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Modeling Tractive Force Requirements of Wheel tractors For Disc Ploughing in Sandy Loam Soil

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ABSTRACT

Tractive force models at different tillage speeds were developed using dimensional analysis, describing the tractor tyre - soil interaction. In this research study, disc ploughing on an experimental plot at twenty different soil moisture levels in loamy sand soil was carried out using trace tractor techniques. The independent variables: drawbar pull force, rolling (motion) resistance, wheel slip, moisture content, cone index, wheel numeric, contact pressure, speed, width of plough, depth of plough, and dependent variable (Tractive force) were measured and compared to computed values. High coefficients of determination R^2 = 0.9492, 0.9555 and 0.9447 for ploughing at tillage speeds of 1.94m/s, 2.22m/s and 2.5m/s were obtained respectively. Standard errors of 0.3672552, 0.8628 and 0.8047 and the percentage (%) errors of -2.272608059 and 2.45655144,-2.304946155 and 2.523126085,-1.424947801 and 2.020155232 at minimum and maximum values, were obtained. These results are clear evidence of the test of goodness of fit of the models between predictive and measured parameters for ploughing at different tillage speeds. The models were verified and validated by comparing the predicted with the measured tractive forces, and shown to closely followed the experimental results.

Keywords: *Tractive, force, disc, ploughing, loamy, sand, soil*

1. INTRODUCTION

Tractive force is derived from contact between the tyre and medium such as soil. The power transmitted requires large frictional force at the soil tyre interface to convert the rotary motion of the tractor crankshaft, into forward motion. Until recently, one of the challenges in design of agricultural field tractor, had been to equip it with a tractive device that can develop effective traction with minimum soil damage. Agricultural tillage involves soil cutting, soil turning and soil pulverization, which require high tractive force to pull the tool through the soil during tillage operations. According to Onwualu et al., (2006), tillage is soil manipulation in order to provide conditions necessary for crop growth. Energy requirements for tillage, varies with draught force, wheel slip, depth and width of cut and soil moisture that must be considered in a true representation of the activities. Energy efficiency is now important consideration in agricultural production in quest for cleaner environment. Optimizing the performance of agricultural tractors could, therefore help to minimize energy waste (Sefa and Kazim, 2004). Energy loss by the pneumatic tyre is therefore of concern to search for improved traction efficiency (Wong, 1993). These positive effects can only be realized through the use of appropriate models that include all important compounding variables.

The objective of this study is to develop mathematical model for predicting the tractive force requirement of disc ploughing using dimensional analysis and to validate the model.

2. MATERALS AND METHODS

2.1 Description

All experiments were conducted in the field (in-situ), using trace tractor technique. It was conducted at National Root Crops Research Institute (NRCRI) experimental farm, in Umudike, Umuahia, Abia State of Nigeria. Umudike is under the derived tropical humid ecological zone of Nigeria, and is 122m above sea level and lies on latitude 05^0 29^1N and longitude 07^0 33^1E. Soil particle size distribution analysis showed the soil to be loamy sand (clay-11.04%, silt-4% and sand-84.96%)

2.2 Experimental Procedure

The instruments and implements used in measuring the tractive forces and other parameters are two tractors of the Massey Ferguson 435 model and 72 horse power, cone penetrometer, dynamometer, measuring tape, disc ploughs, auger, stop watch and instrument for measuring weight of tractor (static hydraulic press). All field tests were conducted in loamy sand soil for which the physical properties were determined. Before the field experiment started, experimental layout area of 90m by 90m was designed with three different blocks of 90m by 27m each. Each of it was divided into 9 strips of 90m by 2m wide with a space of 3m between each strip. Ploughing operation was carried out on each of the blocks. Each day of the experiment were three replications of ploughing operations. This continued until the last day of minimal moisture levels. Hence, the total treatments were 9 x 20 days of the operations. Day 1, the tillage operations started with ploughing on Block 1, Strip 1; Block 2, Strip 1 and Blocks 3, Strip 1. Day 2, ploughing on Block 1, Strip 2; Block 2 Strip 2,and Block 3 Strip 2. Day 3: Ploughing on Block 1 Strip 3; Block 2 Strip 3and Block 3, Strip 3. It followed the same pattern for the remaining days up to the last day when minimum moisture content was achieved. The soil data were collected to the depths of 50mm, 150mm and 200mm respectively using soil auger, core sampler and a hand- operated soil cone penetrometer having an enclosed angle of 30^0, with a base area of ($323mm^2$) mounted on a shaft of 2.03mm for the determination of moisture content, bulk density and soil resistance before tillage operation. In the sampling process, cone penetrometer was positioned between the operator's two legs and with his two hands on the handle pushed into the soil until the marked point on the shaft was reached, before readings were taken. The bulk density was measured using core sampler. Soil moisture content was determined using gravimetric method (oven dry method). The towing force and drawbar-pull forces were determined using trace- tractor technique. Two 72-horse power (hp) tractors were used. The tractor carrying the implement with its engine disengaged (neutral gear) was coupled to another tractor which towed it via the dynamometer between two of them. The first tractor pulled the second tractor coupled to the implement (3 bottoms disc plough).The dynamometer reading was taken to determine the towing force. The drawbar-pull force was the difference between the towing force in neutral gear without implements in tillage operation and towing force when the implement was in tillage operations. Ploughing depths and widths were measured with rule (steel tape).The speeds of operations were obtained by setting the tractor at a suitable gears of a gear reduction unit for targeted speed of 1.94m/s, 2.22m/s and 2.5m/s. Simultaneously, the time taken to cover a fixed distance of 90m was recorded using a stopwatch to calculate the operating speed of the tractor and implement combination. Plate 1, shows the tractors –dynamometer-tractor-implement in action.

Plate 1. A photograph depicting tractor-dynamometer, implement mounted position during disc ploughing operations

3. THEORY

In evaluating the traction requirements of a wheel-tractor, the soil-wheel interaction was considered, using dimensional analysis to develop the predictive equation. Based on the Buckingham Pi Theorem (Murph, 1950, Langhaar, 1951, Kasprazak et al., 1990), the number of dimensionless and independent quantities (Pi terms) required to fully express the relationship between the variables were determined as follows:

$$S = n - b \tag{1}$$

where, S is the number of Pi terms; n is the total number of variables; and b is the number of basic dimensions. Basic dimensions are mass (M), length (L) and time (T) The pertinent variables that affect the traction performance of the wheel tractor in loamy sand soil during tillage are eleven variables, (Table 1) with their corresponding dimensions. Wheel slip(s), moisture content (μ), and wheel numeric (Cn) are dimensionless parameters.

Thus, the dependent variable tractive force (F), may be expressed as a function of the independent variables.

$$F = f\left(F_p,\ F_R, CI,\ Pc,\ V,\ a, b\right) \tag{2}$$

where, f is functional notation for tractive force

This equation may be re-written as

$$f\left(F\ , F_p\ \ F_R, CI,\ Pc,\ V,\ a, b\right) = 0 \tag{3}$$

Therefore, the number of variables are, n = 8, but since the basic dimensions are MLT, = 3. Then, number of dimensionless π - terms,

$$S = n - b, \qquad S = 8 - 3 = 5$$

Hence, five ρ_i - terms say, π_1, π_2, π_3, π_4 and π_5 were generated.

Thus,

$$F = f(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5) \tag{4}$$

∴ The equation (4) may be written as

$$f_1(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5) = 0 \tag{5}$$

where, f_1 is functional notation for π-terms

Table 1: Variables affecting Traction Requirement

Variables	Symbol	Unit	Derivation	Dimension
Dependent variable				
Traction force	F	N	Mass x Acceleration Mass x $\frac{m}{s^2}$	MLT^{-2}
Independent variables				
Drawbar pull	F_p	N	Mass x Acceleration Mass x $\frac{m}{s^2}$	MLT^{-2}
Rolling resistance	F_R	N	Mass x Acceleration Mass x $\frac{m}{s^2}$	MLT^{-2}
Wheel slip	S	%	(No derivation)	$M^0L^0T^0$
Moisture content	μ	%	(No derivation)	$M^0L^0T^0$
Cone index	C1	N/m^2	$\frac{stress}{strain} => \frac{Force}{Area/Number} = \frac{MLT^{-2}}{L^2/1}$	$ML^{-1}T^{-2}$
Wheel numeric	C_n	-	$\left(\frac{CIbd}{W}\right)$	$M^0L^0T^0$
Contact pressure	Pc	Kpa	$kN/m^2 = \frac{Force}{Area} = \frac{MLT^{-2}}{L^2}$	$ML^{-1}T^{-2}$
Speed	V	m/s	$\frac{Length}{Time} = \frac{L}{T}$	LT^{-1}
Width of plough	a	m	-	1. L
Depth of plough	b	m	-	**L**

From equation (5) above, five π-terms (π_1, π_2, π_3, π_4 and π_5) are required to develop a general prediction equation for tractive force of wheel tractor tillage operation (ploughing) on loamy sand soil.

In the dimensionless terms determination exercise, the three dimensionless terms; wheel slip,(s), moisture content,(μ), and wheel numeric, (Cn) are excluded, but has to be added when the other dimensionless terms had been formed. Also, the chosen repeating variables: cone index (CI),tractor speed (V) and width of plough(a) should not form dimensionless term (Barenblat,1987).

The repeating variables are:

$$CI = ML^{-1}T^{2}\ ,\quad V = LT^{-1},\quad a = L$$

When π-terms are formed based on the principle of dimensional homogeneity, the dimensionless π-terms obtained are:

$$\pi_1 = \frac{F}{CIa^2},\quad \pi_2 = \frac{F_p}{CIa^2},\quad \pi_3 = \frac{F_R}{CIa^2},\quad \pi_4 = \frac{P_c}{CI},\quad \pi_5 = \frac{b}{a}$$

and already determined dimensionless π-terms are :

$$\pi_6 = \mu,\quad \pi_7 = S,\quad \pi_8 = Cn$$

A new set of Pi terms are generated by multiplying and/ or dividing present Pi terms with each other. In addition, present Pi terms can be reversed to make new Pi terms, while maintaining independency condition. Some new Pi terms groups were obtained after transformations:

$$\pi_1^1 = \frac{\pi_1}{\pi_2} = \frac{F_p}{CIa^2}\ x\ \frac{CIa^2}{F_p} = \frac{F}{F_p} \tag{6}$$

$$\pi_2^1 = \pi_3\ x\ \pi_4 = \frac{F_R}{CIa^2}\ x\ \frac{Pc}{CI} = \frac{F_R P_c}{CI^2 a^2} \tag{7}$$

$$\pi_2^{11} = \pi_2^1\ x\ \pi_5 = \frac{F_R P_c}{CI^2 a^2}\ x\ \frac{b}{a} = \frac{F_R P_c b}{CI^2 a^3} \tag{8}$$

$$\pi_2 = \pi_2^{11}\ x\ \pi_7\ x\ \pi_8 = \frac{F_R P_c\, b\, C_n S}{CI^2 a^3} \tag{9}$$

$$\pi_3 = \mu s \quad (10)$$

Hence, some existing π -terms were eliminated, and dimensionless Pi terms obtained are as follows:

$$\pi_1 = \frac{F}{F_p}, \quad \pi_2 = \frac{F_R\, P_c\, b\, C_n S}{CI^2 a^3}, \quad \pi_3 = \mu s$$

The tractive force, required is contained only in π_1 – term. Thus, π_1 is related to the other two π- terms as follows:

$$\pi_1 = \theta(\pi_2, \pi_3) \quad (11)$$

Thus, $$\frac{F}{Fp} = \theta\left(\frac{F_R P_C bCnS}{CI^2 a^3}, \mu s\right) \quad (12)$$

for ploughing at tillage speeds of 1.94m/s,2.22m/s and 2.5m/s.

Substituting the dimensionless parameters (Pi terms) gives:

π_1 = constant π_2 ± constant$_3$ π_3 ±constant$_4$ ± constant (C)

$$\frac{F}{F_P} = C_2 \frac{F_R P_C bCnS}{CI^2 a^3} \pm C_3\ \mu S \pm C_4 \quad (13)$$

for ploughing.

Least-square method was used to determine the constants of the polynomials.

$$Y = a + bx + cx^2 + dx^3 \quad (14)$$

Thus, the least-square formulation for the polynomials:

$$\begin{bmatrix} n & \sum x_i & \sum x_i^2 & \sum x_i^3 \\ \sum x_i & \sum x_i^2 & \sum x_i^3 & \sum x_i^4 \\ \sum x_i^2 & \sum x_i^3 & \sum x_i^4 & \sum x_i^5 \\ \sum x_i^3 & \sum x_i^4 & \sum x_i^5 & \sum x_i^6 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \begin{bmatrix} \sum yi \\ \sum x_i y_i \\ \sum x_i^2 y_i \\ \sum x_i^{\backslash 3} y_i \end{bmatrix}$$

The constants a, b, c, and d are determined using the EView software (statistical package). The input variables (independent variables) are π_2 and π_3 and contain drawbar-pull, constant pressure, depth of plough, wheel numeric, wheel slip, cone index, width of plough, moisture content and rolling resistance.

Estimation Equation:

F_N_ = C(1) + C(2)*FP_2 + C(3)*FP_3 + C(4)*FP

The developed models for ploughing with different tillage speeds after substituted coefficients are:

$$F = 4489.72 + 0.001457 F_p \frac{F_R\, P_c\, b\, C_n S}{CI^2 a^3} + 3.145 Fp\mu s + 2.334 F_p, \text{ for ploughing at 1.94m/s} \quad (15a)$$

$$F = 3322.1 + 2.309 F_p \frac{F_R\, P_c\, b\, C_n S}{CI^2 a^3} + 0.000543 F_p \mu s + 1.15259 F_p \quad \text{for ploughing at 2.22 m/s} \quad (15b)$$

$$F = 1151.419 + 2.433855 F_p + 0.000297 F_p \frac{F_R\, P_c\, b\, C_n S}{CI^2 a^3} + 0.8405 F_p \quad \text{for ploughing at 2.5 m/s} \quad (15c)$$

4. RESULTS AND DISCUSSION

The values of constants a, b, c and d coefficients required to determine the predicted equations of 15a, 15b and 15c is shown in Table 2.

The measured and predicted tractive forces for ploughing at different tillage speeds are shown (Appendices A1-3).The highest tractive force values obtained are 15603.3N, 16628.3N and 17728.3N with corresponding predictive force values of 15469.7N, 16530.8N and 17632.9N respectively. Their corresponding residuals analyses of 133.595N, 97.5332N, and 95.4467N, percentage (%) error values of 0.856197087, 0.586549437 and 0.538386083 were obtained respectively. Obtained also were the lowest tractive force values of 12,908.3N, 13928.3N and 15028.3N with corresponding predictive force values 12904.7N, 13992.7N and 15165.4N. Their corresponding residuals analyses of 3.65818N, -64.368N and -137.094N, percentage (%) error values of 0.02833975,-0.462138237 and -0.912238909 depicted. The residual analysis which depicted the differences between measured experimental results and predicted models and ranged from between -310.211N and 321.85N, -339.673N and 363.204N, -293.605N and

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315.761N, percentage (%) errors from -2.272608059 and 2.45655144, -2.304946155 and 2.523126085, -1.853953159 and 2.037825105 for ploughing at tillage speeds of 1.94m/s, 2.22m/s and 2.5m/s, showed no significance differences between measured and predicted results. The compared residual analyses and percentage (%) errors of the tractive forces at minimum and maximum values at both cases were close to negligible values.

Analysis of variances (ANOVA) were therefore conducted to show significant differences between the predicted and measured tractive force values for ploughing operations at different tillage speeds, 1.94m/s, 2.22m/s and 2.5m/s (Appendices B1-3)

Analysis of variance between measured and predicted tractive forces showed that there are no significant differences ($p \geq 0.05$) between the measured and predicted dependent variables (tractive forces). The correlation coefficients R^2 = 0.9492, 0.8999, 0.9447 for ploughing at 1.94m/s,2.22m/s and 2.5m/s are clear evidences of high degrees of correlation between measured and predicted results. These analyses revealed standard errors of 0.3672552, 0.8628 and 0.8047 respectively. The values obtained are negligible and agree with the fact that the smaller the standard error values between measured and predicted results the better the models. The high correlations and no significance difference between measured and predicted data obtained, indicated that the developed models are good. These agree with the findings of Alder and Roessler, (1977) which states that the smaller the root mean square error (RMSE) values between measured and predicted results, the better the models. The predicted and measured values of tractive force for ploughing at 1.94m/s,2.22m/s and 2.5m/s tillage speeds were compared(Figures 1,2 and3).There are positives linear relationships between the predicted and measured values of tractive force respectively. A good agreement between measured and predicted values of tractive force were found with the coefficient of determinations R^2= 0.959, 0.955 and 0.959 for disc ploughing.

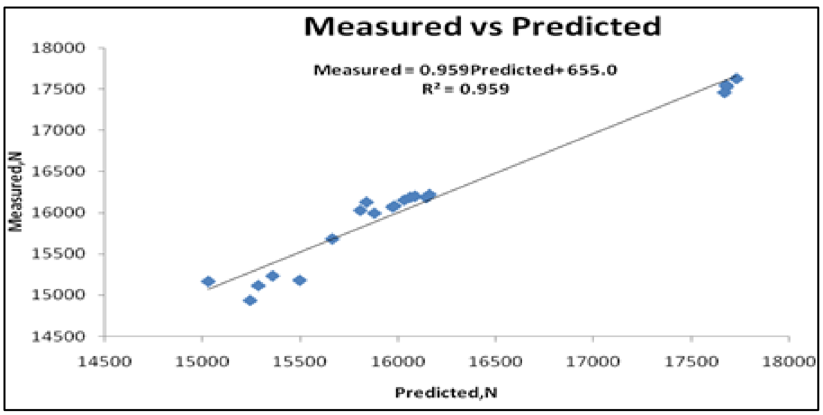

Figure 1: A plot of relationship between Measured and Predicted Tractive Force, at tillage speed of 1.94m/s, ploughing operation

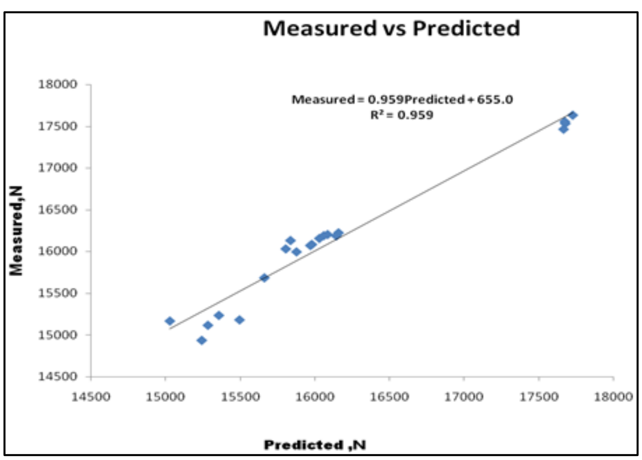

Figure 3: A plot of relationship between Measured and Predicted Tractive Force, at tillage speed of 2.5m/s, ploughing operation.

5. CONCLUSION

This study was conducted to investigate the tractive force effectiveness of wheel tractor on agricultural soil during disc ploughing operation. The tractive force predictive equations were developed using dimensional analysis in reference soil condition. The developed model equations were verified and validated. These equations produced sufficiently accurate results for predicting the tractive force requirements of disc ploughing in loamy sand soil at the reference tillage speeds.

The analysis of variance for measured and predicted tractive forces revealed standard error values of 0.3672552, 0.8628 and 0.8047 respectively. These are negligible and agree with the fact that the smaller the standard error values between measured and predicted results the better the models. Comparing the measured and predicted tractive force results, residual analysis and percentage (%) errors for the tillage operations at various tillage speeds showed no significant difference ($P \geq 0.05$). The residuals analysis and the percentage (%) errors of tractive forces at minimum and maximum values were -0.202069751 and 2.45655144, -0.42551309 and 2.523126085, -0.137191365 and 2.037825105 which in both cases were ineligible values.

In conclusion, tractive force models developed showed good agreement between the predicted and experimental results, and may be used to predict tractive force requirements for ploughing at the reference speeds and soil condition, with reasonable accuracy.

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Table 2: Results of Least Square method on coefficients of multivariable regression equations for ploughing at different tillage speeds

Variables	Ploughing at 1.94m/s				Ploughing at 2.22m/s				Ploughing at 2.5m/s			
	Coefficient	Std. Errors	t-statistic	Prob.	Coefficient	Std. Errors	t-statistic	Prob.	Coefficient	Std. Errors	t-statistic	Prob.
C_1	4489.715	1446.749	3.103313	0.0068	3322.100	1620.130	2.050514	0.0571	1151.419	1698.534	0.677890	0.5075
C_2	0.001457	0.001358	1.073212	0.2991	2.309034	0.289724	7.969763	0.0000	2.433855	0.257868	9.438371	0.0000
C_3	3.145007	3.799150	0.827819	0.4199	0.000543	0.000315	1.726404	0.1035	0.000297	0.000293	1.014968	0.3252
C_4	2.334356	0.3160007	7.387050	0.0000	1.152594	2.759663	0.417657	0.6817	0.840530	0.711583	1.181212	0.2548
R^2	0.949056				0.955526				0.959391			

APPENDIX A1: Verification of Measured and Predicted Tractive Force for Ploughing at 1.94m/s Speed

Measured	Predicted	Residual	% error
13505	13627.7	-122.747	-0.908900407
13331.7	13068.6	263.032	1.97298169
13650	13960.2	-310.211	-2.272608059
13101.7	12779.8	321.85	2.45655144
13696.7	14004.5	-307.803	-2.247278542
12908.3	12904.7	3.65818	0.02833975
13910	14070.1	-160.086	-1.150869878
13950	14117.8	-167.758	-1.202566308
13153.3	12914.8	238.48	1.813081128
13226.7	13085.5	141.157	1.067212532
13761.7	13886.1	-124.46	-0.904394079
13855.3	13980.5	-125.191	-0.90356037
13845	13967.3	-122.298	-0.883336945
14033.3	14113	-79.685	-0.567827952
15603.3	15469.7	133.595	0.856197087
15553.3	15372.3	181.052	1.164074505
15516.7	15306.8	209.858	1.352465408
14050	14078.4	-28.3908	-0.202069751
15600	15393.7	206.33	1.322628205
13930	14080.4	-150.381	-1.079547739

APPENDIX A2: Verification of measured and predicted tractive force for ploughing at 2.22m/s speed

Measured	Predicted	Residual	% error
4561.8	14628.7	-66.9895	-0.460035847
14395	14031.8	363.204	2.523126085
14705	14964.4	-259.448	-1.764352261
14141.7	13842.6	299.034	2.114554827
14736.7	15076.3	-339.673	-2.304946155
13928.3	13992.7	-64.368	-0.462138237
14930	15042.6	-112.584	-0.754079035
14985	15110.7	-125.671	-0.838645312
14183.3	14053.2	130.106	.917318255
14266.7	14151.6	115.013	0.806164004
14776.7	14839.5	-62.8768	-0.425513139
14880	14973	-92.9648	-0.624763441
14870	14958	-88.0268	-0.59197579
15058.3	15160.8	-102.456	-0.680395529
16628.3	16530.8	97.5332	0.586549437
16578.3	16430.2	148.167	0.893740613
16566.7	16368	198.638	1.19901972
15043.3	15123.6	-80.2286	-0.533317823
16625	16450.4	174.623	1.05036391
14960	15091	-131.033	-0.875889037

APPENDIX A3: Verification of measured and predicted tractive force for polughing at 2.50m/s speed

Measured	Predicted	Residual	% error
15661.7	15683.1	-21.4865	-0.137191365
15495	15179.2	315.761	2.037825105
15805	16030.2	-225.213	-1.424947801
15241.7	14933.8	307.906	2.020155232
15836.7	16130.3	-293.605	-1.853953159
15028.3	15165.4	-137.094	-0.912238909
16030	16155.6	-125.61	-0.783593263
16085	16202.4	-117.398	-0.729860118
15283.3	15114.5	168.811	1.104545484
15356.7	15232.9	123.782	0.80604557
15876.7	15994.3	-117.594	-0.74067029
15980	16083.9	-103.93	-0.650375469
15970	16071.1	-101.148	-0.633362555
16158.3	16222.5	-64.154	-0.397034341
17728.3	17632.9	95.4467	0.538386083
17678.3	17532.6	145.769	0.824564579
17666.7	17464.6	202.081	1.143852559
16143.3	16186	-42.6488	-0.264188859
17675	17555.7	119.341	0.675196605
16060	16189	-129.017	-0.803343711

APPENDIX B1 Analysis of variance between measured and predicted tractive force values at ploughing speed of 1.94m/s

Source	df	SS	MS	F	Significance F
Regression	1	12631725	12631725	1.85E-05	1.6859 NS
Residual	18	675704.1	39747.3		
Total	19	13307429			

NS: No significant different (P≥0.05)

Regression Statistics: Multiple R 0.974281038, R Square 0.94922354, Adjusted R Square 0.94623669, Standard Error 0.3672552, Observations 20

APPENDIX B2: Analysis of variance between measured and predicted tractive force values at ploughing speed of 2.22m/s

Source	df	SS	MS	F	Significance F
Regression	1	12875782	12875782	0.00189	1.0243 NS
Residual	18	599052.9	33280.71		
Total	19	13474835			

NS: No significant different (P≥0.05)

Regression Statistics: Multiple R 0.948654, R Square 0.899944, Adjusted R Square 0.894386, Standard Error 0.8628, Observations 20

APPENDIX B3: Analysis of variance between measured and predicted tractive force values at ploughing speed of 2.5m/s

Source	df	SS	MS	F	Significance F
Regression	1	13315772	13315772	0.0929	2.0243 NS
Residual	18	779104.6	43283.59		
Total	19	14094877			

NS: No significant different (P≥0.05)

Regression Statistics: Multiple R 0.971969, R Square 0.944724, Adjusted R Square 0.941653, Standard Error 0.80471, Observations 20.