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Development of a Predictive Model for Tractive Force During Ploughing on a Loamy Sand Soil Using Curve Fitting Technique

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ABSTRACT

A model was developed for the prediction of tractive forces on wheel tractors during ploughing on tilled loamy sand soils of the rainforest zone of Nigeria. The area of study covered, was 90 m by 90 m, which was sub-divided into three blocks of 90m by 27m and a further nine (9) strips of 90m by 2m with alleys of 3m. Randomized soil samples were collected using soil auger. A field moisture content of 25% was determined gravimetrically; and tyre parameters obtained through measurements and from tyre data books. The mobility number connected together with the measured tractor wheel variables of tyre width, diameter, and section height, tyre weight and deflection formed dimensionless term. The plots were ploughed, using trace tractor techniques pattern in randomized three replications at tractor forward speed of 2.5 m/s. The experimental tractive force was measured using EDjunior dynamometer. The cone index (CI) of the ploughed soils was determined with a soil cone penetrometer and used to calculate the mobility number that was correlated with the measured (experimental) tractive forces to obtain the predictive equations. The model developed was validated with graphical comparison between the measured and predicted model tractive force values, and showed a corresponding coefficient of determination of R^2=0.837. There were no significant differences between the measured and predicted values of the tractive forces at (p>0.05). It was further observed that the tractive force decreased as the soil moisture content increased. The model developed indicated good agreement between the measured and predicted results and would, therefore, be useful for predicting tractive forces during ploughing operations.

KEYWORDS: Predictive model, Tractive force, ploughing, tilled loamy sand soils, Rainforest zone.

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1.0 INTRODUCTION:

The wealth of nations is usually measured by their abilities to feed their populations and the enhancement of agricultural productivity plays a vital role. Thus, this is achievable through mechanizing agricultural actives tending to improving tillage and planting operations.

Onwualu *et al.* (2006) defined tillage as soil disturbance operation meant to provide conducive environment for crop growth. Aluko and Lasis (2009) defined soil tillage as the mechanical manipulation of the soil to develop desirable soil structure for establishing a specific surface configuration for planting and sufficient harvesting operations. Ploughing activity is initial tillage operation employed for breaking, loosening and turning soil slices, using such tillage implement as disc plough in rainforest zone of Nigeria (Jakasania *et al.*, 2017). It loosens the soil for its enablement to crops easy penetration into the soil. It brings nutrients to the surface thereby improving the fertility of the soil. Ploughing operation is deeper, more aggressive and leaves a rougher surface relative to secondary tillage operation (Kareem & Sven, 2019; Saeed *at al.*, 2017). In agricultural production, especially in tillage operations, the concern for efficiency in tractive force is very necessary for proper grip into the soil.

Traction is the driving force developed by a wheel track or other traction devices. Traction can be said to be the ability of drive wheel tyres to transmit the driving force without slipping (Ghosal & Das, 2008). A wheel generates

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tractive force by reacting (pushing) against the soil. With advancement in improved agricultural production, the use of tractor in tillage becomes unavoidable; hence farm tractors are essential machinery in mechanized agricultural activities (Darshana *et al.*, 2018). Soil condition is a major factor that affects the performance of field machineries, thus the main criteria for tractability are to establish a specific maximum level or range of soil moisture which must be measured or assumed (Oduma *et al.*, 2018).
When the drive wheel rolls over an agricultural soil, the tractive ability is affected by the vertical soil reaction against the traction wheels. Weight transfer has its effect on soil reaction reduction from the drawbar pull force against the front wheel of the tractor. At any point of adding reaction to tractor rear wheel, there is the tendency of increase in the rear wheel traction ability since the strength of the soil is adequate enough and does not limit traction due soil sinkage.

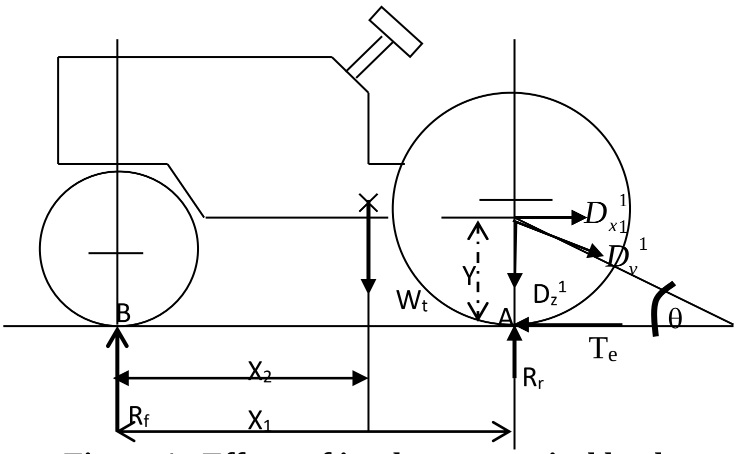

Figure 1. Effects of implement vertical load on tractor rear wheels and tractive ability.

2.0 MATERIALS AND METHODS:

2.1 Description of the Study Area

The experiment was conducted at the National Root Crops Research Institute (NRCRI) Experimental Farm, Umudike, Umuahia, Abia State of Nigeria. Umuahia is approximately 64 km south-east of Owerri, and 128km west of Port Harcourt capital of Rivers State of Nigeria. Annual rainfall in the research area is between 2500 mm and 3000 mm per year. This research was conducted on loamy sand soil of the rainforest zone of Nigeria. The soil is considered favourable for plant growth because it holds more available water than sand and is better aerated and easier to work than clay (Baver *et al.*, 1972).

2.2 Materials Used for the Study

The materials used are: Two tractors of the same model (Massey Ferguson MF5 435), weights 5710 to 6327kgs, and horse power of 72hp (53.7kw), PTO, 62.5hp (46.6kw), front and the rear tyres of 12.4 -24ply and 18.4-30ply, length, 162.6inches (413cm), height, (ROPS) 101.6inches (258cm). A 1180mm wide mounted-type with disc diameter of 660mm of disc plough with three-disc bottom mounted on a gauge wheel. Cone penetrometer, Dynamometer, measuring tape, Disc ploughs, Auger, Stop watch, Instrument for measuring wheel loads of tractor (static hydraulic press). To ensure the accuracy of the measurements, the instruments were calibrated prior to the field tests.

Plate 1: Depicted a trace-tractor technique, with implement mounted position during tillage operations.

Other materials used are standard calibrated weights (blocks) Avery - 50 kg, 100 kg, 1000 kg (1 ton), Fork lift machine (Iron Ropes) sling and scales.

2.3 Experimental Field Design

In investigating interactions between different variables' factors, Randomized Complete Block Design with three replications of two-way factorial treatments was used. The textural

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classification of the top soil layer was determined using mechanical sieve analysis method. Soil samples of the field were taken at random on the field at the depths of 0-50mm, 50-150mm and 150-200mm using soil auger at three replications per sample point. The land area is about 90 m by 90 m divided into three blocks of 90 m by 27 m each. The individual blocks were further subdivided into 3 strips of 90 m by 2 m with alleys of 3m between each strip. The field experiments were conducted twenty-four (24) hrs, after each day of rainfall events. Then soil samples were collected immediately followed by tillage operations with three replications. Hence, the total treatments were 3 x 20 days of replications. The sequences of ploughing operations were: First day rainfall event (Day 1), strip 1 of block 1, strip 1 of block 2, and strip 1 of block 3. Second day rainfall event (Day 2), strip 2 of block 1, strip 2 of block 2 and strip 2 of block 3. Third day rainfall event (Day 3), strip 3 of block 1, strip 3 of block 2 and strip 3 of block 3. The same experimental procedures were repeated. Tractor forward speed of 2.5 m/s was maintained throughout the investigation. .During the field test, the following parameters were measured: tractive force, drawbar pull (net pull force), rolling (motion) resistance (towed forced), cone index (soil strength), soil particle sizes, soil moisture, soil bulk density and wheel slippage (slip). The tyre diameter, tyre width, wheel load, tyre section width, overall unloaded diameter, tyre section height, loaded tyre deflection and rolling radius, which are compounded variables in mobility number which were measured and also obtained from tyre data book.

2.4 Determination of Tractive Force

The Dillon EDjunior dynamometer was employed for recording of the towing force. A trace-tractor technique was used in determining towing force and drawbar-pull (net pull force).These two tractors joined together, Figure 3a, one carrying the implement in its neutral gear position (engine disengaged) was joined to another tractor, which towed it through the dynamometer between two of the tractors. The dynamometer reading was used to determine the towing force.

The auxiliary tractor (tagged 1) pulled the 3 bottoms disc plough- mounted tractor (tagged 2), but in transportation position for Figure 3a, and in ploughed operational position for Figure 3b. The mean drawbar-pull is the differences between the towing forces on unploughed and ploughed operations.

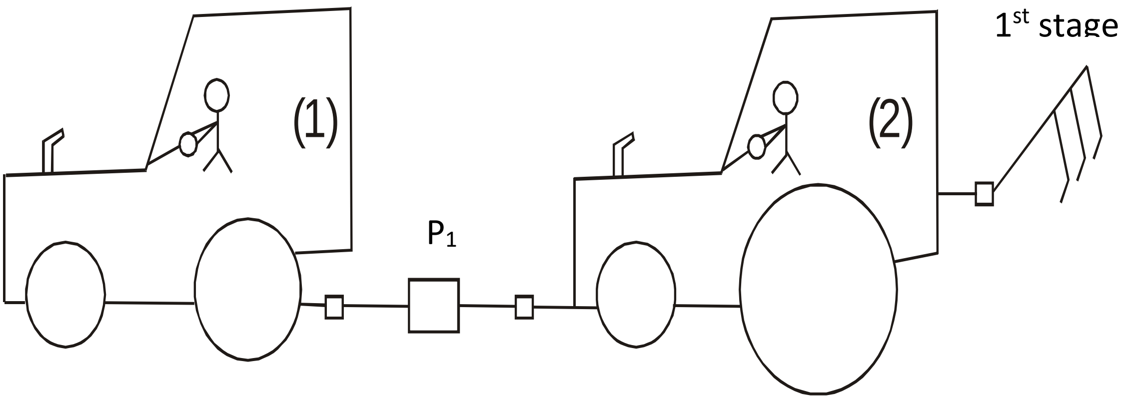

Figure 3a: Tractors-dynamometer, Implement mounted Position during Transportation

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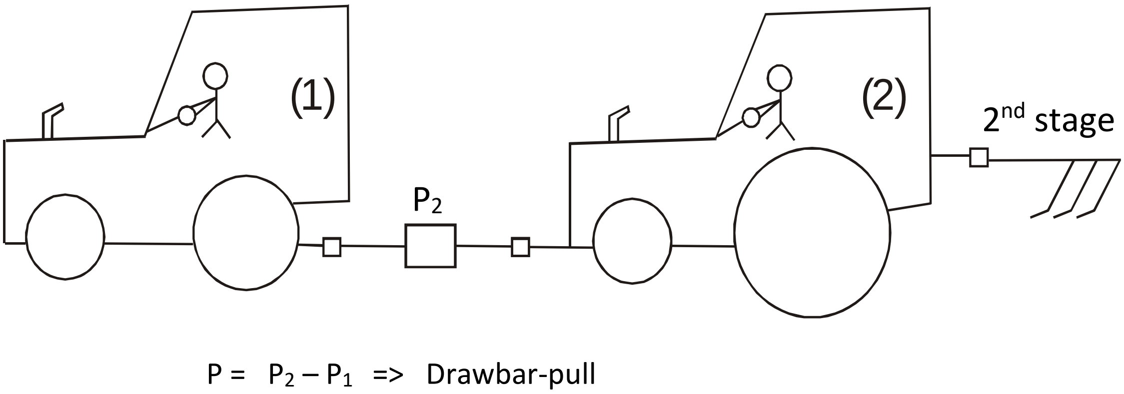

Figure 3b: Tractors-dynamometer, Implement arrangement during Ploughed Operation.

2.5 Determination of Cone Index

Agricultural cone penetrometer having an enclosed angle of 30°, with a base area of 3.23 cm^2 (323 mm^2), marked with depths and mounted on a shaft of 0.203 cm (20.27 mm), was used to determine the cone index. Soil resistance (cone index) to penetration of implements was taken at three different depths 0-100 mm, 100-150 mm, 150- 200 mm respectively, before ploughing operation

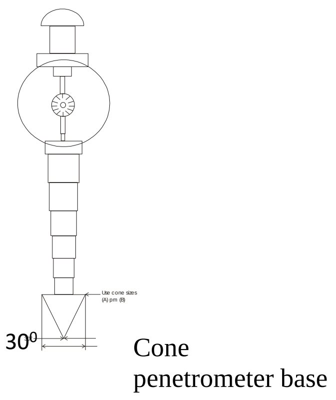

Figure 4: S313.2 Standard for Agriculture (ASAE 2001)

2.6 Measurement of Tyre width, Diameter, Section height and Deflection

The tyre dimensions shown in Figure 5 were obtained from tyre data books and by measuring the tyre. b -the section width (m) is the first number in a tyre size designation (i.e., nominally 18.4 inches) for an 18.4-30 tyre., d - the overall unloaded diameter(m), δ– the loaded tyre deflection(m) h-the section height (m). The rim diameter was estimated by adding 0.05m to the nominal rim diameter, which is the second number in a tyre size designation (i.e., 30 inches for 18.4-30 tyre), r–rolling radius on hard surface (m)

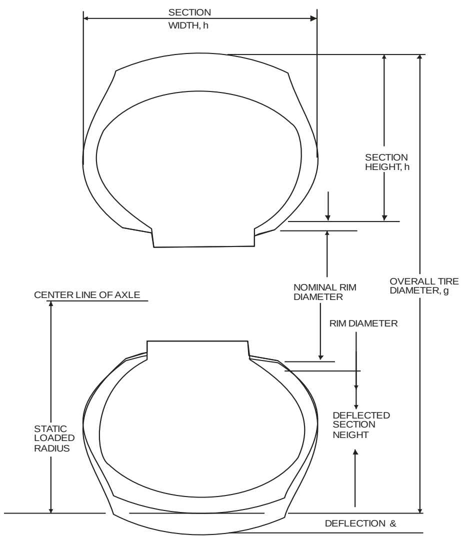

Figure 5. Description of Tyre Parameters (Zoz & Grisso, 2003).

2.7 Measurement of Tyre Weight

The tractor wheel load was measured using a static hydraulic press. The tractor, with a 3-bottoms disc plough onto it, was driven into the weighing platform, positioned with its rear wheels

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and weighed. This is the static tyre load. The dynamic tyre load was measured as the tractor was put in motion with and without the 3 bottoms disc plough mounted on the tractor and the weight taken and recorded.

2.8 Soil Moisture Content Determination

The soil moisture content on each strip was determined gravimetrically. Soil samples were collected randomly at depths of 0-50 mm, 50-150 mm and 150-200 mm, using soil auger at three replications per sample point and the moisture levels including soil moisture content were determined before any ploughing operation. The ploughing operations' days were spaced apart based on the intervals of the rainfall and sunshine intensity. The sunshine intensity was obtained from the agro meteorological station at Umudike Research Center. Soil moisture was replenished only through rainfall since the experiment was in-situ.

2.9 Determination of Wheel Slip

Wheel slippage (slip) is considered for traction modelling. Slip is very important in determining forward speed. The distances covered by tractor when on load and not on load were measured using measuring tape, while the time taken to cover the distance was recorded using a stop watch. The wheel slip was determined from the relationship:

$$S = 1 - \frac{V}{Vo} \tag{1}$$

Where: V = velocity of the vehicle system when implement is disengaged (no load) corresponding to theoretical speed (actual velocity).Vo = initial velocity (speed of tractor) when implement is engaged into the soil (under load) corresponding to actual speed(theoretical velocity).S=wheel slippage

3.0 DEVELOPMENT OF THE PREDICTIVE MODEL

In evaluating the traction requirements of a driven wheel tractor, the soil-wheel interactions were considered. In order to model it, the configurations of the contact surface were determined. Prediction of the configuration of the contact surface was based on modelling the inter related wheel and soil deformations under different operational conditions (Osetinsky & Shmulevich, 2004). Hence, the mathematical tools employed in this work are the dimensional analysis and curve fitting technique. Dimensional analysis was employed by Brixius (1987), and proposed a dimensionless mobility number, which was an expansion of wheel numeric (Cn), but included additional tyre parameters. Equation 2 is Brixius's mobility number (Bn), which were more widely accepted, included tyre deflection and the width - to - diameter ratio.

$$Bn = \frac{CI\,bd}{W}\left(\frac{1+5\,{}^{\delta}\!/_{h}}{1+3\,{}^{b}\!/_{d}}\right), \tag{2}$$

$$Cn = \left(\frac{CIbd}{W}\right), \tag{3}$$

$\left(\frac{\delta}{h}\right)$ = the deflection ratio, $\left(\frac{b}{d}\right)$ = the width-to-diameter ratio. Where: h = tyre section height, m, δ= tyre deflection, m, d = overall unloaded diameter, m, W = wheel- load, kN, CI = cone index, kN/m^2 (kpa), b = section width, m. Mobility number is used in dimensional analysis to effectively reduce the number of variables in the empirical predictive equation of the performance of wheels on different surfaces. The mobility number is used in the equation to predict the combined effect of the soil-wheel parameters on tractive force. Table 1, indicates the summary of mean values of machine parameters, such as tyre section height, tyre deflection, overall unloaded diameter, wheel load, cone index, section width and mobility number, which are used as substituting values of tractive force development for ploughed soil.

3.1 Tractive Force on Ploughed Soil.

Tractive force equation was developed for ploughed soil, using curve fitting procedures to analyse results from field tests. From the data in Table 1, the regression curve for tractive force (TF, kN) vs Bn with respect to ploughed soil operation was plotted in Figure 6 and equation

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was developed with the constants established for the soil type of the rainforest zone of Nigeria.

Therefore, the established predictive equation for ploughed soil at tractor forward speed of 2.5 m/s is:

$$TF = 13.99 + 0.06 \times \frac{CIbd}{W}\left[\frac{1+5\left(\frac{\delta}{h}\right)}{1+3\left(\frac{b}{d}\right)}\right] \quad (4)$$

3.2 Predictive Model Equation Validation

The validation of the equation for tractive force generated during ploughing operation at tractor forward speed of 2.5 m/s was done by substituting values of predictor variables into the model, applying t-test statistical analysis and graphically comparing the experimental and predicted results. The comparison was to establish if there were significance differences at 1% and 5% levels of significance between them. Accordingly,

t-test, $$t = \frac{\bar{x} - \mu}{\sigma_{\bar{x}}} \quad (5)$$

$$\sigma_{\bar{X}} = \frac{\sigma}{\sqrt{n}} \quad (6)$$

then , $t = \dfrac{\bar{x} - \mu}{\dfrac{\sigma}{\sqrt{n}}}$

$\sigma_{\bar{x}} =$ standard error of the mean $\bar{x} =$ arithmetic means, $\mu =$ population mean $\sigma =$ standard deviations, $n =$ number of data.

Validation increases credibility of the developed model for solving a particular problem. Figure 7 shows the graphical comparison between the measured and predicted values of the tractive force

Table 1 Mean Value of Machine, Soil Parameters, Mobility numbers and Tractive Force for Ploughing Operation at 2.5 m/s Forward Speed

CI KN/m^2	W KN	b m	d m	h m	Δ M	$Bn = \frac{CI\,bd}{W}\left(\frac{1+5\delta/h}{1+3b/d}\right)$,	Tractive Force ,KN
984.6	28.9296	0.468	1.56	0.406	0.075	25.15702	15.662
1846.2	28.9296	0.468	1.56	0.406	0.075	47.17134	15.459
1077.8	28.9296	0.468	1.56	0.406	0.075	27.53833	15.805
840.9	28.9296	0.468	1.56	0.406	0.075	21.48542	15.725
1164.0	28.9296	0.468	1.56	0.406	0.075	29.74078	15.836
564	28.9296	0.468	1.56	0.406	0.075	14.41048	15.028
1430.6	28.9296	0.468	1.56	0.406	0.075	36.55255	16.030
1492.2	28.9296	0.468	1.56	0.406	0.075	38.12646	16.085
897.3	28.9296	0.468	1.56	0.406	0.075	22.92646	15.283
969.1	28.9296	0.468	1.56	0.406	0.075	24.76099	15.357
1256.3	28.9296	0.468	1.56	0.406	0.075	32.09909	15.877
1317.8	28.9296	0.468	1.56	0.406	0.075	33.67045	15.980
1338.3	28.9296	0.468	1.56	0.406	0.075	34.19424	15.970
1635.7	28.9296	0.468	1.56	0.406	0.075	41.79295	16.158
1907.7	28.9296	0.468	1.56	0.406	0.075	48.74269	17.728
1969.2	28.9296	0.468	1.56	0.406	0.075	50.31405	17.678
1907.7	28.9296	0.468	1.56	0.406	0.075	48.74269	17.667

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CI KN/m^2	W KN	b m	d m	h m	Δ M	$Bn = \frac{CI\,bd}{W}\left(\frac{1+5\delta/h}{1+3b/d}\right),$	Tractive Force ,KN
1846.7	28.9296	0.468	1.56	0.406	0.075	47.18411	16.143
1943.9	28.9296	0.468	1.56	0.406	0.075	49.66762	17.675
1610.2	28.9296	0.468	1.56	0.406	0.075	41.14142	16.060

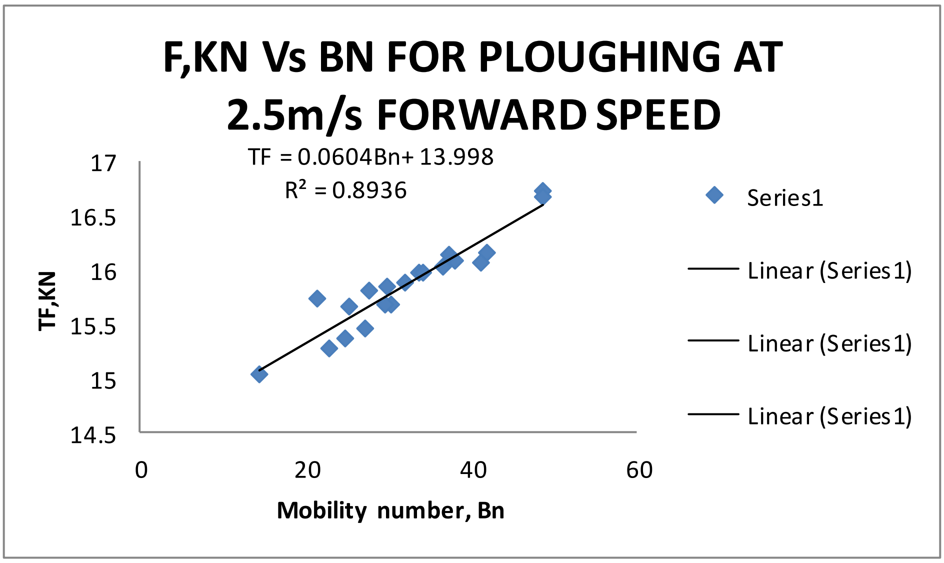

Figure 6. Tractive force and mobility number relation

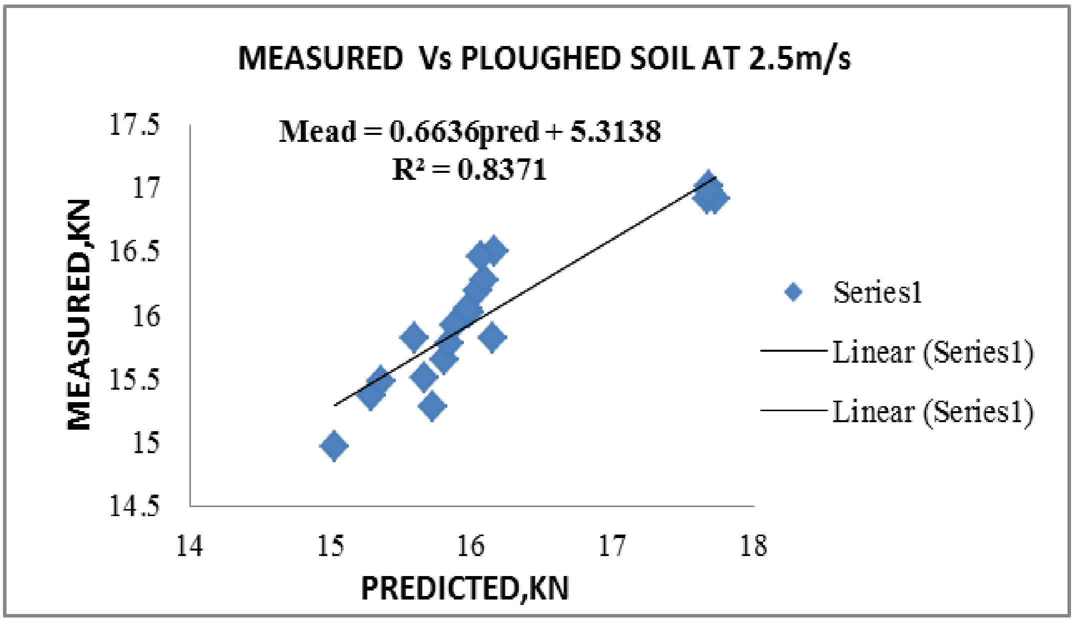

Figure7. A plot of agreement between measured and predicted tractive force, KN of ploughed soil at forward speed of 2.5m/s.

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4.0 RESULTS AND DISCUSSION

4.1 Tractive Force

The established predictive equation for ploughed soil at tractor forward speed of 2.5 m/s as earlier detailed is:

$$TF = 13.99 + 0.06 \times \frac{CIbd}{W}\left[\frac{1+5\left(\frac{\delta}{h}\right)}{1+3\left(\frac{b}{d}\right)}\right]$$

Thus, from the developed equation, the constants 13.99 and 0.06 for ploughed soil in rainforest zone of Nigeria were established. As the mobility number increases the tractive force performance improves.

The validated result showed acceptable agreement with coefficient of determination $R^2 = 0.837$.

Table 2 shows results of the developed model for ploughed soil. In this is shown the summary of the measured and predicted tractive forces as well as their percentage errors. The residuals analysis, which depicted the differences between measured and predicted results ranged between -0.03929 and 0.813769, and percentage (%) errors from -0.18916 to 4.590215 which are negligible values

Table 2. Measured and Predicted Tractive Force, residuals and Percentage error values for Ploughed Soil at 2.5 m/s Tractor Forward Speeds.`

Measured	Predicted	Residual	% error
15.662	15.499	0.162239	1.035898
15.495	16.820	-1.32528	-8.55295
15.805	15.642	0.1627	1.029422
15.725	15.279	0.445875	2.835453
15.836	15.775	0.061213	0.386552
15.028	14.855	0.173701	1.155824
16.030	16.183	-0.15315	-0.95541
16.085	16.278	-0.19259	-1.19731
15.283	15.366	-0.08226	-0.53822
15.357	15.476	-0.119	-0.7749
15.877	15.916	-0.03929	-0.24744
15.980	16.010	-0.03023	-0.18916
15.970	16.042	-0.07165	-0.44868
16.158	16.498	-0.33925	-2.09952
17.728	16.915	0.813769	4.590215
17.678	17.009	0.669487	3.78705
17.667	16.915	0.752099	4.257163
16.143	16.821	-0.67772	-4.19812
17.675	16.970	0.704943	3.988361
16.060	16.458	-0.39849	-2.48123

Table 3. t-test result for Ploughed Soil at Forward Speed of 2.5 m/s.

	Measured	Predicted
Mean	16.17564	16.16211
Variance	0.700766	0.437538
Observations	20	20

	Measured	Predicted
Hypothesized Mean Difference	0	
df	36	
t stat	0.056168	
P(T<=t) one -tail	0.477759	
t Critical one-tail	1.688298	
P(T<=t) two-tail	0.955519	
t Critical two-tail	2.028094	

Statistical analysis of t-test was used to determine the significant differences between the means of predicted and measured tractive forces at 0.05 levels of significance. Table 3 shows the t-test computations. The t critical values of 1.688298 and 2.028094 are greater than t stat of 0.056168 ($t_{tab} > t_{cal}$) at both one and two tails tests. This indicates that there is no significant difference between measured and predicted tractive forces of ploughed soil at tractor forward speed of 2.5m/s, at p>0.05.

5.0 CONCLUSION

This study has developed predictive model for ploughed soils in rainforest zone of Nigeria. The established predictive equation,

$$TF = 13.99 + 0.06 \times \frac{CIbd}{W}\left[\frac{1+5\left(\frac{\delta}{h}\right)}{1+3\left(\frac{b}{d}\right)}\right],$$

has the constants 13.99 and 0.06 for ploughing operation. The model having coefficient of determination R^2 = 0.837 was validated for this tillage operation. The measured and predicted tractive forces, residual analysis value of -0.03929, percentage (%) error of -0.18916 and t-test results are negligible and showed no significant differences at ($P \geq 0.05$). The developed predictive model for ploughing operation in tilled loamy sand soil of the rainforest zone showed good agreement between the measured and predicted model result.

This study has established tractive force equation and constants for wheel tractors, with particular emphasis on ploughed operation in loamy sand soil of the rainforest zone of Nigeria for ploughing operation.

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