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Modelling of Motion Resistance Ratios of Pneumatic and Rigid Bicycle Wheels

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ABSTRACT

The motion resistances of 660 mm pneumatic and rigid bicycle wheels of the same rim diameter were measured experimentally using the developed tractor-towed single non-lug narrow wheel motion resistance test rig for traction studies. The motion resistances measured were taken to be the towing forces determined in real time using Mecmesin Basic Force Gauge (BFG 2500). The test variables included two test surfaces [tilled and wet (mud) surfaces], the dynamic load and the towing velocity. The tyre inflation pressure of 414 kPa was chosen to make the surface synonymous with that of the rigid wheel. Motion resistance ratios of the two wheels were determined empirically and through semi-empirical approach. The motion resistances of the rigid wheel were found to be greater than those of the pneumatic wheel for both surfaces. Consequently, the motion resistance ratios of the rigid wheel were greater than those obtained from the pneumatic wheel. Analysis of variance showed that there were significant differences between the means of the motion resistance measured on the test surfaces, as well as between the two wheels and their interactions with the test surfaces. The motion resistance ratio exhibited a linear relationship with the towing velocity, while the relationship with the dynamic load was quadratic. However, such a relationship is either direct or inverse with the respective variables. The motion resistance ratio models for the pneumatic and rigid wheels showed that on different test conditions of the dynamic loads and the towing velocities, the relationships between the motion resistance ratio and the dynamic load, and motion resistance with dynamic load were also different.

Keywords: Motion resistance, motion resistance ratio, pneumatic and rigid wheels, dynamic load, towing velocity, test surface, regression models

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INTRODUCTION

Motion resistance is defined as the force required to overcome the frictional force between the surface of the tyre and the terrain upon which it rolls in the direction of travel. It is also known as the towing force (Code

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2003, R2009; Arregoces, 1985; Elwaleed, 1999). The other pertinent measures of the tractive performance are net traction ratio, gross traction ratio and tractive efficiency (Elwaleed, 1999; Gheissari & Loghavi, 2010). Plackett (1985) presented the work of Bernstein (1913) and stated the relationship between tyre inflation pressure (*p*) and sinkage level (*z*) in the process of rut formation and with soil factor (*n*-an exponent of soil deformation) and the coefficient or the modulus of soil deformability (*k*), as stated in Equation 1. This relationship forms the basis of most research in mobility studies.

$$p = kz^n \quad [1]$$

Single wheel testers have been developed for both indoor and field mobility tests by a number of researchers, and each researcher has defined performance measure (Yahya *et al*., 2007; Pope, 1971; Gotteland & Benoit, 2006; Kawase, Nakashima, & Oida, 2006; Gheissari & Loghavi, 2010). All these devices measure at least the input parameter torque *T*, and rotational speed ω, as well as the output parameters, pulling force F_p and the driven velocity v of the wheel (Schreiber & Kutzbach, 2007).

Mathematical models were derived for predicting the mobility number, wheel numeric for cohesive soil and for sandy soils, motion resistance ratios, net traction ratio, and tractive efficiencies, with respect to a particular tyre and test surface or terrain. Table 1 summarises some of the existing models and the respective researchers. However, a singular model cannot be used to represent all types of agricultural tyres and test surfaces because of the variation in the tyre design parameters and the soil and the system parameters.

TABLE 1: Existing wheel numeric, mobility number, and motion resistance ratio models

S/N	Measurement Parameters	Models	Source
1	Mobility Number, *M*	$Nc = \frac{CIbd}{W}(\frac{\delta}{h})^{\frac{1}{2}}[\frac{1}{1+\frac{b}{2d}}]$	Turnage (1972)
2	Wheel Numeric /Refined Mobility No (rigid wheel), *Cn*	$Cn = \frac{CIbd}{W}$	Wismer and Luth (1974)
3	Brixius Mobility Number, *Bn*	$Bn = \frac{CIbd}{W}[\frac{1+5\frac{\delta}{h}}{1+3\frac{b}{d}}]$	Brixius (1987)
4	Motion Resistance Ratio	$M_{RR} = 0.04 + \frac{1}{B_n} + \frac{0.5}{\sqrt{B_n}}$	Brixius (1987)
5	Coefficient of Rolling Resistance	$C_{RR} = 0.04 + \frac{0.287}{M}$	Gee-Clough *et al*. (1978)

Researchers are interested in reducing motion resistance force so as to generate higher drawbar pull from the traction device of any agricultural vehicle (Plackett, 1985). The relationship between drawbar pull (*P*), net traction (*H*) and motion resistance (*R*) is stated in Equation 2 (Macmillan, 2002).

$$P = H - R \qquad [2]$$

Motion resistance ratio is preferred to motion resistance in the tractive performance of agricultural wheel or off-road traction and transport devices (Arregoces, 1985; Code, 2003, R2009) , and it is defined mathematically as the ratio of the motion resistance to the dynamic load acting on the wheel (see Equation 3). This relationship is found applicable in the empirical determination of the motion resistance ratio. With the measured motion resistance and the dynamic load on the wheel, the motion resistance ratio can be calculated using Equation 3, as follows:

$$MRR(\tau) = \frac{MR}{W} \qquad [3]$$

where MR is the motion resistance force suffered by the wheel and W is the normal load on the wheel. Saarilahti (2003) classified motion resistance ratios into good, fair and poor, as shown in Table 2.

TABLE 2: Mobility classes based on motion resistance ratio

Mobility and Trafficability Class	Motion Resistance Ratio
Good	<0.20
Fair	0.20 to 0.30
Poor	>0.30

(Source: Saarilahti, 2003)

The semi-empirical or the analytical prediction of motion resistance ratios involves the measurements of tyre design parameters such as tyre overall wheel diameter (d), tyre deflection (δ), tyre sectional width (b), and tyre sectional height (h). Dynamic load (W) is also measured as the system parameter and the main soil parameter is the soil resistance to penetration (cone index) (Wismer & Luth, 1974; Wong, 1984; Pandey & Tiwari, 2006). All these parameters are substituted into the existing models so as to get mobility numbers or wheel numeric. This mobility number or wheel numeric is further substituted into the existing motion resistance ratio models.

Elwaleed (1999) developed motion resistance ratio, net traction ratio, and tractive efficiency for upland rice tyre. He found that the same model could not be used to generalise the tractive performance characteristics of all tyres. Other researchers also investigated the tractive performance of different agricultural tyre types. Each of these motion resistance models developed by Wismer and Luth (1974), and Brixius (1987), was derived for typical agricultural tyres.

Pneumatic wheel (tyre) is a structural vessel which holds a volume of air under pressure in order to support the vertical load imposed by a vehicle (Plackett, 1985). Unlike pneumatic wheels, rigid wheels do not have rubberised carcass materials and do not work under air pressure. Earlier research conducted has shown that the rigid wheels behave similarly to pneumatic wheels at high inflation pressures (Wang & Reece, 1984).

The use of narrow bicycle wheels as traction members in the development of simple agricultural machines for low income farmers and rural dwellers is paramount. The motion resistance ratios predictions for the bicycle wheel will be useful in the design of such simple machines to boost their agricultural productivity. The objectives of this study were to compare the motion resistance and motion resistance ratios of both the pneumatic and rigid bicycle wheels on deformable surfaces using empirical and semi-empirical approaches. In addition, models for predicting the motion resistance ratios of towed pneumatic and rigid bicycle wheels on both the tilled and wet surfaces using the two methods were also derived. The effect of the towing velocity was also modelled on both wheels and test surfaces.

MATERIALS AND METHOD

The empirical and analytical prediction methods were used to obtain the motion resistance ratio data used for model development. The motion resistance ratios obtained from the experimental measurements of the towing force and the dynamic load were compared with those obtained from the analytical prediction. The coefficients of variation obtained between the two sets of data were used as multiplying factors to the Brixius's (1987) motion resistance ration model to obtain a model for the pneumatic and rigid bicycle wheels.

Tilled and wet surfaces were considered for this study and the models were developed with respect to the two test surfaces. The soil physico-mechanical properties of the test surfaces are presented in Table 3 according to ASTM (2005).

TABLE 3: Some soil physico-mechanical properties of the tilled and wet Surfaces

Soil Properties	Values (Range of values) in Designated Unit
Soil Textural Classification	Sandy-clay-loam (60% sand, 32% clay, 8% silt).
Soil Bulk Density	1.48 kg/m^3 – 1.72 kg/m^3 (mean = 1.55 kg/m^3 db)
Liquid Limit	28.06% db
Plastic Limit	11.14% - 24.26% db (mean = 17.09%db)
Soil Moisture Contents range	10.75% - 15.63% wb (Tilled Surface) 35.7% - 45% wb (Wet Surface)
Cone Index (CI) range of the Tilled Surface	0.6 MPa -1.8 MPa (mean CI = 1.15 Mpa)
Cone Index (CI) range of the Wet Surface	0.7 MPa – 1.4MPa (mean CI = 1.15 MPa)
Soil Strength	Tilled Surface: 63.5 kPa-65 kPa (mean= 64.42 kPa) Wet – surface: 20 kPa-30 kPa (mean = 24.75kPa)

The Empirical Method

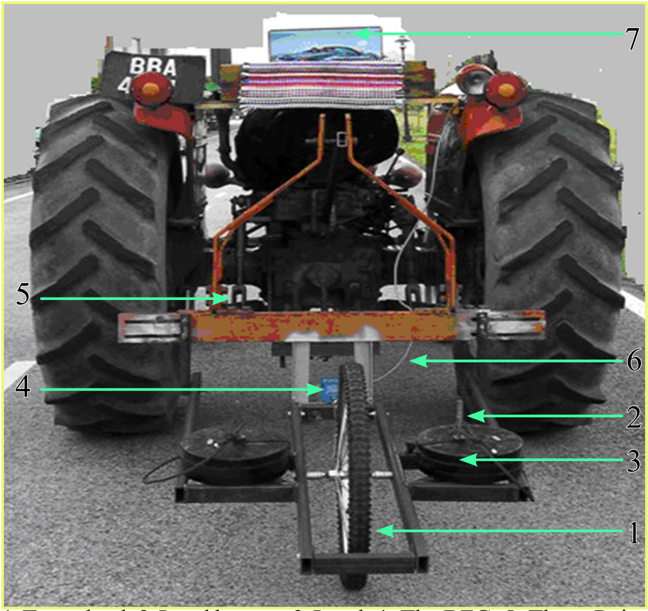
Fig.1 shows a complete test rig developed for motion resistance measurement as a subset of the traction studies on non-lug narrow wheel. The data acquisition system part of the test rig comprising of the Mecmesin Basic Force Gauge 2500 (BFG 2500) RS interfaced with the notebook PC is capable for real time data acquisition of the towing force (motion resistance).

The Test Variables

The test variables considered for this study were the test wheels (pneumatic and the rigid wheels), four levels of dynamic loads (98.1 N, 196.2 N, 392.4 N and 588.6 N), by taking into consideration the average weight of human being of 60kg (588.6 N) and the load bearing capacity of the selected tyre. Two test surfaces (tilled and the wet surfaces), and the three levels of towing velocities (4.44 km/h, 6.3 km/h and 8.28 km/h) were selected to investigate the effect of towing velocity on the motion resistance ratio, as shown in the subsequent section.

The Effect of Towing Velocity

Three levels of towing velocities of 4.44 km/h, 6.3 km/h and 8.28 km/h were selected. This is as a result of different agricultural operations requiring different operating velocities (speeds). The motion resistances and soil cone indices were taken with regard to the empirical and semi-empirical approaches for the determinations of the motion resistance ratios. The process was repeated three times and the average data were taken and recorded for each level of towing velocities for both the pneumatic and the rigid wheel. The tyre inflation pressure of



1-Test wheel, 2-Load hanger, 3-Load, 4- The BFG, 5- Three-Point Hitch Frame, 6-connecting cable and 7- Notebook PC

Fig.1: The complete Test Rig attached to the Towing Tractor

the pneumatic wheel was kept at a constant inflation pressure of 414 kPa, as this pressure was assumed to be equal to the tyre surface of the rigid wheel. Meanwhile, the inflation pressure of the tyre was continuously checked to ensure that it was constant throughout the study.

Rigid Wheel Description

The tyre and tube of the 660 mm diameter steel rim pneumatic wheel were removed. A length of 2075 mm of galvanised sheet plate (1.5 mm in thickness and 50 mm in width) was welded round the circumference of the rim. The 50 mm width tyre having the same thread pattern as the pneumatic wheel with equal length as the sheet metal plate was cut and glued onto the sheet metal covering the rim. For rigidity, the two materials were also joined at the edge by a number of bolts and nuts at an interval of 100 mm round the wheel. Fig.2 shows a schematic diagram of the rigid wheel.

Test Surface Preparation

The preparation for data acquisition on the different test surfaces was different. The tests were conducted in one direction only, with the aim to maintain the same test surface condition (slope) for all the tests.

The undisturbed soil of 45 m x 20 m, located at Taman Pertanian Universiti (TPU-University Agricultural Park), was first ploughed and after 48 hours, the rotavator was used to break the large clods into smaller soil clods which were similar to soil bed preparation ready for planting operation. The tests conducted afterwards used the soil moisture probe that was attached to the *Eijkelkamp (Netherlands)* soil penetrologger series (series 06.15.SA) for *in situ* moisture content measurement. The average soil moisture content was then calculated and the range is as stated in Table 3. The field was re-prepared by using a rotavator to make

Fig.2: The Constructed Rigid Bicycle Wheel

the soil surface even and loose to ensure uniform test conditions. The distance of tractor travel during the test from the starting to the end point was set at 35 m for all the tests conducted on the tilled surface.

A bottom-opened box of a size of 20 m x 0.6 m x 0.2 m was installed in the same tilled field. The dimensions of the box, especially the width and the height, were chosen with reference to the test tractor chassis (wheel base and the height). For the tests conducted on the wet surface, the test distance was set at 20m, which is the length of the box. Prior to the test and in between the test, the box was flooded with water and mixed with the soil so as to get the desired wet surface condition. The average soil moisture contents recorded on the wet surface during the test are as stated in Table 3.

Procedure for Data Acquisition

The tractor towing the test rig was prepared to be in a very good condition for the test. The test rig was assembled (i.e. the test wheel was fixed to the test rig). The first level of an added dynamic load (dead weight) of 98.1 N (10kg) was screwed to the load hanger and the tyre inflation pressure of 414 kPa was maintained. The data acquisition system was put on to facilitate real-time data transfer to the Dataplot software installed on the notebook PC for data acquisition. The test distance (between the starting and ending points) was marked. The tractor was allowed to attain a steady velocity of 4.44 km/h for all the tests, except for the tests conducted to investigate the effects of towing velocities before the starting point, while the start icon on the Dataplot environment was also initiated. The real-time data acquisition to measure the towing force (N) against the time taken (seconds) in the form of Force –Time graph was taken progressively until the end point, i.e. when the stop icon was also clicked to stop the data transfer and the plot. The minimum, maximum and the average towing forces (motion resistance) were obtained from the dataplot. Each of the treatments was replicated three times and the average of at least 95% was taken of the measured data around the mean ($\mu \pm 2\delta$).

The Analytical Prediction Method (Semi-empirical Approach)

The mobility number models derived by Brixius (1987) were used for the prediction of the motion resistance ratio, which was also derived by Brixius (1987). Equations 4 and 5 present the Brixius (1987) models for mobility number and motion resistance ratio respectively. However, Equation 5 had been modified (as presented in Equation 6) as the slip component of that equation is zero (0) for the towed wheels (Gee-Clough *et al*., 1978; Naderi *et al*., 2008).

$$Bn = \frac{CIbd}{W}\left[\frac{1+5\frac{\delta}{h}}{1+3\frac{b}{d}}\right] \qquad [4]$$

$$M_{RR} = 0.04 + \frac{1}{B_n} + \frac{0.5}{\sqrt{B_n}} \qquad [5]$$

$$M_{RR} = 0.04 + \frac{1}{B_n} \quad [6]$$

Equations 5 and 6 are dependent upon Equation 4; therefore, the mobility number was determined from Equation 4, and the value substituted into Equation 6 to determine the motion resistance ratio.

Procedure for Data Acquisition for the Semi-empirical Approach Method

These soil resistances to penetration were measured on the surfaces (path) where the motion resistances were already measured experimentally using the cone penetrologger. Three readings were taken as applicable to the empirical method and the average values were processed for the prediction of the mobility number and the motion resistance ratio.

The procedure for the empirical measurement of the motion resistance on the wet surface was similar to that of the tilled surface. The cone indices were also measured in a similar way to those obtained for the tilled surface. However, the surface of the test wheel, which was in contact with the test surface, was cleaned after every test to ensure similar tyre surface. The test surface was regularly reconditioned to the original state by closing the rut formed during the test and disturbing the test surface and making the surface moist to give uniform test condition.

The sectional width and the sectional height at 414 kPa tyre inflation pressure were measured using the *Mitutoyo* (UK) vernier calliper (series 573) with an accuracy of 0.01cm. The loaded and unloaded radii during the field tests were also measured using the meter rule. The difference is a measure of the tyre deflection, according to Equation 7.

$$\delta = U_R - L_R \quad [7]$$

U_R is the unloaded radius, while L_R is the loaded radius, and δ is the tyre deflection. The rigid wheel has a zero deflection.

RESULTS AND DISCUSSION

From the initial analysis of the experimental data, the analysis of variance showed that at 20kg (196.2 N) added dynamic load, there were significant differences between the mean of the motion resistances measured at 414 kPa inflation pressure and at all levels of the dynamic loads. On this basis, the overall wheel diameter of 660 mm was chosen for this study at 196.2 N added dynamic load and 414 kPa similar to the hard surface of the rigid wheel.

The tyre design parameters, the average soil resistance to penetration, the various dynamic loads are recorded against the respective average moisture contents, as shown in Tables 4a and b. These parameters were substituted into Equation 4 so as to obtain the mobility number for each of the test combinations and these values were substituted into Equation 5 to get the motion resistance ratios. The motion resistance ratio (measured by the empirical methods) and the corresponding dynamic loads were also substituted into Equation 3 to determine the motion resistance ratios. The motion resistance ratios obtained from the two approaches at a constant towing velocity of 4.44 km/h and at varying dynamic loads are presented in Tables

TABLE 4(a): Tyre parameters, soil parameters and dynamic loads on the tilled surface

Test Combinations	Total dynamic load (N)	Motion resistance (N)	Tyre design parameters				Average CI (MPa)	Average mc (%wb)
			d, mm	b, mm	h, mm	δ, mm		
D_pL_1	321.768	28.2374	660	49.3	42.5	5.00	0.60	5.70
D_pL_2	419.868	46.5037	660	49.3	42.5	7.00	0.83	6.00
D_pL_3	616.068	64.1054	660	49.3	42.5	10.00	0.90	11.00
D_pL_4	812.268	90.6656	660	49.3	42.5	13.00	1.20	11.00
D_RL_1	325.201	57.8055	580	49.5	4.0	0	1.23	14.00
D_RL_2	423.301	72.1290	580	49.5	4.0	0	1.43	12.00
D_RL_3	619.501	112.5968	580	49.5	4.0	0	1.10	7.00
D_RL_4	815.701	198.3133	580	49.5	4.0	0	0.90	14.00

*D_P-pneumatic wheel, D_R- rigid wheel, $L_{1\text{-}4}$ –additional load (98.1N, 196.2 N, 392.4 N and 588.6N)

TABLE 4(b): Tyre parameters, soil parameters and dynamic loads on the wet surface

Test Combinations	Total dynamic load (N)	Motion resistance (N)	Tyre design parameters				Average CI (MPa)	Average mc (%wb)
			d, mm	b, mm	h, mm	δ, mm		
D_pL_1	321.768	81.7383	660	49.3	42.5	5.00	1.0333	42
D_pL_2	419.868	94.4724	660	49.3	42.5	7.00	1.2000	44
D_pL_3	616.068	143.6779	660	49.3	42.5	10.00	1.3000	43.7
D_pL_4	812.268	157.9837	660	49.3	42.5	13.00	1.2667	42.3
D_RL_1	325.201	103.4037	580	49.5	4.0	0	0.8000	37
D_RL_2	423.301	148.7016	580	49.5	4.0	0	0.9000	35.7
D_RL_3	619.501	161.3703	580	49.5	4.0	0	1.0333	41.3
D_RL_4	815.701	215.0599	580	49.5	4.0	0	1.3000	45

*D_P-pneumatic wheel, D_R- rigid wheel, $L_{1\text{-}4}$ –additional load (98.1N, 196.2 N, 392.4 N and 588.6N)

5a and 5b. Table 6 shows the motion resistances of the pneumatic and the rigid bicycle wheels, with respect to dynamic loads.

The motion resistances measured on the tilled and wet surface revealed that the rigid wheel had a higher motion resistance and motion resistance ratios than the pneumatic wheel. The motion resistance of the rigid wheel on the tilled surface was about 50% greater than those of the pneumatic wheel. However, on the wet surface, the motion resistances of the rigid wheel were greater than those of the pneumatic wheel by 11-37%. The motion resistance ratios predicted from the Brixius model were lower than those determined using the experimental approach on both the test surfaces. This result is not at variance with the findings of Gee-Clough *et al*. (1978), Perdok (1978), and Islam (1986). The motion resistances determined empirically for both wheels were found to have increased with the increase in the dynamic load, whereas the motion resistance ratios of both the wheels were shown to have decreased with the increase in the dynamic load on wet surfaces, and increased with the increase in the dynamic loads on the tilled surface. Nonetheless, the motion resistances ranged between good and fair according to the Saarilahti (2003) classifications, with the exception of the rigid wheel at lower additional

TABLE 5(a): Motion resistance ratios obtained from the empirical approach

Added Dynamic Load (N)	Tilled Surface		Wet Surface	
	Pneumatic	Rigid	Pneumatic	Rigid
98.1	0.0878	0.1778	0.2540	0.3180
196.2	0.1108	0.1704	0.2250	0.3513
392.4	0.1041	0.1818	0.2332	0.2605
588.6	0.1116	0.2431	0.1945	0.2637

TABLE 5(b): Motion resistance ratios obtained from the analytical approach

Added Dynamic Load (N)	Tilled Surface		Wet Surface	
	Pneumatic	Rigid	Pneumatic	Rigid
98.1	0.1091	0.1052	0.0903	0.1245
196.2	0.1014	0.1098	0.0897	0.1323
392.4	0.0977	0.1431	0.0934	0.1472
588.6	0.1002	0.1792	0.0984	0.1503

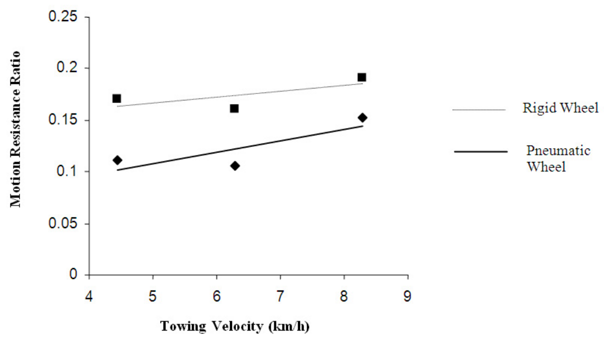
TABLE 6: Motion resistances of pneumatic and rigid wheels measured empirically

Added Dynamic Load (N)	Tilled Surface		Wet Surface	
	Pneumatic	Rigid	Pneumatic	Rigid
98.1	28.2374	57.8055	81.7383	103.4037
196.2	46.5073	72.1290	94.4724	148.7016
392.4	64.1054	112.5968	143.6779	161.3703
588.6	90.6656	198.3133	157.9837	215.0599

dynamic loads which showed poor mobility.

From the semi-empirical approach, it is difficult to conclude the nature of the relationships that existed between the motion resistance ratios and the dynamic loads. However, the motion resistance ratios predicted were directly proportional to the added dynamic load for both the wheels, except for the pneumatic wheel which exhibited an inverse relationship between the motion resistance ratio and the added dynamic load. The motion resistance ratios under this condition fell under a good mobility classification.

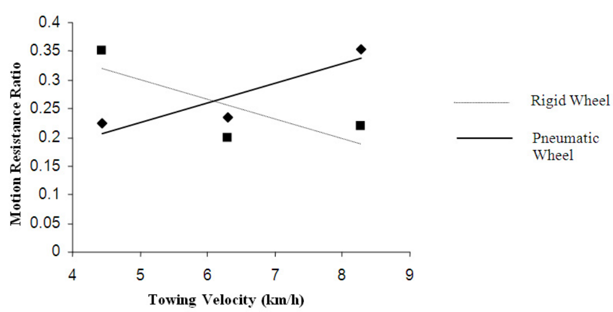
Fig.3 and Fig.4 show the graphical relationships between the motion resistance ratios and the towing velocities of both the wheels on the tilled and wet surfaces, respectively, based on the empirical data. The mathematical relationships between the motion resistance ratio and their towing velocities are presented in Equations 8 to 11. On the tilled surface, the motion resistance ratios of both the wheels had direct relationships with the towing velocity. This could also be inferred from the equation having positive coefficient of towing velocity (v). The pneumatic wheel also showed a similar relationship on the wet surface with a higher coefficient of regression. As shown in Fig.4, when the towing velocities increased, the motion resistance ratio of the rigid wheel would decrease. This can also be seen in Equation 11, where



$\tau_P = 0.0109V + 0.0543,\ R^2 = 0.6709$---- [8]

$\tau_R = 0.0054V + 0.1398,\ R^2 = 0.4642$---- [9]

Fig.3: A Comparison of the Motion Resistance Ratio of Pneumatic and Rigid Wheels on the Tilled Surface in terms of Towing Velocity



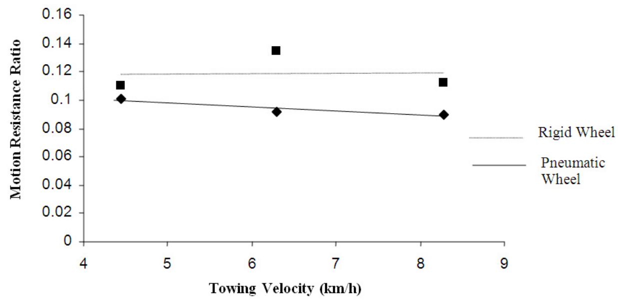
$\tau_P = 0.0333V + 0.0609,\ R^2 = 0.8228$---- [10]

$\tau_R = -0.034V + 0.4708,\ R^2 = 0.6266$---- [11]

Fig.4: A Comparison of the Motion Resistance Ratio of Pneumatic and Rigid Wheels on Wet Surface in terms of Towing Velocity

the towing velocity, v, had a negative coefficient.

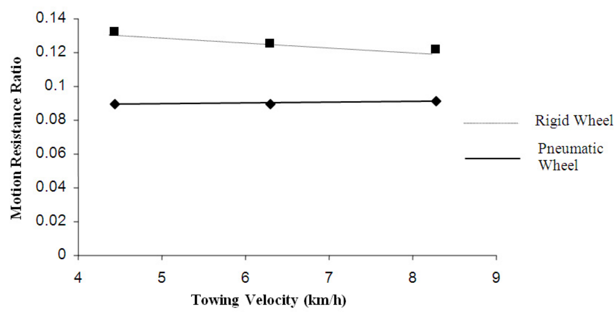
Fig.5 and Fig.6, as well as Equations 12 to 15, present the relationships between the motion resistance ratios of both the wheels obtained from the semi-empirical approach on the tilled and wet surfaces. The relationships between the motion resistance ratios and the towing velocities from the two approaches were found to differ. In particular, the motion resistance ratio of the pneumatic wheel is indirectly proportional to the towing speed at 0.8943 coefficient of regression, while the rigid wheel shows a direct relationship at a very low coefficient of regression on the tilled surface. However, the relationship on the wet surface is similar to that obtained from the empirical method. The motion resistance ratio of the rigid wheel is indirectly proportional to the towing velocity, while the pneumatic wheel has a direct relationship. From these findings, it can be concluded that the rigid wheel is a better traction member on wet surfaces.



τ_P = - 0.003V + 0.1134, R^2 = 0.8943---- [12]

τ_R = 0.0004V + 0.1160, R^2 = 0.0037----[13]

Fig.5: A Comparison of the Motion Resistance Ratio of Pneumatic and Rigid Wheels on Tilled Surface in terms of Towing Velocity: the Analytical Approach



τ_P = 0.0004V + 0.0875, R^2 = 0.7602 ---- [14]

τ_R = -0.0027V + 0.1435, R^2 = 0.945---- [15]

Fig.6: A Comparison of the Motion Resistance Ratio of Pneumatic and Rigid Wheels on Wet Surface in terms of Towing Velocity: The Analytical Approach

The motion resistance ratios, measured by the empirical and the semi-empirical methods, also differed. The motion resistance ratios predicted from the Brixius equation were found to be lower than those measured experimentally, and the main reason for this could be attributed to the size of the tyre used to derive the model. Therefore, a multiplying factor was used to derive the new motion resistance ratio models for the pneumatic and rigid bicycle wheels on two deformable terrains. The factors are stated in Tables 7 and 8, and the models are presented in Equations 16 to 19.

From Brixius' (1987) equation for bias-ply tractor tyres, the motion resistance ratio is as stated in Equation 5. Therefore, for the 660 mm pneumatic bicycle wheels at 414 kPa inflation pressure, the motion resistance ratio was derived, as follows:

$$MRR\ (Bicycle) = 2.0254.\ (0.04 + \frac{1}{B_n})$$
$$MRR\,(Bicycle) = 0.0810 + \frac{2.0254}{B_n} \qquad [16]$$

TABLE 7: Determination of the factors between motion resistance ratio of the pneumatic wheel obtained by empirical and analytical methods at different dynamic loads and 414 kPa

Dynamic Load	A: MRR (Empirical)		B: MRR (Analytical)		C: Factors (A/B)	
(N)	Tilled	wet	Tilled	Wet	Tilled	Wet
98.1	0.0878	0.2540	0.0527	0.0474	1.6660	5.3586
196.2	0.1108	0.2250	0.0504	0.0472	2.1984	4.7669
392.4	0.1041	0.2332	0.0518	0.0482	2.0097	4.8382
588.6	0.1116	0.1945	0.0501	0.0495	2.2275	3.9293
Mean					2.0254	4.7233
Coefficient of variation					12.758%	12.52%

Inflation Pressure, P = 414 kPa and Overall Wheel Diameter (metallic rim), D = 660mm.

Field Condition: Tilled Surface (Sandy-Clay-Loam Soil)
Added Dynamic Load range: 98.1 – 588.6 N

TABLE 8: Determination of the factors between motion resistance ratio of the rigid wheel obtained by empirical and analytical methods at different dynamic loads

Dynamic Load	A: MRR (Empirical)		B: MRR (Analytical)		C: Factors (A/B)	
(N)	Tilled	wet	Tilled	Wet	Tilled	Wet
98.1	0.1778	0.3180	0.0515	0.0578	3.4524	5.5017
196.2	0.1704	0.3513	0.0529	0.0606	3.2212	5.7970
392.4	0.1818	0.2605	0.0646	0.0662	2.8142	3.9350
588.6	0.2431	0.2637	0.0797	0.0675	3.0502	3.9067
Mean					3.1345	4.7851
Coefficient of variation					8.60%	21%

Field Condition: Tilled Surface (Sandy-Clay-Loam Soil)
Added Dynamic Load range: 98.1 – 588.6 N

Field condition: Wet soil (sandy-clay-loam soil) surface
Added dynamic load range: 98.1 – 588.6 N

From Brixius' (1987) equation for bias-ply tractor tyres, the motion resistance ratio is as stated in Equation 5. Therefore, for the 660 mm pneumatic bicycle wheels at 414 kPa inflation pressure, the motion resistance ratio was derived as follows:

$$MRR\ (Bicycle) = 4.7233\ (0.04 + \frac{1}{B_n})$$
$$MRR(Bicycle) = 0.1889 + \frac{4.7233}{B_n} \quad [17]$$

From Brixius' (1987) equation for bias-ply tractor tyres, the motion resistance ratio is as stated in Equation 5. For the rigid bicycle wheel on tilled surface, the motion resistance ratio was therefore derived as follows:

$$MRR\ (Bicycle) = 3.1345.\ (0.04 + \frac{1}{B_n})$$
$$MRR(Bicycle) = 0.1254 + \frac{3.1345}{B_n} \quad [18]$$

Field condition: Wet soil (sandy-clay-loam soil) surface
Added dynamic load range: 98.1 – 588.6 N

From Brixius' (1987) equation for bias-ply tractor tyres, the motion resistance ratio is as stated in Equation 5. Therefore, for the rigid bicycle wheel, the motion resistance ratio was derived as follows:

$$MRR\ (Bicycle) = 4.7841.\ (0.04 + \frac{1}{B_n})$$
$$MRR(Bicycle) = 0.1914 + \frac{4.7841}{B_n} \quad [19]$$

CONCLUSION

In conclusion, the motion resistance and motion resistance ratios of 660 mm pneumatic and the rigid bicycle wheels were determined both empirically and analytically on tilled and wet surfaces. The motion resistances measured on the wet surface by both the wheels were greater than those obtained on the tilled surface with the rigid wheel leading in all the cases. The motion resistance ratios obtained through empirical methods were greater than those of the semi-empirical ones. Hence, different relationships between motion resistance ratios, the dynamic loads and the towing velocities exist on different surfaces with different wheel types. The rigid wheel is a better traction member on the wet surface at any forward velocity compared with its pneumatic counterpart. The semi-empirical approach under-predicted the motion resistance ratios compared to the empirical method. Based on this, a new set of motion resistance ratio models were derived for predicting motion resistance ratios of pneumatic and rigid bicycle wheels on deformable surfaces (tilled and wet surfaces).

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