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ORIGINAL RESEARCH ARTICLE

MODELLING OF TRACTOR FUEL CONSUMPTION FOR HARROWING OPERATION IN A SANDY LOAM SOIL

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ABSTRACT

In the study of agricultural machinery management, fuel consumption is considered as a very important factor that plays a significant role in the selection and management of tractors and equipment. In Nigeria, there are no tractor fuel consumption models developed for harrowing operation. Considering the importance of harrowing operation to tillage practice in Nigerian agriculture, it became necessary to embark on the study on the modelling of tractor fuel consumption in litres per hectare (L/ha) during harrowing operation in a sandy loam soil using available information gathered from the National Centre for Agricultural Mechanization (NCAM) Tractor Test Reports. A multiple linear regression method was used to develop the model. A 10-repeated 10-fold cross-validation method was used to validate the model. The study revealed that the model developed for harrowing operation had a R2-value of 0.477 showing tractor power rating as the only operation parameter contributing to the model developed. Cross-validation revealed that the harrowing operation model had a test error value of 0.986 L/ha. The study also identified other contributing factors to tractor fuel consumption during harrowing operation in a sandy loam soil. The model developed for tractor fuel consumption during harrowing operation in a sandy loam soil is recommended for use in budgeting for diesel consumption.

1.0 Introduction

Tillage of soil is considered to be one of the biggest farm operations (Al-Suhaibani and Ghaly, 2010). It is also a conventional farming system involving the use of the tractors which results in high energy costs. The sustainability of such a system requires a well-controlled resource management leading to a significant reduction in crop production costs derived from savings in fuel consumption (Serrano *et al.,* 2009). Agricultural machinery has become increasingly important in carrying out farm work. The application of machines to agricultural production has been one of the outstanding developments in agriculture. Machinery contributes a major capital input cost in most farm businesses.

In agriculture, the tractor remains a very important machine due to its ability to provide mechanical power to farm implements both on and off the farm. The choice of a tractor based on field performance can be very challenging due to limited information with regards to performance on the field. According to Sirelkatim, *et al.* (2001), land preparation is one of the most energy demanding operations in agriculture, it involves soil cutting, turning and pulverizing and thus demands high energy, hence there is need to optimize tractor performance

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in order to utilize the available energy. This energy utilization depends on many factors such as soil type and condition, operating depth and speed, and hitch geometry.

The use of models for budgeting of tractor fuel consumption has been of great use to farmers in developed nations. Most studies on model development for tractor fuel consumption centres mainly on ploughing operation which is the first tillage operation carried out on the soil. Harrowing operation has been considered as a very important tillage operation that needs to be carried out during land preparation in Nigerian agriculture.

Considering the importance of harrowing operation to tillage practice in Nigerian agriculture, there is a need to develop a simple model equation for predicting tractor fuel consumption in litres per hectare (L/ha) during harrowing operation. The study is aimed at developing a statistical model for predicting tractor fuel consumption during harrowing operation in a sandy loam soil.

2.0 Materials and Methods

2.1 Experimental procedure

The study involves the use of information gathered from the National Centre for Agricultural Mechanization (NCAM) Tractor Test Reports on 41 agricultural tractors compiled by Oyelade (2016) which were tested during harrowing operation on a sandy loam soil. Each tractor was tested on an area of 0.25 hectare (25 m x 100 m) in a randomized complete block design (RCBD). The implement used for the trials was tractor mounted off-set disc harrow. Parameters measured during harrowing operation include speed of operation, fuel consumption, field capacity, field efficiency, wheel slip, duration of operation, draught force, the width of cut, depth of cut, soil cone index, soil moisture content, and soil bulk density. The three soil properties, namely, soil cone index, soil moisture content and soil bulk density were all measured at depths 0 – 7 cm, 7 – 14 cm and 14 – 21 cm. The resulting average values of these three soil properties were part of the data collated. All the parameters of the tractor-implement performance were measured and recorded in line with the recommendations of RNAM test codes and procedures for farm machinery technical series (1983). Out of the 41 tractor test data, 37 tractor test data termed model development data-set was used to generate multiple regression for use in future predictions of tractor fuel consumption in litres per hectare during harrowing operation on a sandy loam soil. The remaining four tractor test data termed model validating data-set were used to validate the model developed.

2.2 Description of the Study Area

The study was carried out at the National Centre for Agricultural Mechanization (NCAM), Ilorin, Kwara State which is located at 370 m above sea level in the Southern Guinea Savanna ecological zone of Nigeria by Longitude 4º 30′ E and Latitude 8º 26′ N. The various test locations where these tractors were tested fall under the sandy loam soil textural class with the following fractions: sand - 56.79% to 69.92%, silt - 15.33% to 28.64% and clay - 6.44% to 18.33%. The soil in the various test locations of the study area were classified as Alfisols (Soil Survey Staff, 1975) under the USDA soil order.

2.3 Particle Size Analysis

Particle size analysis was carried out using the hydrometer method described by Gee and Or (2002). Sodium hexametaphosphate (calgon) was used as the dispersant. The textural class of the soil was determined using the USDA Textural Triangle.

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2.4 Test Parameters

2.4.1 Speed of Operation

The speed of operation was determined by placing two poles 20 m a part in-between the longest distance of the test plot. On the opposite side of the test plot, two poles were placed in a similar position 20 m apart. The speed of operation for each tractor evaluated during harrowing operation was mathematically expressed as:

$$V_S = 3.6\left(\frac{20}{t_1}\right) \quad (1)$$

where,

V_s = Speed of operation (km/h)

t_1 = Time taken to cover 20 m (sec)

2.4.2 Depth and Width of cut

The depth and width of cut during field operation were measured using a steel rule and measuring tape, respectively.

2.4.3 Draught of the Implement

The draught of implement was measured using the trace tractor technique described by Oyelade (2016).

2.4.4 Theoretical Field Capacity

Theoretical field capacity measured in ha/h was expressed mathematically as:

$$G = \frac{E(3600)}{T_a} \quad (2)$$

where,

G = Theoretical field capacity (ha/h),

E = Area of field (ha)

T_a = Actual time taken in doing the main tillage work (sec)

2.4.5 Effective Field Capacity

Effective field capacity measured in ha/h was expressed mathematically as:

$$X_5 = \frac{E(3600)}{T_t} \quad (3)$$

where,

X_5 = Effective field capacity (ha/h)

E = Area of field (ha)

T_t = Total time taken in completing the whole tillage operation (sec)

2.4.6 Field Efficiency

Field efficiency, according to ASAE (2000), is the ratio of effective field capacity to theoretical field capacity, expressed in percent. It was expressed mathematically as:

$$H = \frac{X_5}{G} x 100\% \quad (4)$$

where,

H = Field efficiency (%)

X_5 = Effective field capacity (ha/h)

G = Theoretical field capacity (ha/h)

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2.4.7 Fuel Consumption

The fuel required for each tillage operation was determined by filling the tank to full capacity before and after the test. Amount of refueling after each test is the fuel consumption for the test. The filling of fuel tank before the operation and then refilling after completing the operation in determining the amount of fuel consumed during operation is a common method used in the field for determining tractor fuel consumption in litres per hectare. This same method was as reported by (Ajav and Adewoyin, 2011; Ikpo and Ifem, 2005; Kudabo and Gbadamosi, 2012; Meshack-Hart, 1997; Sirelkatim *et al.,* 2001; Udo and Akubuo, 2004) in determining tractor fuel consumption in litres per hectare.

Fuel consumption measured in either L/ha or L/h was expressed mathematically as:

$$I = \frac{J}{E} \quad (5)$$

$$K = X_5 \, x \, I \quad (6)$$

where,

I = Fuel consumption (L/ha)
J = Volume of fuel consumed (L)
E = Area of field (ha)
K = Fuel consumption (L/h)
X_5 = Effective field capacity (ha/h)

2.4.8 Travel Reduction (Wheel slip)

In determining the wheel slip (travel reduction), a mark was made on the tractor drive wheel with coloured tapes. This was used to measure the distance covered by the tractor drive wheel at every 10 revolutions under no load and the same revolution with a load on the same surface. The travel reduction (wheel slip) measured in % was expressed mathematically as:

$$L = \frac{M_2 - M_1}{M_2} \times 100\% \quad (7)$$

where,

L = Travel reduction (wheel slip) (%)
M_2 = Distance covered at every 10 revs of the wheel at no-load condition (m)
M_1 = Distance covered at every 10 revs of the wheel at load condition (m)

2.4.9 Tractive Efficiency

Tractive efficiency measured in % is the ratio of drawbar power to wheel power and was expressed mathematically according to (Macmillan, 2002) as:

$$Q_t = \frac{D_p}{Q_w} \times 100\% \quad (8)$$

where,

Qt = Tractive efficiency (%)
Dp = Drawbar power (kW)
Qw = Wheel power (kW), power losses in the transmission from engine to the wheels of, say 10% is assumed, it can be written as:

$$Q_t = \frac{D_p}{0.9 \times Q_e} \times 100\% \quad (9)$$

where, Q_e = Engine power (kW)

2.4.10 Duration of Operation

The duration of operation measured in h/ha which is the time spent in completing the whole operation was mathematically expressed as:

$$X_9 = \frac{1}{X_5} \tag{10}$$

where,

X_9 = Duration of operation (h/ha)

X_5 = Effective field capacity (ha/h)

2.5 Soil Parameters

2.5.1 Soil Bulk Density

Soil bulk density (ρ_b) is a measure of the mass of soil per unit volume and is usually reported on an oven-dry basis. The soil bulk density was determined by the core method described by Anwanane (2014). The core samples were oven dried at a temperature of 1050C to a constant weight.

$$\rho_b = \frac{M_s}{V_T} \tag{11}$$

where,

ρ_b = Soil bulk density (g/cm3)

M_s = Mass of dry soil (g)

V_T = Total volume of soil (cm3)

2.5.2 Soil Moisture

Klenin *et al.* (1985) defined soil moisture content as the amount of liquid, usually water that is present in the soil. It is expressed as a percentage of the mass of water in the soil to the mass of the dried soil (for dry weight classification). The soil moisture content (in dry basis) measured in %, can be expressed mathematically as:

$$M_c = \frac{W_w}{W_s} \times 100\% \tag{12}$$

where,

M_c = Soil moisture content (%)

W_s = Mass of oven dried soil (g)

W_w = Mass of water present in soil (g)

2.5.3 Soil Cone Index

The soil cone index (CI) is the soil resistance to penetration and was measured using a cone penetrometer.

2.6 Statistical Tool

2.6.1 Regression Analysis

Multiple linear regression method which is a form of regression analysis was used for establishing the relationship that existed between fuel consumption (the model response variable) and other factors (or predictors of fuel consumption) identified to be factors influencing tractor fuel consumption in litres per hectare during harrowing operation. Multiple regression is when there is one dependent variable but more than one independent variables. In this study, tractor fuel consumption in litres per hectare was the dependent variable while other factors identified as factors influencing tractor fuel consumption in litres per hectare stands as the independent variables.

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In developing this model, the following hypotheses were drawn:
Test of Hypothesis about Full Regression Model of Harrowing Operation
Hypothesis 1: [Test of significance about all regression parameters]
Null hypothesis (H_0): The model does not fits the data/ The model is not adequate
Alternative hypothesis(H_0):The model fits the data/ The model is adequate
Mathematically,
Null hypothesis (H_0): $\beta_j = 0$ [None of the predictors contributes significantly to the model]
Alternative hypothesis (H_0): $:\beta_j = 0$ for at least one j [At least one of the predictors contributes significantly to the model]

Tests statistic: $F_{ratio} = \frac{MS_{Regression}}{MS_{Error}}$ [Global F-test]

Decision rule: Reject thenull hypothesis in favour of the alternative hypothesis at 0.05 significance level if $P - value < 0.05$, otherwise do not reject the null hypothesis.
Hypothesis 2: [Test of significance about individual regression coefficient]
Null hypothesis (H_0): $\beta_j = 0$ [Predictor x_j is not statistically significant in the model given that others are included in the model]
Alternative hypothesis (H_0): : $\beta_j \neq 0$ [Predictor x_j is statistically significant in the model given that others are included in the model]
Tests statistic: $t_{value} = \frac{\beta_j}{\sqrt{C_{jj}\sigma^2}}$ [Individual t-test]
$C_{jj} =$ diagonal element of the covariance matrix corresponding to β_j
$\sigma^2 =$ variance of β_j
This same tests statistic was also used by James *et al.* (2013)
Decision rule: Reject the null hypothesis in favour of the alternative hypothesis at 0.05 significance level if $P - value < 0.05$, otherwise do not reject the null hypothesis.

2.7 Developing models without an intercept term

Models with intercept term are common to all models built round multiple linear regression models. In this study, the assumption was whether a tractor could consume some amount of fuel before commencement of harrowing operation if such variable as air (ambient) temperature could constitute measurable parameters. The study was therefore governed by building models without intercept term because it is the most appropriate model type that fits this study based on the cylinder method of measuring fuel consumption.

2.8 Model Validation

The model validation method adopted for this study is the cross validation method. This validation method is an extremely flexible and powerful technique and widely used approach in validation work for estimating prediction error. The measure of error for cross-validation is the mean square error (MSE) for a quantitative response. The 10-fold cross-validation is commonly used. According to Bouckaert (2003), 10-fold cross-validation remains the most widely used validation procedure.

3.0 Results and Discussion

3.1 Model Development and Validation

One model with p-value < 0.05 was statistically developed for harrowing operation on a sandy loam soil. Details of the pair-wise correlation analysis showing the result of the correlation strength of the developed model for harrowing operation is presented in Table 1. Results obtained for parameter estimates and Analysis of Variance (ANOVA) for the model developed for harrowing operation are presented in Tables 2 and 3, respectively.

Table 1. Pair-wise Correlation result of Fuel Predictive Values of Model 2 with Observed Fuel Values during Harrowing Operation

Model developed	Observed
Model 2 of Harrowing operation	0.690468*

* = significant at 5% level when r-value ≥ 0.338788

Table 2. Table of Parameter Estimates for Model 2 of Harrowing Operation

P-value of Model	Model Multiple R-square value	Model Adjusted R-square value	Coefficients	Estimates	Std. Error	t value	P-value
1.519e-07	0.4767	0.1778	Tractor power rating	0.055996	0.059842	0.936	0.3601
			Width of cut	-0.050569	0.029628	-1.707	0.102
			Depth of cut	0.059737	0.062936	0.949	0.3533
			Draught force	-0.698953	0.954827	-0.732	0.4722
			Effective field capacity	10.673913	8.512772	1.254	0.2237
			Tractive efficiency	0.250983	0.190038	1.321	0.2008
			Field efficiency	-0.031328	0.059421	-0.527	0.6036
			Wheel slip	-0.060759	0.054501	-1.115	0.2775
			Duration of operation	5.464993	3.336067	1.638	0.1163
			Speed of operation	-1.523374	0.598055	-2.547	0.0188 *
			Average soil moisture content	-0.085734	0.115415	-0.743	0.4658
			Average soil bulk density	2.768087	2.346524	1.180	0.2513
			Average soil cone index	0.003298	0.028825	0.114	0.9100

*significant at 5% level

Table 3. ANOVA Table for Model 2 of Harrowing Operation

Source of Variation	Degree of Freedom	Sum of Squares	Means Squares	F-value	P-value
Tractor power rating	1	234.430	234.430	151.6806	4.503e-11 *
Width of cut	1	6.257	6.257	4.0487	0.05721
Depth of cut	1	3.660	3.660	2.3684	0.13875
Draught force	1	4.110	4.110	2.6594	0.11785
Effective field capacity	1	3.300	3.300	2.1349	0.15879
Tractive efficiency	1	11.101	11.101	7.1828	0.01401 *
Field efficiency	1	4.096	4.096	2.6499	0.11847
Wheel slip	1	1.576	1.576	1.0200	0.32401
Duration of operation	1	0.086	0.086	0.0556	0.81594
Speed of operation	1	11.162	11.162	7.2223	0.01379 *
Average soil moisture content	1	0.750	0.750	0.4851	0.49378
Average soil bulk density	1	2.365	2.365	1.5301	0.22975
Average soil cone index	1	0.020	0.020	0.0131	0.90999
Residuals	21	32.457	1.546		

*significant at 5% level

Model 2 of harrowing operation with p-value < 0.05 recorded a R-squared value of 0.4767. The model explains 48% of the proportion of variance in the mean squared errors of tractor fuel consumption for harrowing operation with only speed of operation showing statistical significance with a p-value of 0.0188 in the model. In terms of marginal (individual) significance of the predictor variables, results in Table 4 reveal that we reject the null hypothesis about only tractor power rating, tractive efficiency and speed of operation with corresponding p-values of 4.503e-11, 0.01401 and 0.01379, respectively. This means that each of these variables is statistically significant in the model provided others are included in the model. It also implies that they cannot be removed from the model.

The equation used for expressing Model 2 of harrowing operation as contained in Table 2 was given as:

The equation used for expressing Model 2 of harrowing operation as contained in Table 2 was given as:

$$\widehat{Y} = 0.055996X_1 - 0.050569\,X_2 + 0.059737X_3 - 0.698953X_4 + 10.673913X_5 + 0.250983X_6 - 0.031328X_7 - 0.060759X_8 + 5.464993X_9 - 1.523374X_{10} - 0.085734X_{11} + 2.768087X_{12} + 0.003298X_{13} \quad (13)$$

where,

$\widehat{Y}$ = Tractor fuel consumption (L/ha),
X_1 = Tractor power rating (hp),
X_2 = Width of cut (cm),
X_3 = Depth of cut (cm),
X_4 = Draught force (kN),
X_5 = Effective field capacity (ha/h),
X_6 = Tractive efficiency (%),
X_7 = Field efficiency (%),
X_8 = Wheel slip (%),
X_9 = Duration of operation (h/ha),
X_{10} = Speed of operation (km/h),
X_{11} = Average soil moisture content (%),
X_{12} = Average soil bulk density (g/cm^3) and
X_{13} = Average soil cone index (N/cm^2).

The model equation generated for Model 2 of harrowing operation was used for predicting tractor fuel consumption using the 37 model development dataset. Results obtained from the fuel prediction values of Model 2 of harrowing operation is presented in Table 4. The values for both observed and predicted tractor fuel consumption of Model 2 of harrowing operation as shown in Table 4 were correlated together and gave a correlation coefficient of 0.690468 as shown in Table 1. According to the rule of thumb as provided in http://www.westgard.com/lesson42.html for evaluating correlation coefficient, noted that size of r with correlation values between 0.50 and 0.69 are said to be moderate. It indicates that tractor fuel consumption predictions of Model 2 of harrowing operation is moderately correlated with the observed tractor fuel consumption values obtained during harrowing operation on a sandy loam soil. Figure 1 shows the graph plot of observed and predicted tractor fuel consumption using Model 2 of harrowing operation.

Table 4. Results of Predicted Tractor Fuel Consumption values during Harrowing Operation on a Sandy Loam Soil using Model 2 of Harrowing Operation

Tractor Observations	Observed fuel values (L/ha)	Predicted fuel values (L/ha)	Residuals (L/ha)
1	3.28	2.711058	0.568942
2	4.12	3.783405	0.336595
3	5.47	4.624426	0.845574
4	1.44	1.972107	-0.53211
5	4.76	3.74173	1.01827
6	5.26	3.453034	1.806966
7	3.2	3.192731	0.007269
8	0.9	2.68324	-1.78324
9	3.8	2.452152	1.347848
10	3.53	4.300108	-0.77011
11	3	2.040149	0.959851
12	0.85	1.749665	-0.89966
13	3.92	3.35114	0.56886
14	0.92	1.557942	-0.63794
15	2.32	2.938795	-0.6188
16	2.24	1.525242	0.714758
17	1.84	2.549917	-0.70992
18	0.8	1.956347	-1.15635
20	1.68	2.904075	-1.22407
21	1.04	1.58534	-0.54534
22	0.9	1.847902	-0.9479
24	3.4	2.173657	1.226343
25	3	2.561103	0.438897
26	4	3.364288	0.635712
27	1.6	3.417445	-1.81745
28	1.9	2.857485	-0.95749
29	2.8	3.153878	-0.35388
30	2.1	1.820463	0.279537
32	2.88	1.907434	0.972566
33	2	2.748966	-0.74897
34	4.53	5.363732	-0.83373
35	4	2.156639	1.843361
36	1.2	1.338286	-0.13829
37	4.13	3.083001	1.046999

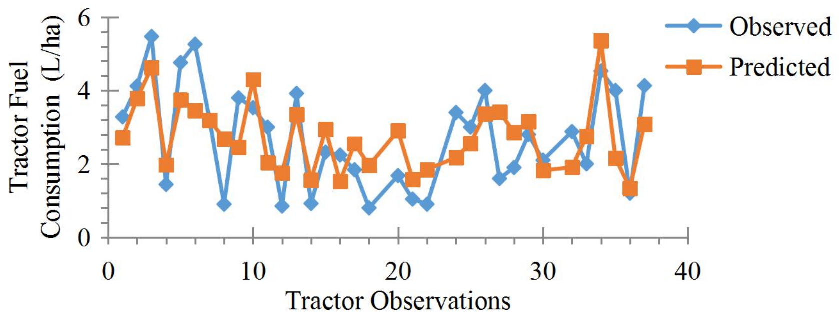

Figure 1. The plot of Observed and Predicted Tractor Fuel Consumption using Model 2 of Harrowing Operation

3.2 Model Predictors for Harrowing Operation

The results of the parameter estimates and Analysis of Variance (ANOVA) for the only model developed for harrowing operation on a sandy loam soil as shown in Tables 2 and 3, respectively, have revealed that the only developed model for harrowing operation contains some important predictors found to be significant at 5% level. These predictors include tractor power rating, tractive efficiency and speed of operation. These three set of predictors are harrowing operation parameters affecting tractor fuel consumption in litres per hectare during harrowing operation on a sandy loam soil. Among these three factors affecting tractor fuel consumption during harrowing operation on a sandy loam soil, only tractor power rating contributed highly to the model developed. Therefore, tractor power rating, strongly determine tractor fuel consumption in litres per hectare during harrowing operation on a sandy loam soil.

3.3 Model Validation for Harrowing Operation Model

Result of 10-repeated 10-fold cross-validation method as presented in Table 5 was used for validating the model developed for harrowing operation on a sandy loam soil. It can be deduced from Table 5, that Model 2 of harrowing operation recorded a root mean square error of 0.98643 L/ha serving as the model's test error value using the four model validating datasets presented in Table 6.

Table 5. Results of 10-repeated 10-fold Cross-validation for Model 2 of Harrowing Operation

Replicate No.	MSE Value
1.	0.967218
2.	1.023916
3.	0.967739
4.	0.967430
5.	0.967155
6.	0.967337
7.	0.967429
8.	0.967726
9.	0.967282
10.	0.967218
Average MSE (L2ha-2)	0.973045
Average RMSE (Lha-1)	0.98643

Key:
MSE – Mean Square Error
RMSE – Root Mean Square Error
Note that each replicate contains the average mean square error value of 10-fold cross-validation

Table 6. Results of Fuel Predictive and Residual values of Model 2 of Harrowing Operation used for Model Validation data

Observed fuel values (L/ha)	Predicted Fuel values (L/ha)	Residual (L/ha)
4.00	3.384845	0.61516
1.60	3.1639	-1.5639
2.60	1.671801	0.9282
1.42	0.802705	0.6173

4.0 Conclusion

A study was carried out to develop a model for future prediction of tractor fuel consumption during harrowing operation in a sandy loam soil using information gathered from NCAM Tractor Test Reports. From the outcome of this study, it can be concluded that:

One effective model with p-value < 0.05 was developed for harrowing operation. Model 2 of harrowing operation developed for future prediction of tractor fuel consumption in litres per hectare during harrowing operation on a sandy loam soil recorded a coefficient of multiple determination (R-squared) value of 0.4767.

Harrowing operation parameters such as tractor power rating, the speed of operation and tractive efficiency were found to be statistically significant at 5% level in Model 2 of harrowing operation with only tractor power rating contributing highly to the model developed.

The model for harrowing operation based on cross-validation result had a test error of 0.98643 L/ha.

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