Performance evaluation of disc ridging tractive force model in loamy sand soil using sensitivity measured parameters

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Abstract: Disc ridging operations in a loamy sand soil, at tillage speeds of 1.94 m/s, 2.22 m/s and 2.5 m/s, using trace tractor techniques, were conducted. The dependent and independent variables involved in the models were measured. The sensitivity of measured parameters was used for evaluating performance of developed models which described the tractors tyre-soil- interactions parameters. Results showed performance of the wheel-tractors tractive force models having sensitivity coefficients ranging from -0.00164 to 0.2505, -0.00698 to 0.0979 and -0.00258 to 0.2595 for Disc ridging, with all the independent variables at 1.94 m/s, 2.22 m/s and 2.50 m/s tillage speeds respectively. The lowest sensitivity coefficient of -0.00698 to 0.0979 was obtained at speed of 2.22 m/s. This indicates that tillage speed of 2.22 m/s is the best for disc ridging operation. Results showed that performance efficiencies increase with decreasing sensitivity coefficient values.

Keywords: modelling, tractive force, disc ridging, performance, tillage, loamy, sand, soil, sensitivity measurement, soil moisture

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1 Introduction

Tractive force in tillage operations has been a long term problem in farming activities, and has remained a ridiculous and messy operation till now. Traction is required to pull the tillage tool through the soil during tillage operations.

Researchers have reported that animals in the form of oxen provided the traction necessary to pull implements, preparing the soil for the seeding of crops. However, this source for traction has gradually phased out with the introduction of mechanical powered tractors.

Tillage is the mechanical manipulation of the soil, usually in agricultural activities to changing of soil conditions for crop production (ASAE standards, 2002). It is achieved when the tillage machinery applies enough power to overcome the soil strength, which leads to soil failure (Onwualu et al., 2006). Kayombo et al., (2002), Aluko and Lasis (2009) defined soil tillage as the mechanical manipulation of the soil to develop desirable soil structure to establish a specific surface configuration for crop planting. A good tillage operation should provide a suitable soil pulverization. Ridging is a tillage operation intended for heaping up of tilled soil from two sides to form long stripes of mounds having furrows in between. Mechanised ridging is always done after ploughing and harrowing operations (Nkakini et al., 2008). This tillage operation is accomplished with the aid of tillage implement called disc ridger.

The needs for tractive force requirements have increased research towards solving the problems of traction. Traffic ability, refers to the capability of the terrain under consideration to provide the mobility conditions for a particular vehicle. Ani et al., (2004) referred to the traffic ability of a particular terrain as the ability of that terrain to support vehicle and also to provide the capability of the particular vehicle to establish

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mobility.

Thangaradivelu and Colvin, (1990), also stated that the decision to whether or not to carry out field operation is largely influenced by the traffic ability of the field in question. A field is said to be trafficable if tractors or other farm machines can perform their functions satisfactorily without much damage to the soil (Nwokedi, 1992).

The traffic ability of agricultural lands determines the tractor performance and efficiency of cultivations which is related to the compaction and structural deformation, caused by farm machinery (Nwokedi, 1992).

The criteria of performance are the initial step in evaluating a traction device (Nwokedi, 1992). Therefore, evaluating traction is generally a subjective judgement that attempts to weigh the importance of the various desired actions of the traction device. When traction requirements are needed, such as travelling over loose soil during farming operations some factors other than pull or efficiency, may be the most important criterion of performance. The concepts of thrust and rolling resistance are used as criteria for evaluating traction because they are compounded variables and occur in the same physical area. These variables are on the assumption that each medium acts as a force between the traction device and the medium (Nwokedi, 1992).

For off-road vehicle engineering the measurement of the soil properties is one of the fundamental tasks for the prediction and evaluation of tractive performance. Performance evaluation of terrain-vehicle systems involves both the design parameters for the vehicle, the measurement and evaluation of the physical environment within which the vehicle operates.

The assessment of developed models for field operations using sensitivity analysis is important in creating a condition that allows for the optimization of the dependent and independent variables. The developed tractive force models were verified using sensitivitymeasured parameters. Hence, sensitivity analysis of any developed model makes the relative role of each variable to that model known. This is done by taking notice of the change of dependent variable in the model with respect to the change in each of the several independent variables (Simonyan, 2006).

The objective of the study is to predict the variations of dependent and independent variables in disc ridging operations, so as to optimize tractive force process.

2 Materials and methods

2.1 Description

Experiments were conducted in the field (in-situ) using trace tractor technique. It was conducted at the 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 122 m above sea level and lies on latitude 05°29′N and longitude 07°33′E. 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 of 72 hp, cone penetrometer, dynamometer, measuring tape, disc ridger, auger, stop watch and instrument for measuring weight of tractor (static hydraulic press). All field tests were conducted in a loamy sand soil for which the physical properties were determined. Before the field experiment started, experimental layout area of 90 m by 90 m was designed with three different blocks of 90 m × 27 m each. Each block was divided into 9 strips of 90 m by 2 m wide with a space of 3 m between each strip. Disc ridging operations were carried out on each of the blocks, 24 hours after each rainfall event. Three replications of ridging operations were conducted after every rainfall event. There were altogether 20 rainfall events. Hence, the total treatments were 9 × 20 rainfall events. The sequence of tillage operations was: Rainfall event 1, disc ridging on block 1, strip 1; block 2, strip 1; and block 3 strip1. Rainfall event 2, disc ridging on block1, strip 2; block 2, strip 2; and block 3 strip 2. Rainfall event 3, disc ridging on block 1, strip 3; block 2, strip 3; and block 3 strip 3. This pattern was followed for the remaining number of rainfall events up to the last day when minimum moisture content was achieved. Soil data were collected to the depths of 0 - 50 mm, 50 - 150 mm and 150 - 200 mm respectively using soil auger, core sampler and a hand operated soil cone penetrometer having an enclosed angle of 30°, with a base area of 323 mm^2 mounted on a shaft of 2.03 mm for the determination of moisture content, bulk density and soil resistance before tillage operation. During the sampling process, cone penetrometer was positioned between the operator's two legs and pressed down 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 Massey Ferguson 435 model tractors of 72 hp were used. The tractor carrying the implement with its engine disengaged (neutral gear) was coupled to another tractor which towed it with the dynamometer in between them. The first tractor pulled the second tractor coupled to the implement (disc ridger). 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 engaged in tillage operations. Height and width of ridges were measured with a 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 1.94 m/s, 2.22 m/s and 2.5 m/s. Simultaneously, the time taken to cover a fixed distance of 90 m was recorded using a stopwatch to calculate the operating speed of the tractor and implement combination. Figure 1, shows the tractor -dynamometer-tractor-implement combination in action.

Figure 1 A photograph depicting tractor-dynamometer, implement mounted position during ridging operations

3 Theory

The developed tractive force models for disc ridging at different tillage speeds after substituted coefficients are Equations (1) to (3):

For ridging at 1.94 m/s

$$F = 11297.04 + 98.03998F_p\mu + 0.319058F_p\mu\frac{F_R h\mu}{Pc} - 0.174889\,Fp\mu\frac{SC_n}{\mu} \quad (1)$$

For ridging at 2.22 m/s

$$F = 11602.23 - 2.218802F_p\mu - 0.796318F_p\mu\frac{F_R h\mu}{Pc} + 0.042181F_p\,\mu\frac{SC_n}{\mu} \quad (2)$$

For ridging at 2.5 m/s

$$F = 12627.30 + 88.21908F_p\mu - 0.382268F_p\mu\frac{F_R\mu h^2}{Pc} + 0.270136F_p\mu\frac{SC_n}{\mu} \quad (3)$$

Sensitivity measured parameters, is defined as the rate of change in the output of the model with respect to the change in the value of the parameter while keeping other parameters constant. Sensitivity equation (also called error equation) is developed for a function using (Equation (4))

$$N = f(U_1, U_2 \ldots. U_n) \quad (4)$$

Sensitivity analysis was done by mathematically differentiating the developed models (1, 2 and 3) using error equation in the form (Equation (5)):

$$N = f(U_1, U_2, U_n) \quad (5)$$

where, N = dependent variable; (U_1, U_2, U_n) = Independent variable.

Using Taylor's Theorem

We differentiate the independent function Equation (6)

$$N + \Delta N = f\left(U_1 + \Delta U_1, U_2 + \Delta U_2, \ldots.. U_n + \Delta U_n\right) \quad (6)$$

Taylor's theorem says

$$f(a) = f(a) + hf^1(a)$$

$$f(N) = f(U_1, U_2 \ldots.. U_n) + hf^1(U_1, U_2 \ldots.. U_n)$$

Using function of functions method

$$\frac{\partial N}{\partial t}=\frac{\partial N}{\partial x}\cdot\frac{\partial x}{\partial t}$$

$$=> \frac{\partial N}{\partial t}=\frac{\partial N}{\partial x}\Delta_x$$

Hence Equation (7) and Equation (8)

$$N+\Delta N=f(U_1+\Delta U_1,\ U_2+\Delta U_2,......,U_n+\Delta_u) \quad (7)$$

and

$$\Delta N=\frac{\partial N}{\partial_{u1}},\ \Delta U_1+\frac{\partial N}{\partial U_1}\Delta U_1+\frac{\partial N}{\partial u_n}\Delta U_n \quad (8)$$

We can represent Equation (8) as Equation (9):

$$\Delta N=\sum_{i=1}^{n}\Delta Ni \quad (9)$$

Then applying Taylor's theorem and neglecting squares, products, higher powers and also not considering other variables when discussing one variable causes other variables to be zero, hence Equation (10),

$$\Delta N=\frac{\partial N}{\partial u_1}\Delta U_1+\frac{\partial N}{\partial U_2}\Delta U_2 \quad (10)$$

Relative changes or error was defined as following Equation (11) and Equation (12)

$$N\xi=\frac{\Delta N}{N} \quad (11)$$

$$u\xi=\frac{\Delta u}{U} \quad (12)$$

Putting Equation (11) into Equation (12)

$$N\xi=\frac{\frac{\partial N}{\partial u_1}\Delta U_1+\frac{\partial N}{\partial U_2}\Delta U_2}{N}$$

$$N\xi=\frac{\partial N}{\partial u_1}\cdot\frac{\Delta U_1}{N}+\frac{\partial N}{\partial U_2}\frac{\Delta U_2}{N} \quad (13)$$

from Equation (12)

$$U\xi=\frac{\Delta u}{U}$$

$$\Delta_u=U\xi u$$

Hence Equation (14)

$$\Delta U_1=U_1\,\xi\,U_1,\quad \Delta U_2=U_2\,\xi\,U_2 \quad (14)$$

as was the case with the following.

$$\Delta N=\sum_{i=1}^{n}\Delta Ni$$

$$\Delta_u=\sum_{i=1}^{n}\Delta u_i$$

Introducing Equation (14) into Equation. (13) we obtain Equation (15)

$$N\xi=\left(\frac{\partial N}{\partial u_1}\cdot\frac{\Delta U_1}{N}\right)+\left(\frac{\partial N}{\partial u_2}\cdot\frac{\Delta U_2}{N}\right)$$

$$N\xi=\frac{\partial N}{\partial u_1}\cdot\frac{U_1\,\xi\,U_1}{N_x}+\frac{\partial N}{\partial u_2}\cdot\frac{U_2\xi}{N}U_2$$

$$N\xi=\left(\frac{\partial N}{\partial u_1}\cdot\frac{U_1}{N}\right)U_1\xi+\left(\frac{\partial N}{\partial u_2}\cdot\frac{U_2}{N}\right)U_2\xi \quad (15)$$

This has to express the relative change of N with respect to the sum of the relative changes of each variable. If the error or change that occurs in only one variable is considered, all the other terms would be zero, i.e., only one variable causes others to become zero.

Hence, $N\xi=\left(\frac{\partial N}{\partial u_1}\cdot\frac{U_1}{N}\right)U_1\,\xi+O$

Therefore, $N\xi=\left(\frac{\partial N}{\partial u_1}\cdot\frac{U_1}{N}\right)U_1\xi \quad (16)$

The bracketed terms become dimensionless coefficient, which expresses the percentage of the relative variable change, transmitted to the relative dependent variable. This is the sensitivity coefficient which shows the relative importance of each of the variables to the models solutions. The developed and the calculated sensitivity equations for the tractive force developed models are shown as:

For ridging at 1.94 m/s

$$F=11297.04+0.98039977F_p+0.319058F_p\frac{F_R\,h\,\mu}{P_c}-0.174889$$

(1) $\frac{dF}{dF_p}=0.98039977+0.319058\frac{F_Rh\mu}{Pc}$

(2) $\frac{dF}{dF_R}=0.319058\frac{F_ph\mu}{Pc}$

(3) $\frac{dF}{dh}=0.319058\frac{F_pF_R\mu}{Pc}$

(4) $\frac{dF}{dP_c}=-0.319058\frac{F_pF_Rh\mu}{Pc^2}$

(5) $\frac{dF}{d\mu}=0.319058F_p\frac{F_Rh}{Pc}+0.174889\frac{S\,Cn}{\mu^2}$

(6) $\frac{dF}{dCn}=0.174889\frac{S}{\mu}$

(7) $\frac{dF}{ds}=0.174889\frac{Cn}{\mu}$

For ridging at 2.22 m/s

$$F = 11602.23 - 2.218802F_p - 0.796318F_p \frac{F_R h\mu}{Pc} + 0.042181\frac{SCn}{\mu}$$

(1) $\frac{dF}{dF_p} = -2.218802 - 0.796318\frac{F_R h\mu}{Pc}$

(2) $\frac{dF}{dF_R} = 0.796318\frac{F_p h\mu}{Pc}$

(3) $\frac{dF}{dh} = 0.796318\frac{F_p F_R \mu}{Pc}$

(4) $\frac{dF}{dP_c} = -0.796318\frac{F_p F_R h\mu}{Pc^2}$

(5) $\frac{dF}{ds} = 0.042181F_p\frac{Cn}{\mu}$

(6) $\frac{dF}{dCn} = 0.042181\frac{S}{\mu}$

(7) $\frac{dF}{d\mu} = 0.796318F_p\frac{F_R h}{Pc} - 0.042181\frac{SCn}{\mu^2}$

For ridging at 2.5 m/s

$$F = 12627.30 + 0.8821908F_p - 0.382268F_p\frac{F_R h\mu}{Pc} + 0.270136\frac{SCn}{\mu}$$

(1) $\frac{dF}{dF_p} = 0.8821908 - 0.382268\frac{F_R h\mu}{Pc} + 0.270136\frac{SCn}{\mu}$

(2) $\frac{dF}{dF_R} = 0.382268\frac{F_p h\mu}{Pc}$

(3) $\frac{dF}{dh} = 0.38268F_p\frac{F_p F_R \mu}{Pc}$

(4) $\frac{dF}{dP_c} = -0.3822.68\frac{F_R h\mu}{Pc^2}$

(5) $\frac{dF}{ds} = 0.270136\frac{Cn}{\mu} = 0$

(6) $\frac{dF}{dCn} = 0.270136\frac{S}{\mu}$

(7) $\frac{dF}{d\mu} = 0.3822681F_p\frac{F_R h}{Pc} - 0.270136F_p\frac{SCn}{\mu^2}$

4 Results and discussion

The sensitivity of measured parameters during disc ridging was used for evaluating performance of developed models of tractive force describing the tractors tyre-soilinteractions parameters.

In Table 1, the independent variables and their respective sensitivity coefficients were shown. It also depicts the sensitivity coefficients values of -0.00164, -0.00695 and -0.00258 for P_c (Pressure contact) during disc ridging at various tillage speeds of 1.94 m/s, 2.22 m/s, 2.50 m/s respectively. The lowest sensitivity coefficient value of 0.0979 for draw bar pull force was obtained at 2.22 m/s tillage speed. These results might be due to the degree of soil pulverisation in ridging tillage operations. The sensitivity coefficients of these developed models of tractive force for all the independent variables fit experimental data.

Table 1 Sensitivity coefficients of the tractive force model parameters for ridging at 1.94, 2.22, 2.5 m/s tillage speeds

Parameters	Sensitivity coefficients	Parameters	Sensitivity coefficients	Parameters	Sensitivity coefficients
at 1.94 m/s		at 2.22 m/s		at 2.5 m/s	
F_P	0.2505	F_P	0.0979	F_P	0.2595
F_R	0.00164	F_R	0.00695	F_R	0.00258
h	0.00164	h	0.00695	h	0.00258
P_C	-0.00164	P_C	-0.00695	P_C	-0.00258
μ	0.99164	μ	0.00695	μ	0.00107
Cn	1.3746E^{-06}	Cn	9.6046E^{-07}	Cn	4.1332E^{-06}
S	1.3746E^{-06}	S	4.4008E^{-07}	S	1.8936E^{-06}

In view of the results obtained in these various tillage speeds for all the independent variables, it is evident that a 10% change in independent variable (U_1) would cause dependent variable (N) a negligible change. The same negligible changes occur at 50% and 100% changes in the operation. This indicates that the sensitivity of developed predicted model to changes in the constituent independent variables is negligible and insignificant.

Figures 2 to 4 show the graphical comparison between the measured and predicted tractive force values of disc ridging operations at tillage speeds of 1.94 m/s, 2.22 m/s and 2.5 m/s.

The model equations of tractive force prediction developed for this tillage speeds operations at 1.94 m/s, 2.22 m/s and 2.5 m/s were employed to test the validity of tractive force by showing the graphical comparison between the measured and predicted forces. The results showed acceptable agreement with coefficient of determinations R^2=0.996, 0.996, and 0.986, respectively.

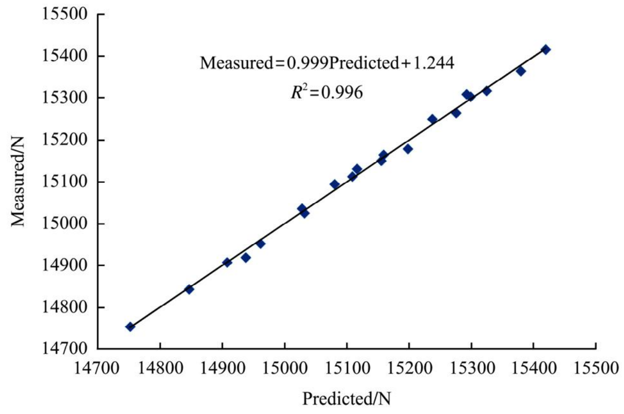

Figure 2 A plot of relationship between Measured and Predicted Tractive Force, N at tillage speed of 1.94 m/s ridging

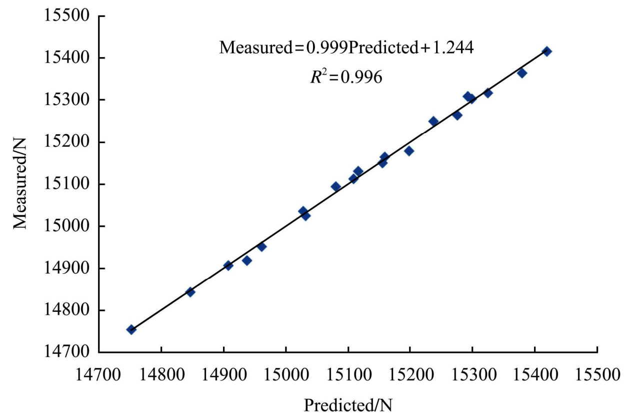

Figure 3 A plot of relationship between Measured and Predicted Tractive Force, N at tillage speed of 2.22 m/s ridging

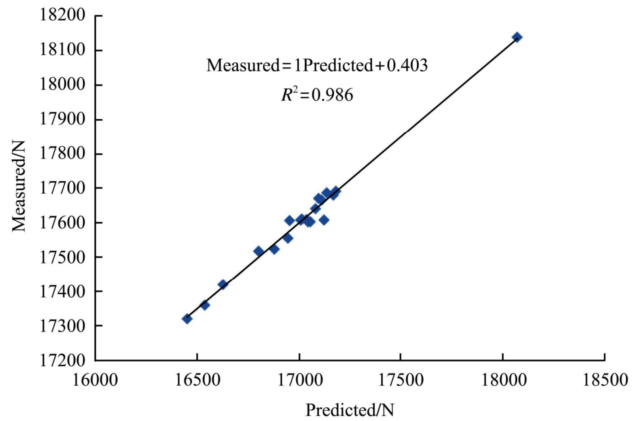

Figure 4 A plot of relationship between Measured and Predicted Tractive Force, N at tillage speed of 2.5 m/s ridging

5 Conclusions

The sensitivity coefficients of the tractive force models parameters for disc ridging at tillage speeds of 1.94 m/s, 2.2 m/s and 2.5 m/s showed negligible changes. The lowest sensitivity coefficient value of 0.0979 for draw bar pull force was obtained at 2.22 m/s tillage speed. This indicates the best tillage speed operation for ridging which might be as a result of the level of soil pulverization. These developed predicted equations are recommended for use in farming operations.

Nomenclature

μ Moisture content, %

a Widths of ridge, mm

C_2 Constants

C_3 Constants

C_4 Constants

CI Cone index, N/m^2

Cn Wheel numeric

F Tractive force, N

F_P Drawbar Pull, N

F_R Rolling resistance, N

h Height of ridge, mm

N Dependent variable

P_C Tyre Contact Pressure (ground pressure), kPa

S Wheel Slip, %

U_1 Independent variable

U_2 Independent variable

V Tractor speed, m/s

Z Wheel Sinkage, mm

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