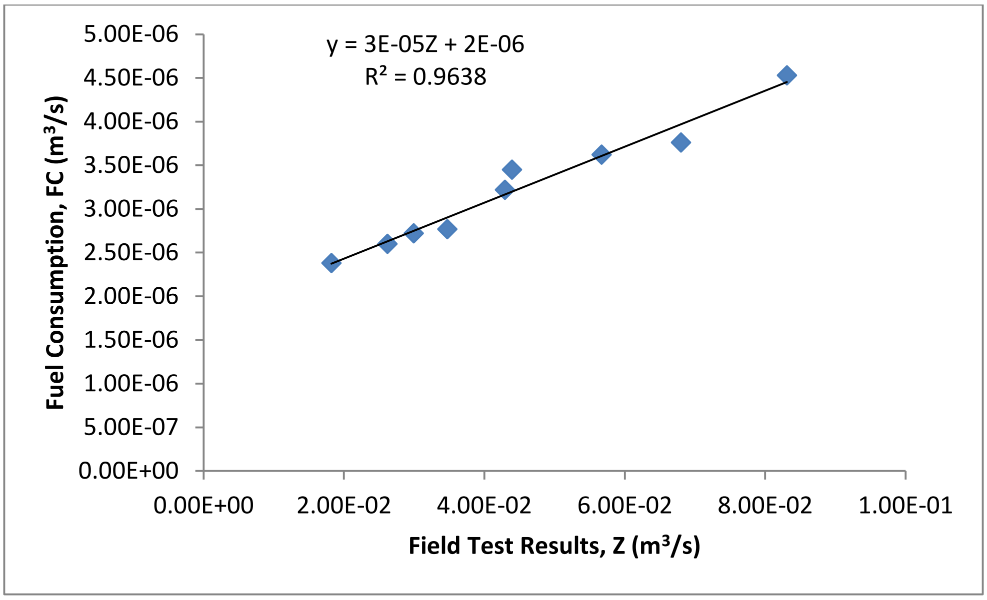

Figure 3: Fuel consumption (m^3/s) and field test results (m^3/s) relationship

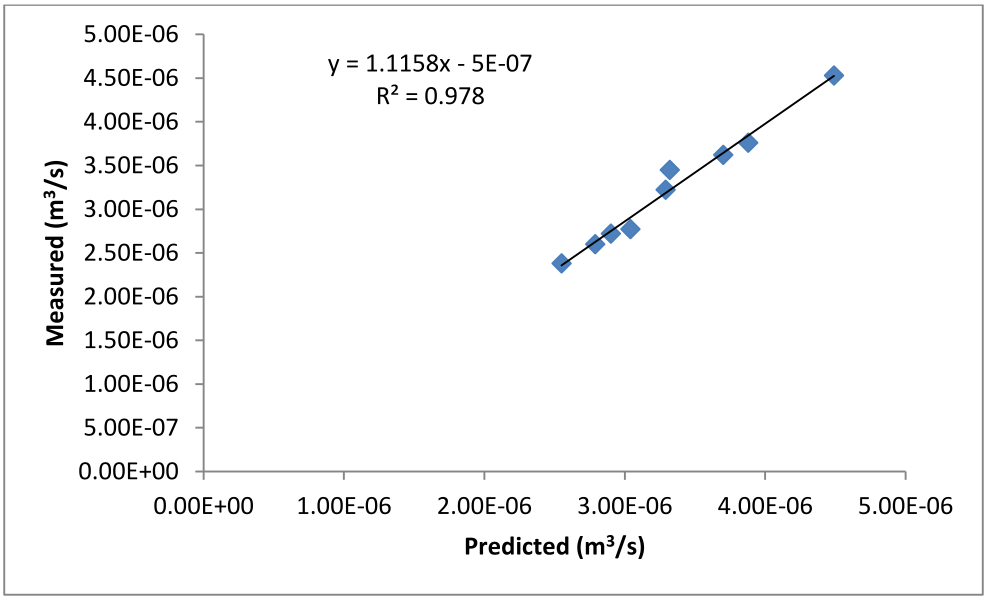

Figure 4: Measured (m^3/s) and predicted (m^3/s) relationship

The result of soil textural classification revealed that the tillage site soil was loamy sand soil (80.40 % sand, 5.30 % silt and 14.30 % clay) (Table 2). Table 3 showed field test parameters (draught (D), tractor forward speed (V), harrowing depth (d), moisture content (MC), Cone Index (CI), and width of cut (W)) that were evaluated and used as indices for assessment of the fuel consumption model equation prior and during harrowing operation. The Dimensional analysis (Buckingham pi theorem) was used to develop fuel consumption model equation to analyse the result from field test. The results of the test performed during harrowing are shown in Table 3 and mean field test results (Z) for the

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harrowing operations were presented in Table 4. From tables 3 and 4, regression graph was plotted for fuel consumption (FC, m^3/s) against mean field test results (Z, m^3/s) and the values for the constants (φ and C) were established for harrowing operation (Fig 3) and the linear regression equation was fitted into the fuel consumption equation developed. This is similar to Nkakini (2013) that used regression curve fitting to established constants in his equation of modeling of tractive force on ploughed soil and also Kumar and Pandy (2015) used multiple linear regression analysis with excel spread sheet and fitted to the model structure formulae to calculate the coefficient. The result showed acceptable agreement with coefficient of determination $R^2 = 0.9624$. Also, the established predictive fuel consumption model equation for harrowing operations at speed of 1.39, 1.94 and 2.50 m/s with depth of 0.1, 0.13 and 0.16 m respectively is:

$$FC = 3.00 \times 10^{-5} Z + 2.00 \times 10^{-6} \text{Or } FC = 3.00 \times 10^{-5}\left(\frac{DVdMc}{CIW}\right) + 2.00 \times 10^{-6} \qquad (15)$$

DISCUSSION

The mean field test was used in the equation to predict the combine effect of soil-implement parameters on tractor fuel consumption performance. For that reason, from equation (15) constants of 3.00×10^{-5} and 2.00×10^{-6} for harrowing operation were established Genuineness of a developed model equation for solving a particular problem depends on its predictions and validation. Figure 4 showed the relationship between measured and predicted fuel consumption values. The result indicated good treatment with coefficient of determinations $R^2 = 0.978$. Table 5 shows results of the developed model fuel consumption equation for harrowing operations by substituting the values of a number of experimental records which is being compared with the measured fuel consumption. The error analysis which described the differences between the measured and predicted model results ranged between -1.00E-07 to 1.00E-07 while the RMSE was 9.84E-08 that is low. Also t Test was used to determine the significance difference between the means of measured and predicted fuel consumption at 0.05 and 0.01 % significance (i.e. 95 and 99 % confidence) levels. The result of the paired t Test showed that $t_{calculated}$ (1.45) is less than t_{table} (2.306 and 3.355). This indicated that there were no significant difference between the measured and the predicted tillage operations to regulating FC output have been established.

CONCLUSION

The study had developed a model for fuel consumption equation during harrowing operation. The predictive model equaton established is:

$$FC = 3.00 \times 10^{-5}\left(\frac{DVdMc}{CIW}\right) + 2.00 \times 10^{-6} \text{ for harrowing}$$

The constants for harrowing operation were obtained as 3.00×10^{-5} and 2.00×10^{-6}. The equaton's ceofficient of determinations of $R^2 = 0.978$ was obtained. The results reviewed acceptable agreement with the measured and predicted model equaton results. This proved that the model equation can predict precisely. Furtermore, selecting the right harrowing parameters needed for harrowing operations and good soil condition will accomplish good estimation, saving fuel and reducing cost. Also the equation will be as guide to farmers, tractor users and people interested in machinery management for decision making.

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