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Investigative Studies on the Effects of Tyre Inflation Pressure on the Motion Resistance of Pneumatic Bicycle Wheels on Hard and Deformable Surfaces

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Abstract: The effects of tyre inflation pressures on the motion resistance of four pneumatic bicycle wheels on four test surfaces were investigated using the previously developed motion resistance test rig for traction studies. The motion resistances which is equal to the towing force were measured with the aid of the Mecmesin Basic Force Gauge (BFG 2500) mounted on the test rig and RS 232 interfaced to the notebook PC for real time data acquisition. Four pneumatic bicycle wheels of overall wheel diameter of 660 mm, 610 mm, 510 mm and 405 mm. The four test surfaces were the paved, grass field, tilled and wet surfaces. Three inflation pressures of 276 kPa (40 psi), 345 kPa (50 psi) and 414 kPa (60 psi) were chosen and investigated in the study. This study was conducted at four levels of added dynamic loads at a constant tractor towing velocity of 4.44 km/h. There were significant differences between motion resistances measured on different test surfaces and at different dynamic loads and different tyre inflation pressures. The motion resistances measured against each wheel show that at lower inflation pressure (276 kPa), the motion resistances were higher and decreased as the tyre inflation pressure increased especially with 660 mm and 610 mm wheels. With higher dynamic load and higher inflation pressure, the motion resistance was considerably lower compared with low pressure and higher loads. This information would be useful in the development of the low cost and easy to maintain agricultural machinery for low income farmers and rural dwellers.
Key words: Motion resistance, motion resistance ratio, overall wheel diameter, test surfaces, dynamic loads, test rig

NTRODUCTION

The behaviour of wheels differs from surface to surface. Wheels which could be pneumatic or rigid. Wheels could also be wide or narrow. Agricultural wheels are of different sizes and dimensions known as the tyre design parameters. As a result of different design parameters, the tractive performance measures also differ and therefore, the need to study the individual tyre tractive performance is pertinent. Mobility studies of agricultural wheels for on and off-road performance is of great significance for agricultural vehicle designers.

The tractive performance of wheels can be measured in terms of net traction ratio, gross traction, tractor drawbar pull, motion resistance, motion resistance ratio, tractive effort and tractive efficiency.

In this study, the tractive performance measure investigated is the motion resistance of narrow wheels (pneumatic bicycle wheels). Motion resistance could be defined with respect to tractive and transport devices. It is defined in terms of tractive device as the difference between the gross and the net tractions **(MR = GT-NR),** and in terms of transport device, it is the force required in the direction of travel to overcome the resistance from the supporting surfaces or the surface upon which it rolls and the internal resistance of the device (tyre) (references).

Over-inflation and under-inflation of tyre affect tyre tractive performance and tyre life. Therefore, the need to select appropriate tyre inflation pressure for a particular tyre (wheel) on a specified terrain is important to on- and off-road vehicle designers and users.

Plackett (1985) showed that the motion resistance may be expressed as

$$MR_T = MR_c + MR_b + MR_t \quad (1)$$

The total motion resistance force, (MR_T) is therefore made up of the component due to soil compaction, (MR_c), the component due to horizontal soil displacement (MR_b) and the components due to flexing of the tyre (MR_t). For vehicle operating on a hard surface, MR_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 tyre. However, in off-road situation, the components MR_c and MR_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 motion resistance.

Motion 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. The later definition being suitable for a study of the nature of the stresses on the soil–wheel interface. Usually, the motion resistance is expressed in terms of coefficient of rolling resistance preferably called motion resistance ratio, τ, (Code, 2003-S296.5). Thus, mathematically, the motion resistance ratio is as expressed in equation 2 (Arregoces, 1985; Code, 2003).

$$MRR(\tau) = \frac{MR}{W} \quad (2)$$

Where; MR is the motion resistance force suffered by the wheel and W is the normal load on the wheel.

There are two approaches for determining the motion resistance ratio of a test wheel. Macmillan (2002) classified the two methods as the empirical method (experiment) which involves the direct measurement of the motion resistance (towing force) from a test rig. And applying the equation 2 for determining the motion resistance ratio. The second approach is the semi empirical or the analytical prediction which involves the measurement of the tyre design parameters, the soil parameters and the system parameters, and substituting these values into existing models such as Tunage (1972) model, Wismer and Luth (1974) model, Gee-Clough (1978) and Brixius (1987) motion resistance ratio models.

The objective of this paper is to investigate the effect of tyre inflation pressure on the motion resistance of four bicycle wheels of different overall wheel diameters on the paved surface, grass field, tilled surface and on wet surface at four levels of added dynamic loads of 98.1 N, 196.2 N, 392.4 N and 588.6 N. This paper will also suggest the appropriate tyre inflation based on the manufacturer's recommendation.

MATERIALS AND METHOD

In this study, we employed the empirical method described by Macmillan (2002) using a previously developed motion resistance test rig presented in Figure1. The test rig is a simple on field apparatus pulled by the tractor at a predetermined towing velocity of 4.44 km/h for all tests on all the test surfaces for measuring the towing force in real time with the aid of the Mecmesin BFG and the data acquisition system.

Test Variables.

Tyre inflation pressure- three levels of tyre inflation pressures considered were; 276 kPa, 345 kPa and 414 kPa, these pressures were chosen from the range specified by the manufacturer.

Overall wheel diameter- Four pneumatic bicycle wheels of equal sectional width of 50 mm and overall wheel diameter of 405 mm, 510 mm, 610 mm and 660 mm were considered for the study.

Dynamic Load- Four levels of added dynamic loads were used in this study which were added to the total weight of the wheel and the test rig frame (See Table 1). These added loads were; 98.1 N (10 kg), 196.2 N (20 kg), 392.4 N (40 kg) and 588.6 N (60 kg).

Test Surface- Four test surfaces were considered for this study, the paved surface and the grass field (Hard surface), and the tilled and wet surfaces (deformable surface).

Deformable surface (soil) properties- Table 2 shows the summary of some of the physico-mechanical properties of the deformable surfaces.

Test surface preparation: The preparation for data acquisition on the different test surfaces was different. All the test surfaces were located within the Universiti Putra Malaysia. On the paved surface a test area of 60 m x 2 m was demarcated and the starting and the end points were marked out. The tests were conducted in one direction only.

On the grass field, the test area of 45 m x 4 m was demarcated for the tests and the same travel direction was used for all the test wheels and the test variables. The starting and the end points were also marked as done on the paved surface.

The undisturbed soil of 45 m x 20 m was first ploughed and after 48 hours, the rotavator was used to break the large clods into smaller soil clods similar to soil bed preparation ready for planting operation. The loose soil was left for another 3 days before the tests commenced. The soil moisture probe attached to the *Eijkelkamp* soil penetrologger for in-situ moisture contents measurement was used to measure the average soil moisture content. Since it was difficult to get a large area of land for these tests considering the number of test runs, after the completion of two pressure levels (experimental runs at 276 and 344 kPa), the field was re-prepared by using a rotavator to make 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 as 35 m for all the tests conducted on the tilled surface.

For the tests conducted on the wet surface, the test distance was set at 20 m which is the length of the soil box installed on the tilled surface prior to wetting.

Procedure for field data collection- 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 added dynamic load (dead weight) of 98.1 N (10 kg) was screwed to the load hanger and the first level of inflation pressure (276 kPa) was maintained. The data acquisition system was put on to facilitate real time data transfer to the Dataplot software installed on the notebook for data acquisition. The test distance (starting and the end points) was marked. The tractor was allowed to attain a steady velocity of 4.44 km/h as stated above before the starting point and the start icon on the Dataplot environment was also initiated and the real time data acquisition of measuring the towing force (N) against the time taken (seconds) in the form of Force-Time graph was taken progressively until at the end point when the stop icon was also clicked to stop the data transfer and the plot. The minimum, maximum and the average towing force (motion resistance) was obtained from the dataplot. Each of the treatments was replicated three times and the average was taken at least 95% of the measured data around the mean ($\mu \pm 2\delta$).

Experimental design and statistical analyses- A 2 X 2 factorial design was adopted for this study. This is done by keeping the test surface and the test wheel constant and varying the tyre inflation pressure and the added dynamic loads.

The Analyses of Variance (ANOVA) of the mean values of the motion resistance measured experimentally were carried out to determine significance differences between the means of the motion resistance ratio measured on all the test surfaces, the different wheel sizes, and the interactions between the test surfaces and the various wheel sizes. The Analysis of Variance was also conducted determine significant differences between the mean of the motion resistance on all the test surfaces, the three levels of tyre inflation pressures, and the four levels of dynamic loads and their respective interactions with the means motion resistance on all the test surfaces The regression analyses was used to The regression analysis was used to show the type of mathematical relationships between the respective independent test variables of wheel diameter, tyre inflation pressures, dynamic loads and the motion resistance ratio and motion resistance in some cases. Various mathematical models such as the linear, pure quadratic, full quadratic and the logarithmic models were tested for different test surface to get the best relationship (model) for the particular surface. The relationships between the combinations of the independent variables and the response variable (Motion resistance ratio) were also established for each test surface.

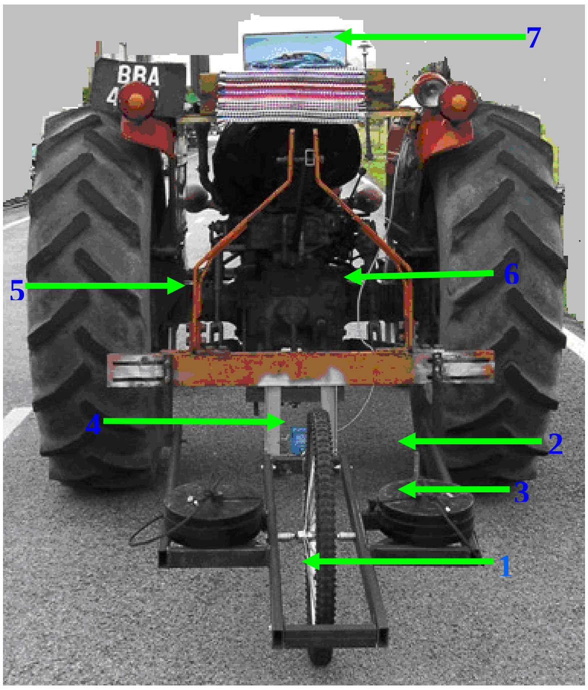

Figure 1. The complete single wheel motion resistance test rig (1-Test wheel, 2-Load hanger, 3-Load, 4- The BFG, 5- Three-point Hitch frame, 6- Connecting cable and 7- Notebook PC)

RESULTS and DISCUSSION

Tables 3 to 6 show the average motion resistance ratios of all the test wheels on the wet surface, tilled surface, paved and the grass field respectively. Where P1, P2, and P3 represents the three levels of tyre inflation pressures of 276 kPa, 345 kPa and 414 kPa respectively. And the four levels of added dynamic loads; 98.1 N, 196.2 N, 392.4 N and 588.6 N were denoted by L1, L2, L3 and L4 respectively.

From tables of results presented in Tables 3-6, 52.4% of the motion resistance ratios measured decreased when the tyre inflation pressure was increased from 276 kPa to 345 kPa and 414 kPa. While, 47.6% shows an increase in the motion resistance ratio with increase in the tyre inflation pressure from 276 kPa to 345 kPa and 414 kPa. A further analysis shows that the there was a significant decrease in motion resistance ratio with respect to the wheel size, with 660mm wheel having the highest reduction in motion resistance ratio with increase tyre inflation pressure, followed by the 610mm wheel. Equal chances were observed with respect to the test surfaces and the added dynamic loads with 40 and 60 kg added dynamic load having the highest frequencies of reduced motion resistance ratio as the tyre inflation pressure increases. With this difference, we can infer that with increase in tyre inflation pressure, the motion resistance ratio of towed pneumatic bicycle wheels reduces.

From the tables of results presented in Tables 3-6, it was observed that the 660 mm wheel had the lowest occurring motion resistance ratio followed by 610 mm. The 660 mm wheel was therefore selected to use the regression analysis to investigate the relationship between the motion resistance and the tyre inflation pressure. Figures 2-5 show the graphical relationships between the motion resistance ratios and the tyre inflation pressure at the four levels of added dynamic loads on the four test surfaces. Equations 3- 15 show the mathematical relationships between the motion resistance ratios and the tyre inflation pressures. The coefficient of determination of regression (R^2) against each equation is also stated, but the generalised relationship has been established irrespective of the values of (R^2). From these relationships we can infer that increasing the tyre inflation pressure will lead to a decrease in the motion resistance ratio.

Table 1. Analysis of total dynamic loads

Wheel Dia. Inches (mm)	Weight of wheel and the frame (N)	Dynamic Loads levels (N)				Total vertical loads (N)			
16" (405)	21.88 (214.64)	98.1	196.2	392.4	588.6	312.74	410.84	607.84	803.24
20" (510)	22.18 (217.59)					315.69	413.79	609.99	806.19
24" (610)	22.50 (220.73)					318.83	416.93	613.13	809.33
26" (660)	22.52 (220.92)					319.02	417.12	613.32	809.52

Table 2. 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)

Table 3. Summary of motion resistance ratios of the test wheels on wet surface using the empirical approach

Test Combination	Overall wheel Diameter (mm)				Selected Wheel. (mm)
	405	510	610	660	
P_1L_2				0.2116	
P_2L_2				0.1623	

Table 4. Summary of motion resistance ratios of the test wheels on tilled surface using the empirical approach

Test Combination	Overall wheel Diameter (mm)				Selected Wheel. (mm)
	405	510	610	660	
P_1L_1	0.1596	0.1882	0.1184	0.1554	**610**
P_1L_2	0.1849	0.1429	0.1050	0.1373	**610**
P_1L_3	0.2244	0.1858	0.1305	0.1746	**610**
P_1L_4	0.2202	0.1813	0.1257	0.1326	**610**
P_2L_1	0.1477	0.1121	0.1056	0.1017	**660**
P_2L_2	0.1616	0.0955	0.1530	0.0862	**660**
P_2L_3	0.1563	0.1298	0.1346	0.1011	**660**
P_2L_4	0.2045	0.1317	0.1306	0.0925	**660**

Table 5. Summary of motion resistance ratios of the test wheels on paved surface using the empirical approach

Test Combination	Overall wheel Diameter (mm)				Selected Wheel. (mm)
	405	510	610	660	
P_1L_1	0.0192	0.0107	0.0186	0.0184	**610**
P_1L_2	0.0217	0.0180	0.0144	0.0178	**610**
P_1L_3	0.0239	0.0132	0.0197	0.0155	**610**
P_1L_4	0.0238	0.0218	0.0179	0.0134	**660**
P_2L_1	0.0237	0.0247	0.0222	0.0173	**660**
P_2L_2	0.0270	0.0211	0.0174	0.0156	**660**
P_2L_3	0.0225	0.0188	0.0171	0.0147	**660**
P_2L_4	0.0254	0.0234	0.0152	0.0116	**660**
P_3L_1	0.0278	0.0227	0.0150	0.0156	**610**
P_3L_2	0.0240	0.0239	0.0136	0.0175	**610**
P_3L_3	0.0278	0.0174	0.0162	0.0129	**660**

Table 6. Summary of motion resistance ratios of the test wheels on grass field using the empirical approach.

Test Combination	Overall wheel Diameter (mm)				Selected Wheel. (mm)
	405	510	610	660	
P_1L_1	0.0200	0.0140	0.0194	0.0250	**510**
P_1L_2	0.0228	0.0214	0.0194	0.0205	**610**
P_1L_3	0.0221	0.0164	0.0159	0.0193	**610**
P_1L_4	0.0181	0.0188	0.0157	0.0179	**610**
P_2L_1	0.0212	0.0130	0.0209	0.0180	**510**
P_2L_2	0.0226	0.0139	0.0188	0.0193	**510**
P_2L_3	0.0229	0.0186	0.0197	0.0176	**660**
P_2L_4	0.0195	0.0165	0.0154	0.0177	**610**
P_3L_1	0.0238	0.0149	0.0206	0.0187	**510**
P_3L_2	0.0208	0.0148	0.0205	0.0214	**510**
P_3L_3	0.0189	0.0156	0.0182	0.0150	**660**
P_3L_4	0.0193	0.0180	0.0176	0.0165	**660**

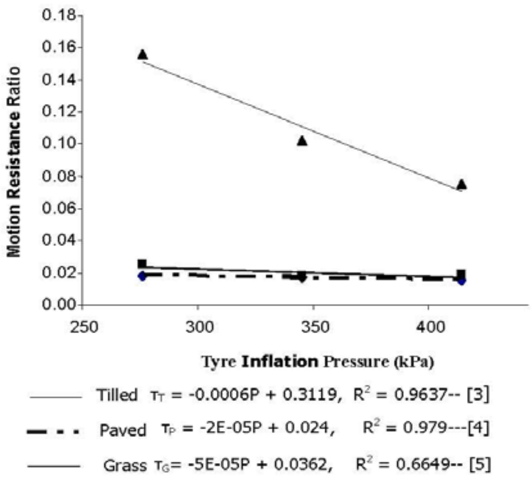

Figure2. Relationship between motion resistance ratio and tyre inflation pressure at 98.1 N added dynamic load on 660mm wheel

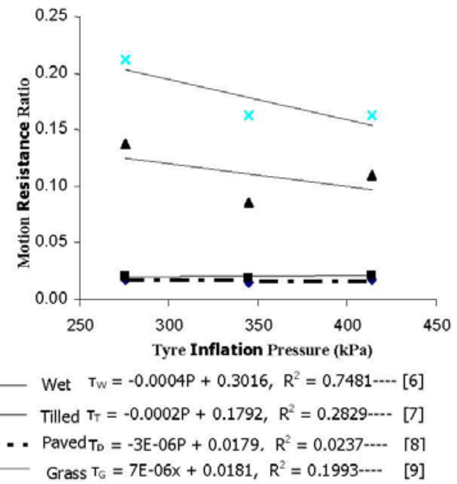

Figure 3. Relationship between motion resistance ratio and tyre inflation pressure at 196.2 N added dynamic load on 660mm wheel

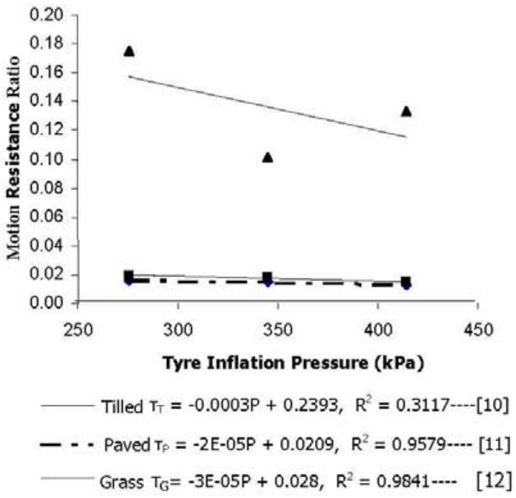

Figure 4. Relationship between motion resistance ratio and tyre inflation pressure at 392.4 N added dynamic load on 660mm Wheel

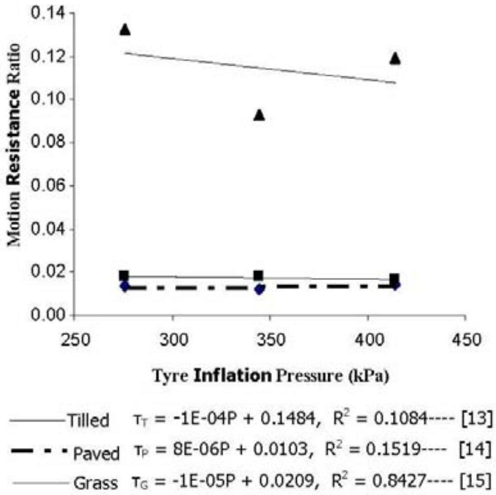

Figure 5. Relationship between motion resistance ratio and tyre inflation pressure at 588.6 N added dynamic load on 660mm wheel

CONCLUSIONS

The following were concluded from the study:

- The motion resistance ratios of the bicycle wheels were indirectly proportional to the tyre inflation pressure on all the test surfaces at all levels of added dynamic loads.
- The 660 mm wheel had the lowest occurring motion resistance ratio on all the test surfaces except on the grass field.

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