Present State of Research on Narrow Wheels: A Prerequisite for Traction Studies on Non-Lug Narrow Wheels

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Abstract

The use of narrow wheels as traction members of simple agricultural machinery and equipment has been investigated. This equipment can be easily acquired and maintained by low income earners and the rural dwellers whose occupation is predominantly farming. The off road performance of these narrow wheels in terms of rolling resistance, coefficient of rolling resistance, and the net traction ratio as they affect the tractive efficiency are discussed. The various factors such as the wheel diameter, inflation pressure, axle load and the operating speed on different soil conditions as they affect the off road performance are also highlighted. The size of the wheel and its weight is a good measure to combat the negative effects of soil compaction on agricultural soils. Existing models describing the tractive performance of agricultural wheels are stated and analyzed and the generalization of such models for predicting the tractive performance is discouraged.

Keywords
Narrow Wheel; Off Road Performance; Pneumatic Wheel; Rigid Wheel; Rolling Resistance; Net Traction Ratio; Tractive Efficiency.

Introduction

Narrow wheels referred to in this context are the pneumatic bicycle tyres, motorcycle tyres and tyres whose width ranges between 35 mm and 100 mm. Rigid wheels (lug type) and the cage wheels are found mostly in swamp development (soft soil or paddy soils, muskeg) to aid traction.

Narrow wheels as defined above have not been given much attention especially the non- lug types. Reviewing of past researches on tractive performance of agricultural wheels show that many researches have been carried out on the tractive performance of off-road vehicles with special emphasis on the wheels on soil analytically [1, 2] and through experimentation (empirically and semi-empirically) [3-5]. These are either carried out on the fields or in a soil bin in the laboratory. However, research by Werner and Mauersberger [6] revealed that the effect of high inflation pressure narrow wheels is insignificant on soil compaction when compared with low pressure wider tyres on soil compaction detriments.

An affordable bicycle-wheel wood-frame handcart has been developed in Malawi for use by small holder farmers and by city dwellers for whom animal drawn carts are unaffordable or impractical or both. The Malawi Cart can be made from readily available materials and does not require any expertise, in fact, it can be built by any carpenter possessing common hand tools [7].

This paper reviews the off- road performance of narrow wheels with special emphasis on the rolling resistance with a view to providing adequate information to assist in the design and development of low cost agricultural machinery for low income earners and rural populace who are predominantly farmers to boost their agricultural productivity and eliminate or reduce to the barest minimum the drudgery experience and associated with farming. These agricultural machines will have the narrow wheels as traction members. And as such, it will require little or no technical know how to maintain these equipment.

Tractive Performance

Tractive resistance depends on the soil properties and the condition of the wheels such as the inflation pressure of the pneumatics tyres, the axle load and the speed of operation, which is a determinant of the drawbar power of the machine. In his study on the tractive performance of a wide - low-pressure tyre compared with conventional tractor drive tyres. Dwyer [8] used the following parameters and definitions:

Coefficient of Traction = Tractive Force/Vertical Load (1)

Coefficient of Rolling resistance = Rolling resistance/Vertical Load (2)

Tractive efficiency, η = Drawbar Output/Axle Load Input (3)

According to Elwaleed et al. [9], Net Traction Ratio (NTR) is one of the pertinent measures of tyre tractive performance. An adequate knowledge and understanding of the basic principle of the tyre traction is essential to help managers and engineers for the proper designing of new machinery and the appropriate matching and selection of the tractor-implement system. Research studies indicate that about 20-55% of the energy developed to the drive tractor wheels is wasted in the tyre- soil interaction. This energy is not only wasted but the resulting soil compaction created by a portion of this energy may be detrimental to crop production [10, 11].

Pneumatic and Rigid Wheels

Pneumatic wheels are tyres that worked by air under pressure and are classified into two basic types; the radial-ply tyres and the biased-ply tyres. Researches conducted to compare the tractive performance of the radial-ply tyres with the biased-ply tyres in different soils and concrete and at different tyre inflation pressure show that the radial-ply tyres developed more drawbar pull than do the bias-ply tyres [12-14]. Gee-Clough et al. 1977 [12] reported the tractive performance benefits of using radial-ply tyre increased from 5-8% in the coefficient of traction at 20% wheel slippage with no change in the maximum tractive efficiency when the tyres are not highly inflated.

***Rigid Wheel and Cage Wheel*:** Rigid wheels are wheels that do not require any inflation. Some are made by welding a sheet metal of a particular thickness only round the circumference of the rim, while some are made by covering the welded sheet metal or the solid metal wheel by rubber having similar surface and look like pneumatic tyres but are not because they require no inflation. Such wheels have similar characteristics as do the pneumatic wheels of high inflation pressure. It could also be made from other materials like wood and plastics. Cage wheels are made of steel but not covered by rubber but have steel lug placed at a predetermined angle round the circumference of the steel wheel to aid traction. Both wheels are used as traction members of agricultural machines especially in swamp development where pneumatic wheels have low tractive efficiency as a result of rut formation and loss of traction [15].

An understanding of the basic characteristics of the interaction between the running gear and the ground is essential to the study of the performance characteristics and the handling behaviour of ground vehicles [16]. The running gear of a ground vehicle is generally required to fulfil the following conditions: i) support the weight of the vehicle ii) cushion the vehicle over surface irregularities iii) provide sufficient traction for driving and braking and iv) provide adequate steering control and directional stability. Pneumatic tyres wheels can perform these functions efficiently, thus they are exclusively used in road and off-road vehicles.

In the process of investigating the off-road performance of agricultural wheels which encompasses the tractive performance of the wheels under different off road conditions, the determination of the rolling resistance and the coefficient of rolling resistance are of major importance, as these form the major factors affecting the off road performance of the wheels. These parameters form the basic variables in all the models developed to describe the tractive performances of agricultural wheels.

Rolling Resistance Concept

Rolling resistance refers to the motion of a wheel caused by the absorption of energy in the contacting surfaces of the wheel and the soil upon which the wheel rolls [4].

Inns and Kilgour [17] reported in 1978 that the rolling resistance of a wheel with pneumatic tyres has two components: the internal rolling resistance which is caused by loss of energy resulting from the continuous flexing of the tyre carcass as the wheel rotates in contact with the ground and external rolling resistance arising from energy which the wheel has to expend in deforming the soil surface.

Plackett 1985 [18] showed that the rolling resistance may be expressed as

$$R = R_c+R_b+R_t \quad (4)$$

The total motion resistance force, R is therefore made up of the R_c, the component due to soil compaction, R_b, the component due to horizontal soil displacement and R_t, the components due to flexing of the tyre. For vehicle operating on a hard surface, R_t, constitutes the largest percentage of the motion resistance force and this, can be slightly reduced by increasing the inflation pressure and the effective stiffness of the of the tyre. In off-road situation, however, the components R_c and R_b make up the largest proportion of the motion resistance force and increasing the inflation pressure and the tyre stiffness have shown to increase the rolling resistance.

Arregoces [19] stated that rolling resistance may be described as the total drag opposite to the steady motion of a free rolling wheel across a horizontal surface. It can also be defined as integral of the horizontal component of the radial stresses. Usually, the rolling resistance is expressed in terms of coefficient of rolling resistance (τ). Thus, mathematically, the coefficient of rolling resistance is as expressed in equation 5:

$$\tau = R/Q \quad (5)$$

where R is the rolling resistance force suffered by the wheel and Q is the normal load on the wheel.

Plackett [18] reported that a semi-empirical approach to predicting forces acting on wheels operating in soil was first initiated by Bernstein [20]. Bernstein observed that the rolling resistance acting on a wheel was due to the work done in forming a rut and he proposed a theory based upon the pressure / sinkage characteristics of a regular plate and it is as stated in equation 6:

$$p = k \times z^n \quad (6)$$

The pressure acting on the plate is represented by p, k is the modulus of soil deformation, z is the sinkage and n is an exponent of deformation. Experiments undertaken by Bernstein proposed that the value of n for agricultural soil is 0.5.

In off road conditions, vehicle designers prefer to minimise the rolling resistance in order to minimise the energy wasted to overcome the motion resistance [18]. The drawbar pull is a measure of the tractive performance of off road agricultural vehicle and it's related by equation 7, decreasing the rolling resistance, will increase the drawbar pull [21].

$$P = H - R \tag{7}$$

where *P* is the drawbar pull, *H* is the tractive effort or net traction and *R* is the rolling resistance, *P* and *H* are function of slip, but the rolling resistance is predicted at zero slip.

Tiwari and Pandey [22] stated that the most important performance parameter of the towed wheel is the rolling resistance and it is influenced by the tyre design, the system design and the terrain characteristics.

Factors Influencing Rolling Resistance

Traditionally, as reported by Pandey and Tiwari [23] the tyre design parameters are diameter, sectional width, sectional height, inflation pressure and the load deflection relationship which has diverse degree of influence on the soil-tyre interaction [24]. While the terrain characteristics includes the soil type, soil moisture content and it cone index as a measure of soil-compaction, and the system parameters involves the normal load acting on the wheel and the forward speed [23].

The main factors affecting the rolling resistance of a pneumatic tyre on deformable soil are: soil displacement, elastic flexing of the tyre, friction and soil adhesion. Other factors include, wheel diameter, inflation pressures, axle load as reported by Arregoces [19] in his investigative studies on the effects of wheel diameter, axle load and inflation pressures on the coefficient of rolling resistance of bicycle tyres shows that the wheel diameter has an indirect relationship with the coefficient of rolling resistance, while axle load showed a direct relationship, but the inflation pressures has no noticeable effect on the coefficient of rolling resistance. Inns and Kilgour [17] stated that the coefficient of rolling resistance of pneumatic tyres decrease with increase of wheel diameter at any specified inflation pressure. The inflation pressure contributes directly to stiffness of the tyre [9] hence control the tyre contact area and tyre-soil ground pressure distribution, both of which influence the traction capability of the tyre. Generally, as inflation pressures are decreased, traction is improved. However, tyre life will be shortened by under-inflation as well as over-inflation [24, 25]

Forces acting on a rolling wheel

In order to obtain the optimum performance from an off-road vehicle, it is necessary to understand the interaction between the wheel and the medium on which it operates. Plackett

1985 [18] described the forces acting on a rolling wheel and classified them into: rolling resistance, vertical load, tractive force, steering force and ground support force.

State of The Art on Narrow Wheel

A lot of work has been carried out on the tractive performance of off road vehicles.

Islam 1986 [4] studied the off road performance of pedal- driven machines for field use. In his studies, the performance of four pneumatic bicycle wheels of different diameters and one rigid bicycle wheel was investigated and compared with special emphasis on the rolling resistance and the coefficient of rolling resistance of the two wheels on different surfaces using a previously designed rig.

The basic instruments were the four arm active strain gauge circuits and the ultra-violet recorder. The tests were conducted on three typical soil surface conditions as compact soil, loose soil, and grass field. The test variables were; wheel diameter, tyre inflation pressure, load and speed.

He conducted another test using a cone penetrometer to measure the penetration resistances of the soil and making use of existing models (empirical formula), the coefficients of rolling resistances were calculated and the values were compared to that obtained by the strain gauge method.

He found out that on the average, the rolling resistances of the rigid wheels were found to be higher than that of the pneumatic wheels on all the tested surfaces which is also confirmed by Perdok [26]. Also, the rolling resistances predicted by the penetrometer methods were lower than the values measured by the strain gauge method. Some empirical formulas were developed for the prediction of coefficients of rolling resistances of bicycle tyres and similar sizes of rigid tyre on different tested surfaces. These empirical equations showed indirect relationships between the coefficient of rolling resistance and the mobility number under different tested conditions. For example, equations 8 and 9 show the coefficient of rolling resistance of bicycle tyres under compact and loose soil respectively for wheel diameters of 660 mm, 610 mm, 457 mm and 355 mm, while equations 10 and 11 represent the model for coefficient of rolling resistance of the bicycle wheel at different inflation pressures on compact and loose soil respectively, equations 12 and 13 represent the coefficient of rolling resistance of the pneumatic bicycle at different loads on compact and loose soil respectively. Conversely, the coefficient of rolling resistance of the rigid bicycle wheel of diameter 476 mm at different loads on compact and loose soils are presented in equations 14 and 15 respectively.

$$C_{RR} = 0.073+0.249/M \tag{8}$$

$$C_{RR} = 0.144+0.668/M \tag{9}$$

$$C_{RR} = 0.086+0.504/M \tag{10}$$

$$C_{RR} = 0.136+0.799/M \tag{11}$$

$$C_{RR} = 0.083+0.4874/M \tag{12}$$

$$C_{RR} = 0.1211+0.709/M \tag{13}$$

$$C_{RR} = 0.069+2.08/M \tag{14}$$

$$C_{RR} = 0.071+2.141/M \tag{15}$$

where M is the mobility number and C_{RR} is the coefficient of rolling resistance, τ, and *Cn* is the refined mobility number. (Cn = cbd/w, c=cone index, b=wheel width, d=wheel diameter**)**

Gee-Clough [3] investigated the effect of wheel width on the rolling resistance of rigid wheel in sand some of his conclusions were: there is a very strong relationship between the width and the rolling resistance in sand; the coefficient of rolling resistance increases rapidly with increase in width at a given sinkage, the drag per unit width increased but lift per unit width decreased as width increased at a given sinkage, wheel skid increased rapidly with increase in width at a given sinkage and multiple narrow wheels will give lower rolling resistance than single wide narrow wheels in towed configuration in sandy soils.

Elwaleed [5] studied in 1999 the motion resistance ratio, net traction ratio and tractive efficiency of a Riceland type tyre (Bridgestone 5-12, 4 ply, lug-M) using the UPM indoor tyre traction testing facility [11]. He tested the accuracy of Wismer -Luth and Brixius equations in predicting the tyre motion resistance ratio, net traction ratio and tractive efficiency of the Riceland tyre. The tyre was tested on a sandy clay loam soil in an indoor UPM tyre traction testing facility. The experiments were conducted by running the tyre in two modes; towing mode for the formulation of tyre motion resistance ratio equation and the driving mode for the formulation of tyre net traction ratio and the tractive efficiency equations.

The tyre motion resistance ratio was determined at three different levels of inflation pressures (i.e. 221, 193 and 166 kPa) and selected wheel numeric ranging between 0 to 70. Statistical analysis showed that both inflation pressure and wheel numeric had significant effects on the tyre motion resistance ratio.

According to Elwaleed [5], the tyre net traction ratio and tractive efficiency were determined at the same selected inflation pressure and two wheels numeric (19 and 29) representing two extreme types of soil strength under different level of travel reduction ranging from 0 to 40%. Regression analysis was conducted to determine the prediction equation describing the tyre torque ratio. Marqurdt's method used by Wismer-Luth for predicting non- linear equation was found not suitable for predicting the torque ratio of the tested tyre for its low coefficient of determination and inadequacy. The logarithmic model was found suitable for predicting the torque ratio. From the analysis of the covariance, the mean effect travel reduction, tyre inflation pressure, and the wheel numeric were found to be highly significant whereas the interaction of inflation pressure and wheel numeric was not significant.

Elwaleed [5] formulated two models for the tyre net traction ratio; one in terms of wheel numeric and travel reduction and the other in terms of mobility number and the travel reduction to describe the tested tyre performance at different soil strength and at the nominal tyre inflation pressure (221 kPa). (Equations 16 and 17)

$$T/r_0Q = \ln(Cn)\times[0.0214\ \ln(s)+0.208] \quad (16)$$

$$T/r_0Q = \ln(Bn)\times[0.0196\ \ln(s)+0.189] \quad (17)$$

where *Cn* is the wheel numeric, Bn is the mobility number, *T* is the torque on the driven wheel, s is the travel reduction or the wheel slip, r_0 is the rolling radius, and *Q* is the vertical load on the wheel.

Another model was found to describe the tyre torque ratio for different strength in terms of wheel numeric and mobility number at 193 kPa tyre inflation pressure as shown in equations 18 and 19.

$$T/r_0Q = \ln(Cn)\times[0.0247\ \ln(s)+0.215] \quad (18)$$

$$T/r_0Q = \ln(Bn)\times[0.0224\ \ln(s)+0.196] \quad (19)$$

The new models for the Riceland tyre motion resistance at the nominal tyre inflation pressure in terms of wheel and mobility numbers are as presented in equations 20 and 21 [5].

$$TF/Q = 0.0682\ \ln(1/Cn) +0.3719 \quad (20)$$

$$TF/Q = 0.0682\ \ln(1/Bn) +0.3617 \quad (21)$$

where *TF* is the towing force which represents the rolling resistance or the motion resistance.

The new motion resistance ratio models at 193 kPa inflation pressure which was found to be better in performance than the nominal inflation pressure for both the wheel numeric and mobility number are as stated in equations 22 and 23 below [5].

$$TF/Q = 0.0627 \ln(1/Cn) + 0.3443 \quad (22)$$

$$TF/Q = 0.0627 \ln(1/Bn) + 0.336 \quad (23)$$

Table 1 presents the various measurement parameters in the models developed by the respective authors and researchers.

Table 1. Tractive performance measurement models

S/N	Measurement Parameters	Models	Source
1	Mobility Number, *M*	$Nc = (CIbd/Q)\ (\delta/h)^{1/2}\ [1/(1+b/2d)]$	[27]
2	Wheel Numeric /Refined Mobility No (rigid wheel), *Cn*	$Cn = CIbd/W$	[1]
3	Brixius Mobility Number, *Bn*	$Bn = (CIbd/W) \times [(1+5\delta/h)/1+3b/d]$	[2]
4	Tractive force, *H* (Net Traction)	$H = (Ac+Q\tan\varphi)\ [1-(1/J)(1 - e^{-j})$ where, $J=sl/k]$	[28]
5	Wheel Slippage, *s*	$s = 1-V_a/V_t$	[1, 2]
6	Towing Force, *TF*	$TF = \{[b(p_i+p_c)](^{n+1)/n}\}/(n+1)(k_c+bk_\varphi)^{1/n}+Qu/p_i^a$	[29]
7	Rolling radius, r_o	$r_0=(2.5\times U_R\times L_R)/(1.5\times U_R - L_R)$	[30]

Conclusions

The state of art the of research on the off road performance of agricultural wheels have been reviewed, and the parameters required to determine the off road performance in terms of rolling resistance/motion resistance, net traction ratio, wheel numeric, mobility numbers, tractive force, wheel slip, tractive efficiency have been discussed in detail. The soil factors and the nature of the tyres as they affect the tractive performance of the wheels have been reviewed.

Existing models used to determine the tractive performance of off road vehicles have been stated and the modifications of these models to study the off road performance of narrow wheels has been emphasized.

Abbreviations

a empirical exponent of tire stiffness (dimensionless)	C_{RR} coefficient of rolling resistance (dimensionless)
b tyre width, m.	F_P pulling force, N
c soil cohesion, N/m^2	G sand penetration resistance, N
d tyre unloaded diameter, m	H tractive force/effort, N
h tyre section height, m	M mobility number (dimensionless)
j horizontal deformation of the ground in track slip (m)	Nc clay-tyre numeric, dimensionless
k modulus of deformation kg/m^{n+2})	Ns sand-tyre numeric, dimensionless
k_c cohesive moduli of deformation, KN/m^{n+1}	P_{in} input power, kW
$k_ø$ frictional moduli of deformation, KN/m^{n+2}	P_{out} output power, kW
l length of contact patch, m	Q normal load on the wheel, N
n exponent of soil deformation (dimensionless)	R rolling resistance, N
p pressure acting on the plate, kPa	R_b resistance component due to horizontal soil displacement, N.
p_c tyre carcass pressure, kPa	R_c resistance component due to compaction, N
p_i tyre inflation pressure, kPa	R_t resistance component due to flexing of the tyre, N
r effective moment arm, wheel radius, m	*T* torque, Nm.
r_o rolling radius, m	TF towed force, N
s slip, travel reduction (%)	V_a tyre actual velocity, m/s
u empirical coefficient of tyre stiffness,kg/m^{2a}	V_t tyre theoretical velocity, m/s
v tyre linear velocity, m/s	ω tyre angular/rotational speed, rpm
z wheel sinkage, m.	τ co efficient of rolling resistance (dimensionless)
A tyre contact area, m^2	δ tyre deflection, m
B_n mobility number, dimensionless	ø soil friction angle, degree
CI cone index, N/m^2	η tractive efficiency, %.
Cn wheel numeric, dimensionless.	C_{RR} coefficient of rolling resistance (dimensionless)

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