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PREDICTION OF WHEEL NUMERIC FOR SANDY-TIRE

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ABSTRACT

The various techniques for evaluating the wheel numeric and vehicle performance have been studied. The wheel numeric depends on many parameters; vehicle weight, tire geometry, and soil strength in terms of cone index. The tire geometry includes tire width, tire diameter, section height and tire deformation. The tire deflection is very difficult to accurately measure. So the main purpose of this paper is to develop a new wheel numeric formula with a new parameter depending on the inflation pressure inside the tire instead of the tire deflection.

A theoretical study to investigate the effect of soil cone index, tire geometry and vehicle weight on different wheel numeric has been carried out and so their effects on the vehicle performance have been carried out. The performance of off road vehicle on soft soil in terms of rolling resistance, drawbar pull and tractive efficiency has been studied and investigated using variety of methods. These include; theoretical, semi-empirical and empirical methods based on wheel mobility number. The results showed that the new numeric formula gives a good correlation with published results at different soil cone index, vehicle weight, tire width, tire diameter and tire inflation pressure. Also the predicted performance has a good agreement with published experimental results at same conditions.

KEY WORDS

Off-road vehicle performance, wheel numeric number, inflation pressure.

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NOMENCLATURE

b	Tire section width [m]
CI	Cone index, [kN/m^2]
C_n, N_c,N_{CI},B_n,N_R,N_m	Wheel numeric (wheel mobility numbers)
C_{nn}	New wheel numeric
d	Overall tire diameter [m]
G	Cone index gradient
h	Tire section height [m]
k	Constant (fit parameter)
k_c	Soil deformation modulus for cohesive components [kN/m^{n+1}]
k_φ	Soil deformation modulus for frictional components [kN/m^{n+2}]
n	Sinkage exponent
NT	Net Traction, [kN]
NTR	Net Traction Ratio
P	Pull force, [kN]
P_i	Inflation pressure [kPa]
RR	Rolling resistance, [kN]
r	Rolling radius [m]
TDF	Tire deflection factor
TE	Tractive efficiency
W	Weight on tire, [kN]
W_r	Nominal tire load, (rated tire load) [kN]
W_{TW}	Vehicle weight, [kN]
z	Sinkage [m]
μ_{mrr}	Motion rolling resistance ratio
μ_{tr}	Torque ratio
μ_{ntr}	Net traction ratio
$\mu_{ntr_{max}}$	maximum coefficient of net traction ratio
δ	Tire deflection [m]
θ	Moisture content

ABBREVIATION

WES	Waterways Experiment Station

INTRODUCTION

The first steps in the development of a method for evaluating the off road vehicle performance consists of experimental testing of tires on natural terrain surfaces to develop approximate relations between vehicle performance and terrain conditions, many relations have been proposed to predict the tire dimensionless performance. The analytical approach is concerned with predicting the performance of a traction device. The distribution of normal and shear stress at the soil-tire/track interface and the geometry of the 3-D contact surface must be determined. There are two other approaches; empirical and semi-empirical. The empirical approach is based on the cone index for predicting the mobility of vehicles by dimensionless tire performance coefficients (the main task in this paper). The semi-empirical approach involved in measuring soil deformation parameters then calculating the shear-stress. The shear deformation of the soil under a traction device is assumed to be similar to the shear generated by a torsion shear device. Bekker [1-2] assumed the normal stress under a flat plate depends on sinkage, plate width and soil coefficient.

Freitag [3] developed the first dimensionless wheel numeric and empirical mobility models based on wheel numeric. The wheel performance was measured at different weight on standard soils using soil bin and test lanes on terrain. Turnage [4] developed the method further, and presented separate methods for determining the soil properties for friction and cohesion soils and the corresponding mobility models. For cohesion soil the author used an average cone index, and a cone index gradient for the friction soils. Wismer & Luth [5] combined mobility models with soil shear model and included the slip into mobility models. This model became one kind of basic mobility model for several later researches. Gee-Glough [6-7] found out, that soil shear strength was somewhat correlated with penetration resistance, and added a soil shear factor into the model. Brixius [8-9] developed a more generalized expression for tractive characteristics of bias-ply pneumatic tires. The approach is based on a modified mobility number. Maclaurin [10-13] studied the influence of soil surface properties and tire patterns on wheel performance using WES-method as a frame of reference. Rowland [14], Rowland and Peel [15], developed WES modeling depending on a new wheel numeric, and extended it also for tracked vehicles. The author presented the concept of mean maximum pressure MMP, which is the maximum allowable calculated soil contact pressure at no-go situation. Several authors in different countries have used available models, or presented improved versions of empirical mobility models using penetrometer resistance as soil parameter.

WHEEL NUMERIC

The Wheel numeric is a dimensionless variable calculated using a special formula, which includes tire and soil parameters. Different authors have proposed different empirical Wheel numeric models for determining the best fitting combinations of tire dimensions and deflection with observed tire performance. The wheel numeric concept was first derived by Freitage [3] one for clay and the other for sand soil. The wheel performance was measured at different weight on standard soils, using on soil bin and test lanes on terrain.

For clay

$$N_C = \frac{CI\ b\ d}{W}\sqrt{\frac{\delta}{h}} \quad (1)$$

For sand

$$N_S = \frac{G\ (b.d)^{3/2}}{W}.\frac{\delta}{h} \quad (2)$$

Turnage [16-18] developed the method further, and presented separate methods for determining the soil properties for friction and cohesion soils and the corresponding mobility models. For cohesion soil the author used an average cone index, and a cone index gradient for the friction soils. The most empirical relationships to predict the vehicle traction are based on this wheel numeric:

$$N_{CI} = \frac{CI\ b\ d}{W}\sqrt{\frac{\delta}{h}}.\frac{1}{1+\frac{b}{2.d}} \quad (3)$$

Wismer and Luth [5] combined mobility models with soil shear model and included the slip into mobility models. This model became one kind of basic mobility model for several later research offices using a simple wheel numeric:

$$C_n = \frac{CI\ b\ d}{W} \quad (4)$$

Brixius [6-7] developed a more generalized expression for tractive characteristics of bias-ply pneumatic tires. The approach is based on a modified wheel numeric:

$$B_n = \frac{CI\ b\ d}{W}\left(\frac{1+\frac{5\delta}{h}}{1+\frac{3b}{d}}\right) \quad (5)$$

Rowland, D & Peel, J. W. [15] proposed a wheel numeric, used for determining the MMP, with similar results:

$$N_R = \frac{CI\ .b^{0.85}\ .d^{1.15}}{W}\sqrt{\frac{\delta}{h}} \quad (6)$$

Maclaurin [12-14] studied the influence of soil surface properties and tire patterns on wheel performance, and he concluded that a weak surface layer decreases the wheel performance, and that the influence of the surface layer becomes more pronounced with the use of special terrain tires. The factor δ/h replaced by δ/d, which is easier to use without affecting the accuracy of the model. He presented somewhat simpler wheel mobility number, Nm, which seemed to give the best estimates.

$$N_m = \frac{CI \,.\, b^{0.8}\, d^{0.8}\, \delta^{0.4}}{W} \qquad (7)$$

Several authors in different countries have used available models, or presented improved versions of empirical mobility models using penetrometer resistance as soil parameter.

Each one developed empirical relationships between tractive performance parameters and the above wheel numeric which are found.

WHEEL NUMERIC INVESTIGATION BASED ON TIRE INFLATION PRESSURE (CASE STUDY)

A case study of a real test wheel data for Jeep off road 750-R16 from Abdel-Bary [19-20] has been done for examining the wheel numeric's according the effect of their parameters (CI, b, d, W, h, δ). The tire was tested under different load and at different inflation pressure. The tire width, height, diameter and deflection were measured in Table (1). A theoretical study of the parameters (CI, b, d, W, h, δ) as an independent variables [26] is investigated.

Table (1): Experimental tire testing at various loads and inflation pressures [2].

Tire size	Inflation pressure Pi [kPa]	Vertical load W [kN]	Tire width b [mm]	Tire diameter d [mm]	Tire sec. height h [mm]	Tire deflection δ [mm]
750-16	100-250	2-7	205-226	657-776	125-180	0-25

(a) Effect of soil strength
The soil cone index is varied from 400 to 600 kPa and all other parameters are fixed in Equations 1-7. The effect of soil strength in terms of cone index on all wheel numeric is shown in the figure (1). As the cone index increases, the wheel numeric increases where the soil strength has a great effect on wheel numeric by 48%.

(b) Effect of tire width
The tire width is varied from 205 to 226 mm and all other parameters are fixed in Equations 1-7. The effect of tire width on all wheel numeric is shown in the figure (2), as the tire width increases, the wheel numeric increases where the tire width has a considerable effect on wheel numeric by 10 %.

(c) Effect of tire diameter
The tire diameter is varied from 657 to 776 mm and all other parameters are fixed in Equations 1-7. The effect of tire diameter on all wheel numeric is shown in the figure (3). As the tire diameter increases, the wheel numeric increases where the tire diameter has a considerable effect on wheel numeric by 20 %.

(d) Effect of tire weight

The tire weight is varied from 2 to 7 kN and all other parameters are fixed in Equations 1-7. The effect of tire weight on all wheel numeric is shown in the figure (4). As the weight on tire increases, the wheel numeric decreases where the tire weight has a great affect on wheel numeric by 70 %.

(e) Effect of tire section height

The tire section height is varied from 125 to 180 mm and all other parameters are fixed in Equations 1-7. The effect of tire section height on all wheel numeric is shown in the figure (5). As the tire section height increases, the wheel numeric decreases with 12 %.

(f) Effect of tire deflection

The tire deflection is varied from 1 to 25 mm and all other parameters are fixed in Equations 1-7. The effect of tire deflection (δ) on all wheel numeric is shown in the figure (6). As the tire deflection increases, the wheel numeric increases where the tire deflection has a great effect on wheel numeric by 70 %.

From Figures (1 to 6) three intervals of wheel numeric are obtained, the first for the Wismer and Luth wheel numeric C_n. The seconed interval for the Freitage (N_C), Turnage (N_{CI}), Rowland, D & Peel (N_R), Maclaurin (N_m) and the third interval for the Brixus wheel numeric (B_n) which comes in the middle. These intervals lead to conclude that the most accurate range is the second intervals of the majority of wheel numeric for Freitage (N_C), Turnage (N_{CI}), Rowland, D & Peel (N_R), Maclaurin (N_m)

All wheel numeric that published and introduced in equations (1- 7) which studied at different parameters has not included the effect of tire inflation pressure, so the main purpose of this paper is to investigate a new wheel numeric depending on the tire inflation pressure inside the tire deflection.

The author made some iteration using a tire inflation pressure; a new proposed wheel numeric's is investigated using Freitage wheel numeric for sand equation (2) is modified to be dimensionless with a new parameter, tire inflation pressure instead of tire deflection as follows:

$$C_{nn} = \frac{5\ CI\sqrt{P_i}\ (b\ d)^{\frac{3}{2}}}{7\ W^{\frac{3}{2}}} \tag{8}$$

$$C_{nn} = \frac{5\ \frac{kN}{m^2}\sqrt{kPa}\ (m^2)^{\frac{3}{2}}}{7\ kN^{\frac{3}{2}}} = \frac{5\ \frac{kN}{m^2}\sqrt{\frac{kN}{m^2}}\ (m)^3}{7\ kN^{\frac{3}{2}}} = \frac{5}{7} = K \tag{9}$$

This formula is tested for different types of tires (shown in Appendix 1) and it gives good results on sand soil –using manufacture low inflation pressure on Sand– compared with Turnage [18] wheel numeric in equation (2) as in the Table 2.

The tire inflation pressure is varied from 100 to 250 kPa and all other parameters are fixed in Equation 8. The effect of tire inflation pressure on the proposed wheel

Table 2: Comparison of Turnage wheel numeric against proposed wheel numeric based on equation (8) and Appendix (1).

Tire Size	Pi (kPa)	Turnage (N_{CI})	Proposed (C_{nn})	Accuracy %
900-13	103-241	5.221	5.35	97
780-15	82-206	3.647	3.586	98
750-16	100-244	2.665	3.045	88
1200-18	105-322	3.448	4.144	83
1250-20	107-334	3.377	3.968	85

numeric is shown in the figure (7), as the tire inflation pressure increases, Wheel numeric increases. The variation of wheel numeric with the tire inflation pressure change is 57%.

MOBILITY EVALUATION (EMPIRICAL EQUATIONS)

The following methods of evaluating the vehicle mobility using wheel mobility number have been reviewed.

Wismer & Luth [5] developed the following widely used vehicle mobility equations for not highly compactable soils

- Motion resistance ratio:

$$\mu_{mrr} = \frac{RR}{W} = \frac{1.2}{C_n} + 0.04 \tag{10}$$

- Torque ratio:

$$\mu_{tr} = \frac{T}{r * W} = 0.75\,(1 - e^{-0.3 C_n s}) \tag{11}$$

- Net traction ratio (Pull ratio):

$$\mu_{ntr} = \frac{NT}{W} = \mu_{tr} - \mu_{mrr} = 0.75\,(1 - e^{-0.3 C_n s}) - (\frac{1.2}{C_n} + 0.04) \tag{12}$$

- Tractive efficiency:

$$TE = \left[\frac{\frac{NT}{W}}{\frac{T}{r.W}}\right](1-s) = \frac{\mu_{ntr}}{\mu_{tr}}(1-s) = \frac{\mu_{ntr}}{\mu_{ntr} + \mu_{mrr}}(1-s) \tag{13}$$

These equations are valid for the following situations:

$$\frac{b}{d} \approx 0.3\,, \qquad \frac{\delta}{h} \approx 0.2\,, \qquad \frac{r}{d} \approx 0.475$$

- Wismer & Luth mobility number (Cn)-modified:

$$C_{nw}' = \frac{CI\, n\, b\, d}{W.TDF} \quad (14)$$

where: TDF ..... Tire deflection factor.

- This can be calculated from the following equation:

$$TDF = \sqrt{\left[\frac{1-\frac{\delta}{h}}{0.8}\right]^3} \quad (15)$$

Ashmore [21] added a term (W/Wr) to Wismer and Luth type equations to predict log-skidder tire performance.

- Motion resistance ratio:

$$\mu_{mrr} = \frac{RR}{W} = -0.1\left(\frac{W}{W_r}\right) + \frac{0.22}{C_n} + 0.2 \quad (16)$$

- Torque ratio:

$$\mu_{tr} = \frac{T}{r * W} = 0.47\,(1 - e^{-0.2C_n s}) + 0.28\left(\frac{W}{W_r}\right) \quad (17)$$

- Net traction ratio:

$$\mu_{ntr} = \frac{P}{W} = \mu_{tr} - \mu_{mrr} = 0.38\left(\frac{W}{W_r}\right) + 0.47\,(1 - e^{-0.2C_n s}) - \frac{0.22}{C_n} - 0.2 \quad (18)$$

Gee-Glough [6- 7] found out, that soil shear strength was somewhat correlated with penetration resistance, and added a soil shear factor into the model.

- Motion resistance ratio:

$$\mu_{mrr}(C_R) = \frac{RR}{W} = 0.049 + \frac{0.287}{N_{CI}} \quad (19)$$

- Net traction ratio:

$$\mu_{ntr}(C_T) = \mu_{ntr_{max}}\,(1 - e^{-k\,s}) \quad (20)$$

Where: $\mu_{ntr_{max}}$ ($C_{T.max}$) ..... Maximum coefficient of net traction ratio
k .... Constant

$$\mu_{ntr_{max}}(C_{T.max}) = 0.796 - \frac{0.92}{N_{CI}} \quad (21)$$

$$k = \frac{4.838 + 0.061N_{CI}}{C_{T.max}} \quad (22)$$

- Tractive efficiency:

$$TE = \frac{\mu_{ntr}}{\mu_{tr}}(1-s) = \frac{\mu_{ntr}}{\mu_{ntr}+\mu_{mrr}}(1-s) \quad (23)$$

Dwyer [22- 23] developed expressions for coefficient of rolling resistance and net traction at 20% slip, and maximum traction coefficient.

- Motion resistance ratio:

$$\mu_{mrr} = \frac{RR}{W} = 0.05 + \frac{0.287}{N_{CI}} \quad (24)$$

- Torque ratio:

$$\mu_{tr} = \frac{T}{r * W} = 0.796 - \frac{0.92}{N_{CI}} \quad (25)$$

- net traction ratio at 20% wheel slip:

$$\mu_{ntr} = \frac{P}{W} = \left(0.796 - \frac{0.92}{N_{CI}}\right).(1 - e^{-(4.838+0.061.N_{CI}).S}) \quad (26)$$

Brixus [8-9] developed a more generalized expression for tractive characteristics of bias-ply pneumatic tires. Their approach is based on a modified mobility number which it called Bn

- Motion resistance ratio:

$$\mu_{mrr} = \frac{RR}{W} = \frac{1}{B_n} + \frac{0.5\,s}{\sqrt{B_n}} + 0.04 \quad (27)$$

Where:

$$B_n = \frac{CI\,b\,d}{W}\left(\frac{1+\frac{5\delta}{h}}{1+\frac{3b}{d}}\right)$$

- Torque ratio:

$$\mu_{tr} = \frac{T}{r * W} = 0.88\,(1 - e^{-0.1B_n})(1 - e^{-0.75s}) + 0.04 \quad (28)$$

- Net traction ratio:

$$\mu_{ntr} = \frac{NT}{W} = \mu_{tr} - \mu_{mrr} = 0.88\,(1 - e^{-0.1B_n})(1 - e^{-0.75s}) - \left(\frac{1}{B_n} + \frac{0.5\,s}{\sqrt{B_n}}\right) \quad (29)$$

Rowland & Peel [15] developed WES modelling, and extended it also for tracked vehicles. He presented the concept of mean maximum pressure, MMP, which is the maximum allowable calculated soil contact pressure at no-go situation.

- Motion resistance ratio:

$$\mu_{mrr} = \frac{RR}{W} = 3\,(1+S)\;N_R^{-2.7} \quad (30)$$

where:

$$N_R = \frac{CI\,.b^{0.85}\,.d^{0.15}}{W}\sqrt{\frac{\delta}{h}}$$

- Net traction ratio:

$$\mu_{ntr} = \frac{P}{W} = 0.12\,N_R^{0.88}\left(1 - 0.61(1 - S)^4\right) \quad (31)$$

Upaduhaya [24-25] developed a new technique for evaluating the vehicle mobility factor without a wheel numeric but taking in consideration the effect of tire inflation pressure

- Net traction ratio:

$$\mu_{ntr} = \frac{NT}{W} = a\left(1 - e^{-cS}\right) \quad (32)$$

- Gross traction ratio:

$$\mu_{gtr} = \frac{T}{r * W} = a'\left(1 - b'\,e^{c'S}\right) \quad (33)$$

where:

a,c,a',b',c' soil, tire and loading coefficient as follows:

$$c = c' \quad (34)$$

$$a = 0.311 + 0.067\left(\frac{CI}{P_i}\right) + 1.089(\theta) - 0.933\left(\frac{CI}{P_i}\right)\left(\frac{W}{CI.b.l}\right)^2 \quad (35)$$

$$a' = 0.345 + 0.411(\theta) + 0.474(a) + 0.251\left(\frac{a}{l}\right) - 0.001a\left(\frac{a\,W}{l}\right)^2 \quad (36)$$

$$\frac{1}{c} = -5.376 - 0.764\,\frac{a\,W}{l} + 4.923\frac{b}{l} - 211.152\frac{W.\theta}{CI.b.l} + 101\frac{a.W}{CI.b.l^2} + 32646\,(\theta) + 30.913\,a \quad (37)$$

$$b = 0.2993 + 0.5343\left(\frac{a}{a}\right) + 0.1336\left(\frac{a}{a'.l}\right) - 0.0002\left(\frac{a}{a}\right)\left(\frac{aW}{l}\right)^2 \quad (38)$$

The analytical plot of net traction ratio and traction efficiency of all empirical methods using real data on has shown in figures (8, 9). From Figs, the range of net traction ratio (Pull ratio) for the case study is 0.4-0.6 at maximum point and the tractive efficiency at maximum point is 0.45-0.65.

Then for vehicle mobility evaluation the pull ratio is compared. Net traction ratio is a dimensionless number that indicates the vehicle's towing ability, by using the new wheel numeric the vehicle mobility (net traction ratio) have been predicted.

The plot of the new proposed wheel numeric based on equation (9) with the pull ratio is shown in figure (10). From Fig., the maximum point of pull ratio at 0.5 which considered in optimum range when compared with the published by Abdel-Barry [20] a good correlation is found with one constrain of using the off road inflation pressure given by tire manufacture manual in Appendix 1.

CONCLUSION

The different parameters affecting wheel numeric has been investigated. As the weight on tire increases, the wheel numeric decreases where the tire weight has a great affect on wheel numeric by 70 %. Also as tire section height increases, the wheel numeric decreases with 12 %. The soil strength has a great affect on wheel numeric where as soil strength increases, the wheel numeric increases by 48%. Also as the tire deflection increases, the wheel numeric increases. The tire deflection has a great affect on wheel numeric by 70 %. While the tire diameter has a considerable affect on wheel numeric by 20 %. The tire width has a considerable affect on wheel numeric by 10 %. The effect of tire inflation pressure on the proposed wheel numeric has been investigated where the tire inflation pressure has a great affect on wheel numeric by 57 %.

A case study is carried out using experimental tire testing parameters to investigate a new wheel numeric based on tire inflation pressure. The results are compared with results given by other wheel numerics; a good correlation has been obtained. The theoretical vehicle performance in terms of net traction ratio and tractive efficiency versus slip has been predicted based on proposed wheel numeric and Brixius tractive equations which are most commonly used and accepted by the ASAE Standards. Fig (10) shows the theoretical results which are compared with published data; there is a good agreement between them.

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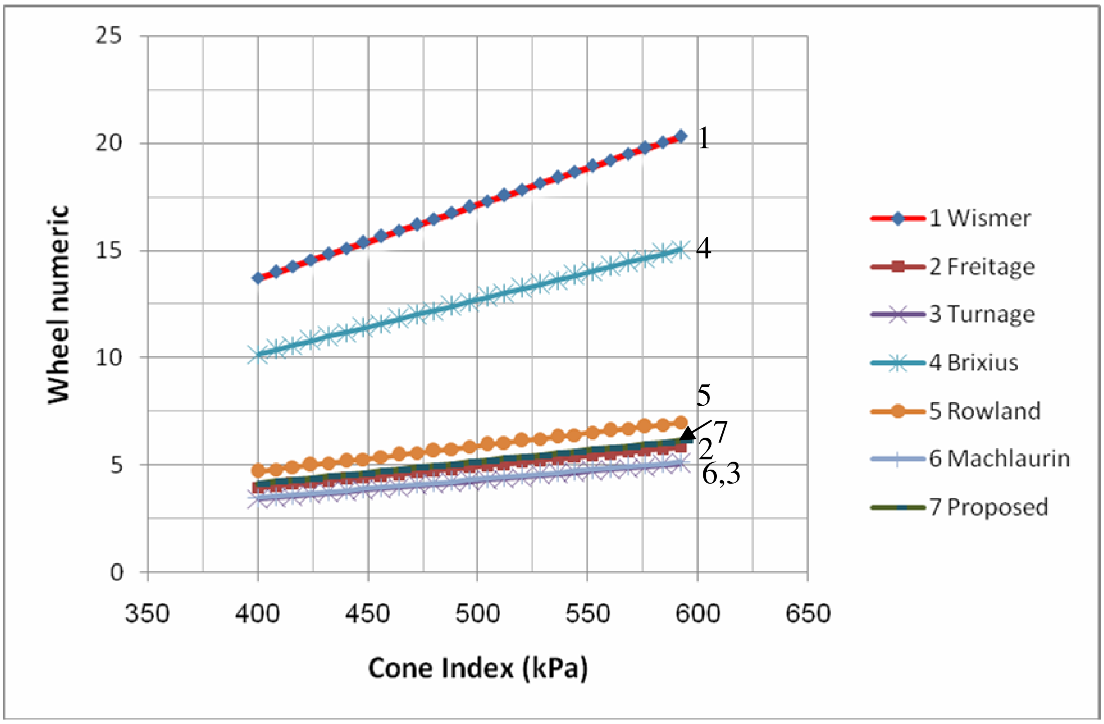

Fig. 1. Variation of wheel numeric with soil cone index.

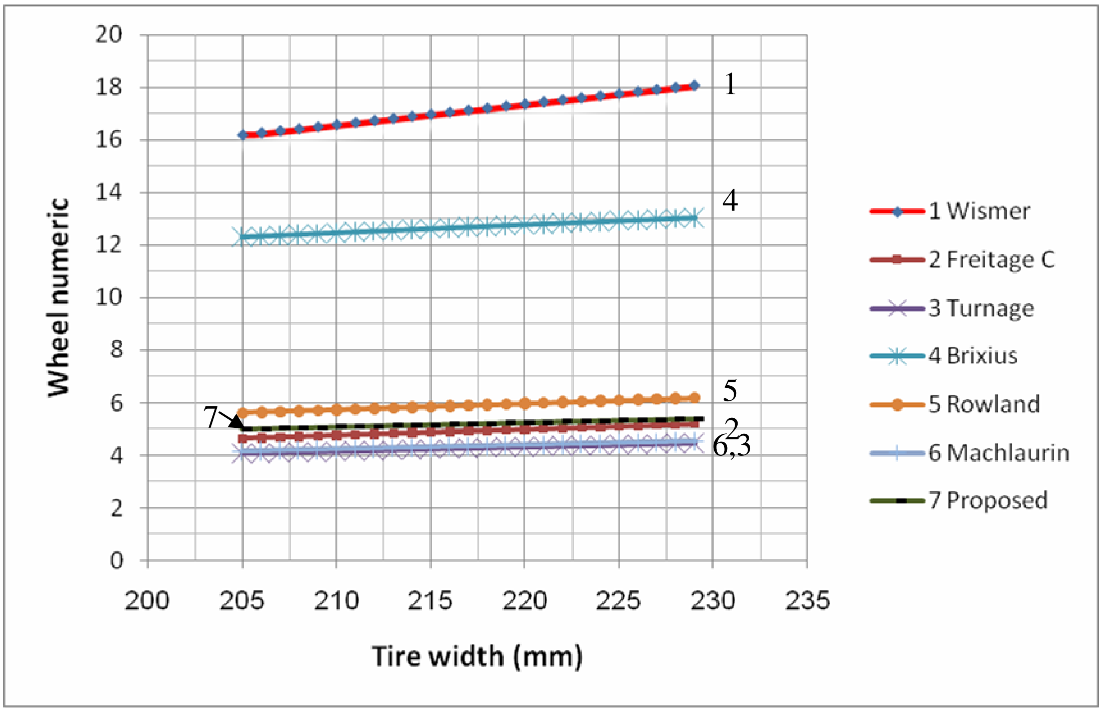

Fig. 2. Variation of wheel numeric with tire width.

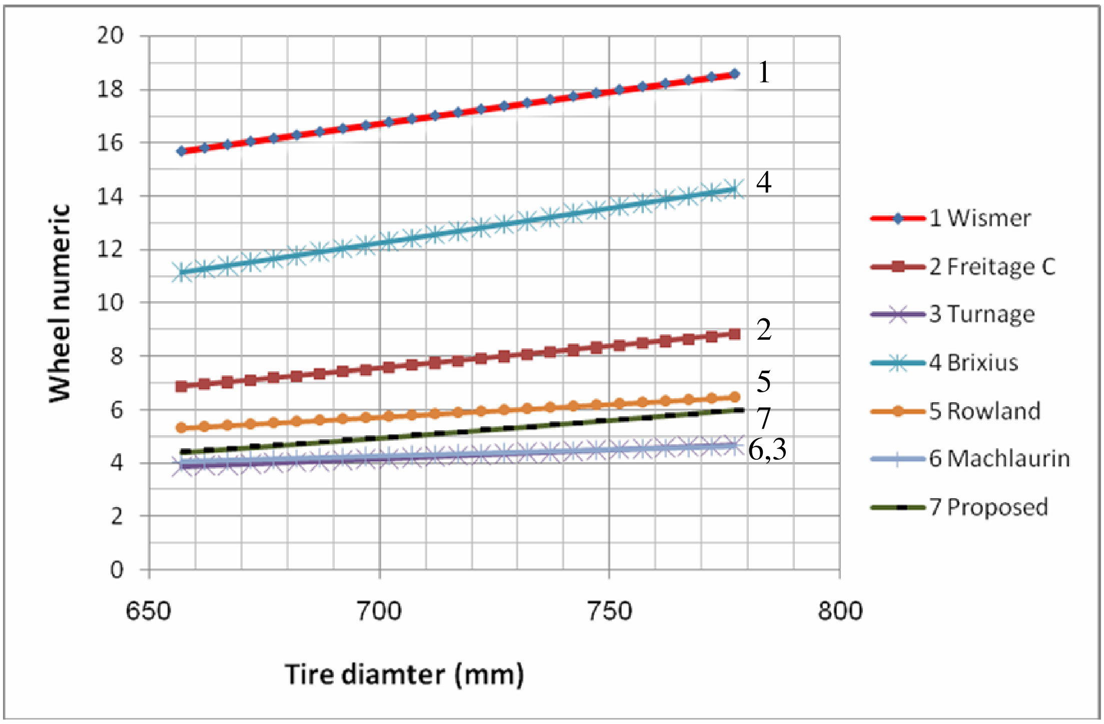

Fig. 3. Variation of wheel numeric with tire diameter.

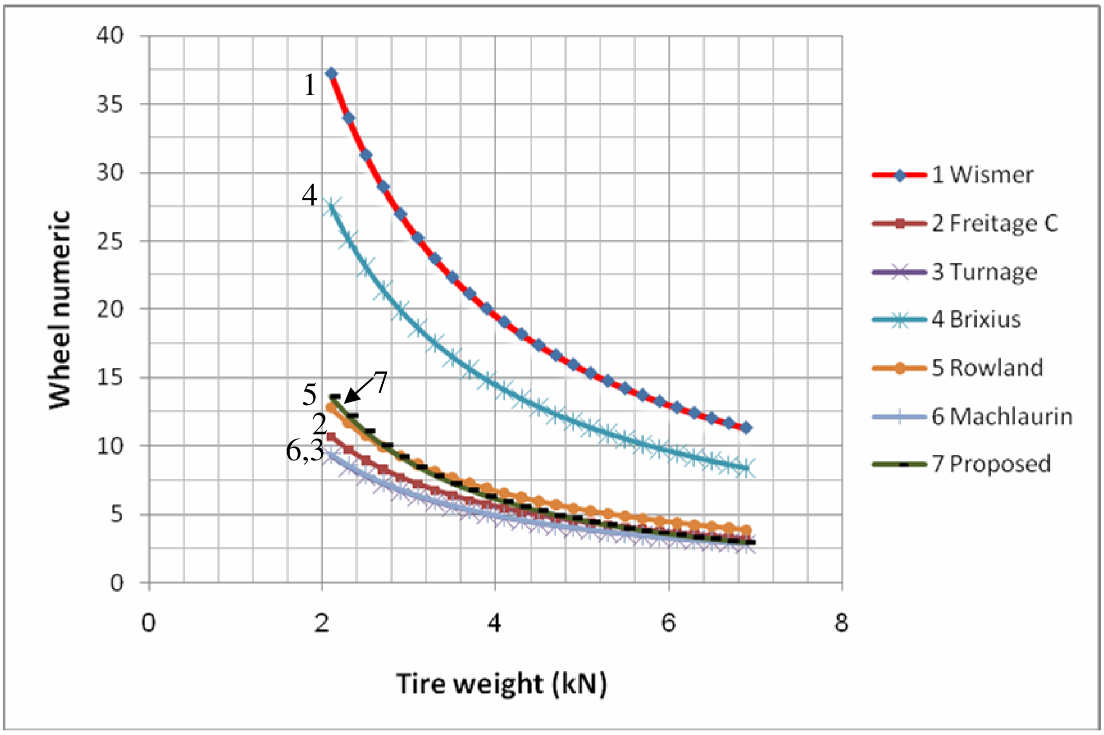

Fig. 4. Variation of wheel numeric with tire weight.

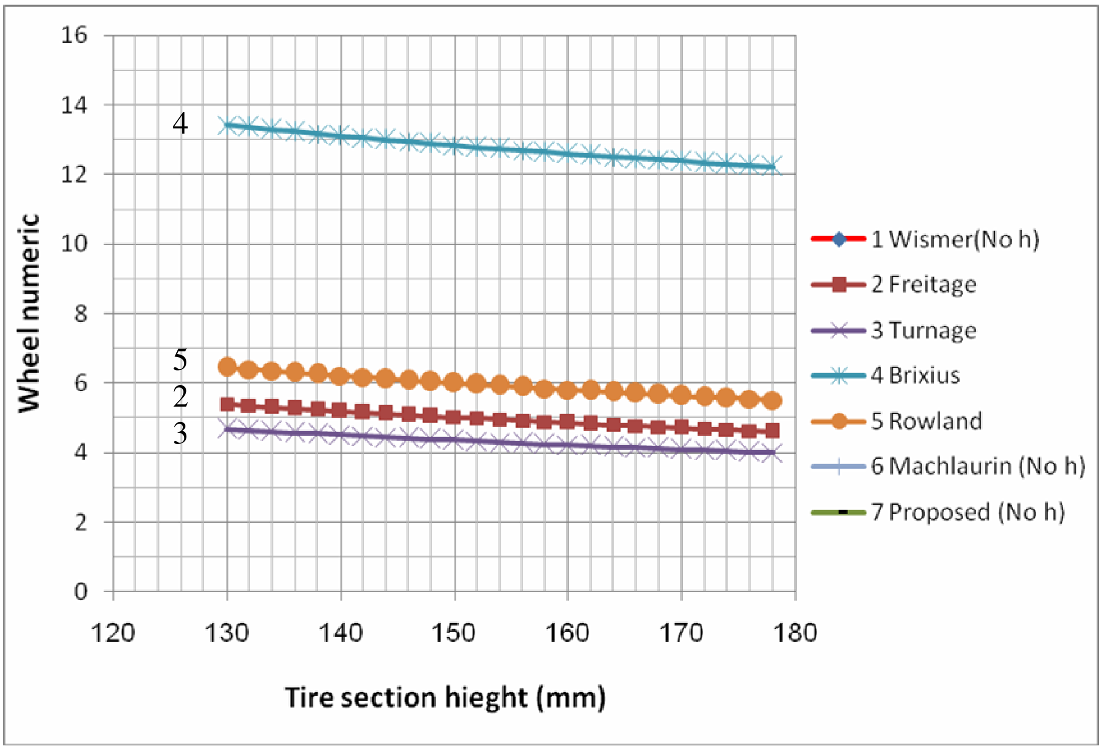

Fig. 5. Variation of wheel numeric with tire section height.

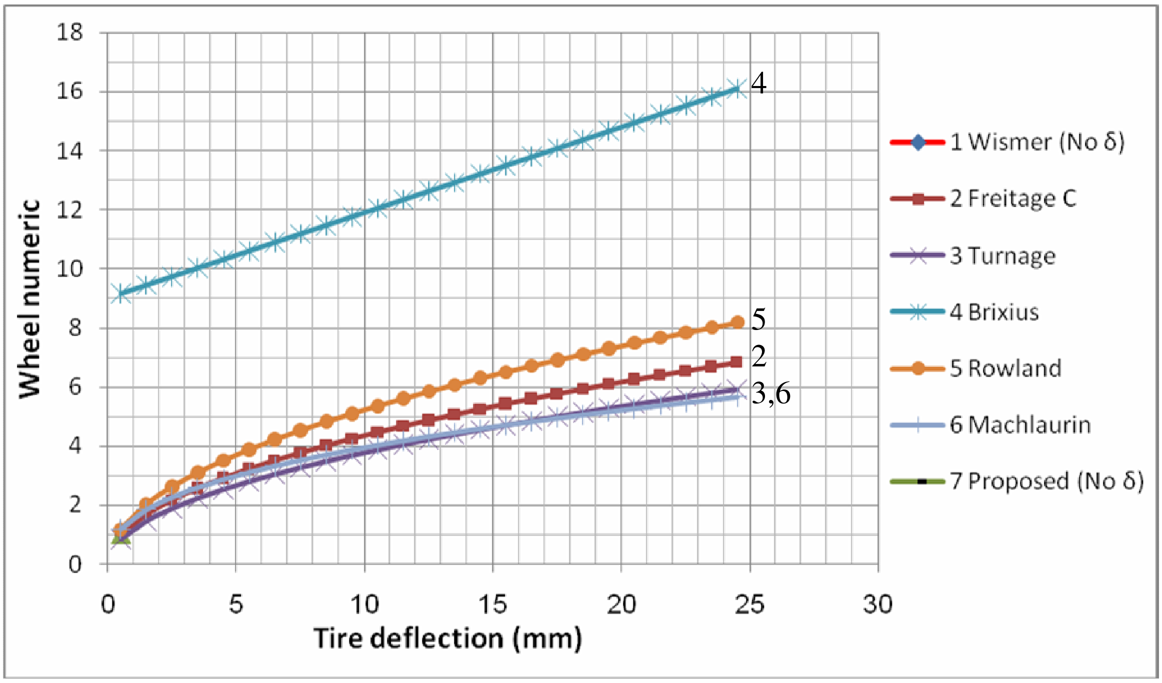

Fig.6. Variation of wheel numeric with tire deflection.

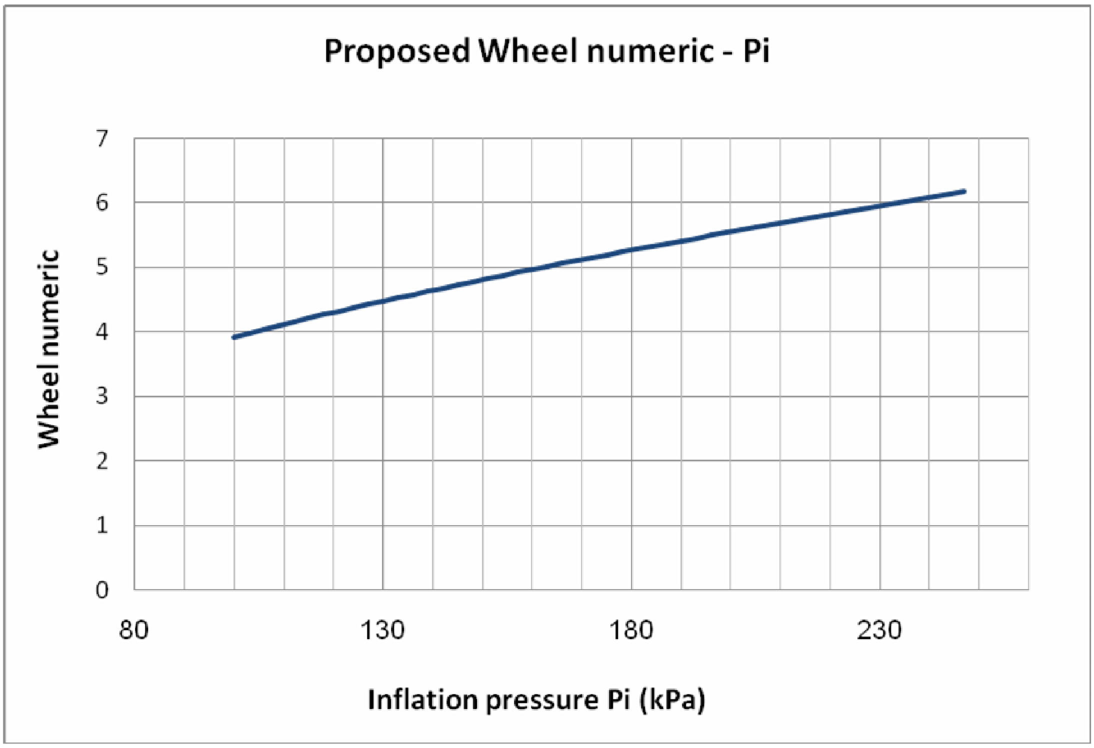

Fig.7. Variation of wheel numeric with tire inflation pressure.

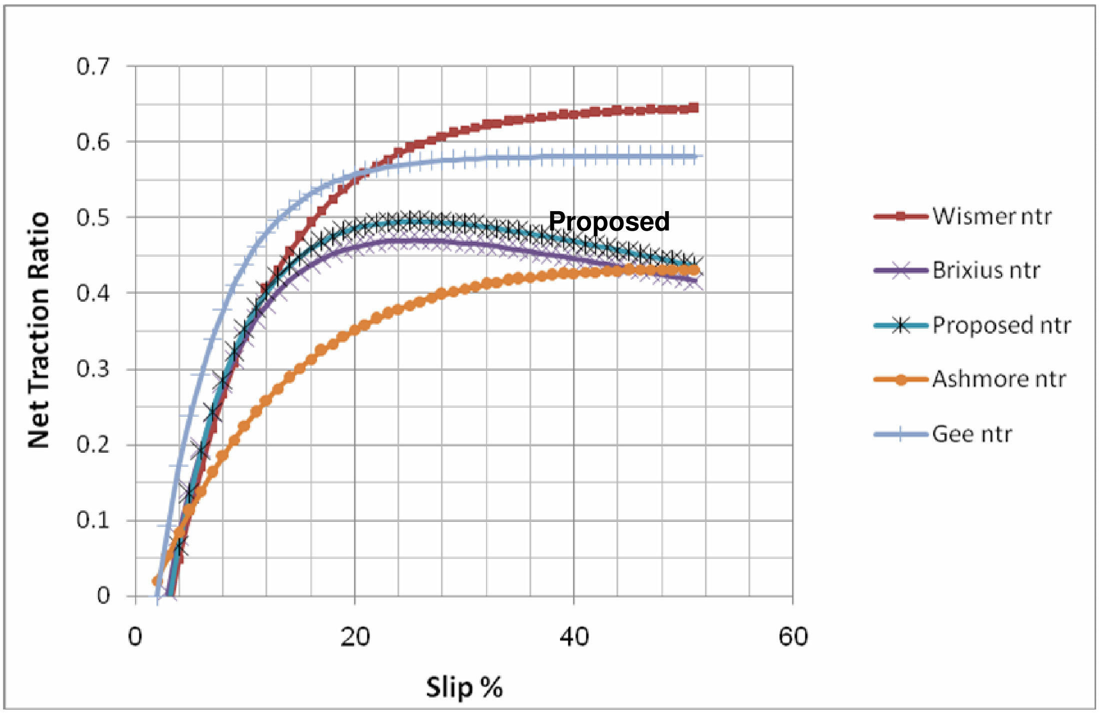

Fig. 8. Variation of net traction ratio with slip.

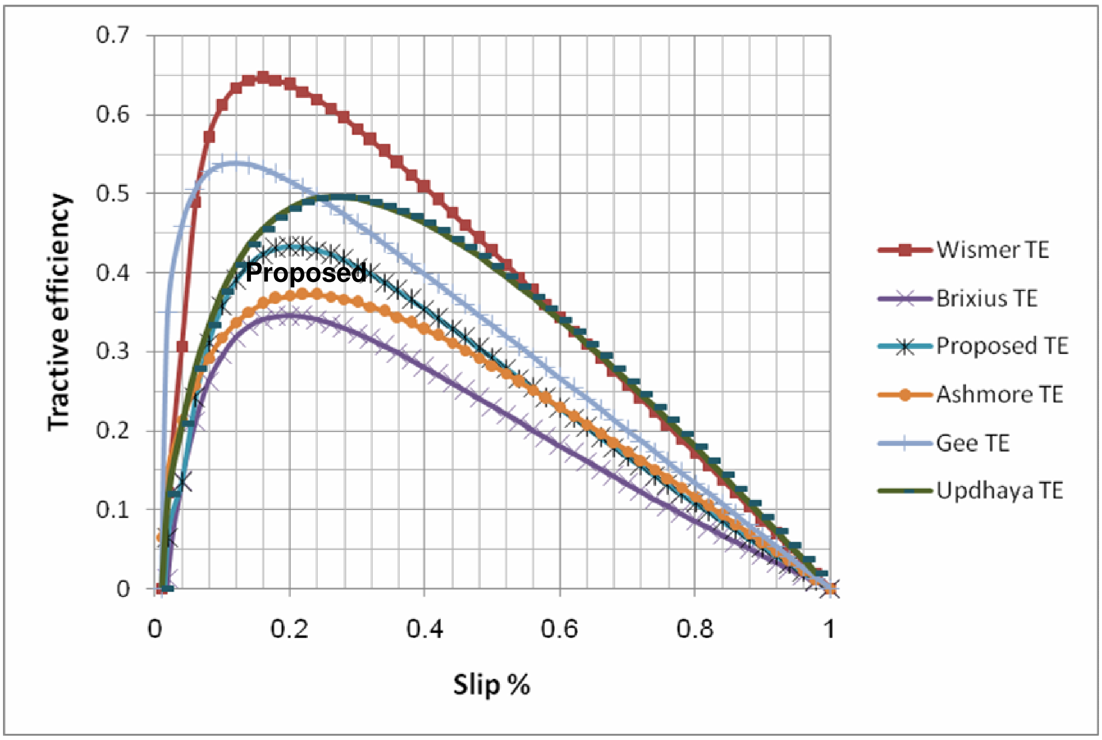

Fig. 9. Variation of tractive efficiency with slip.

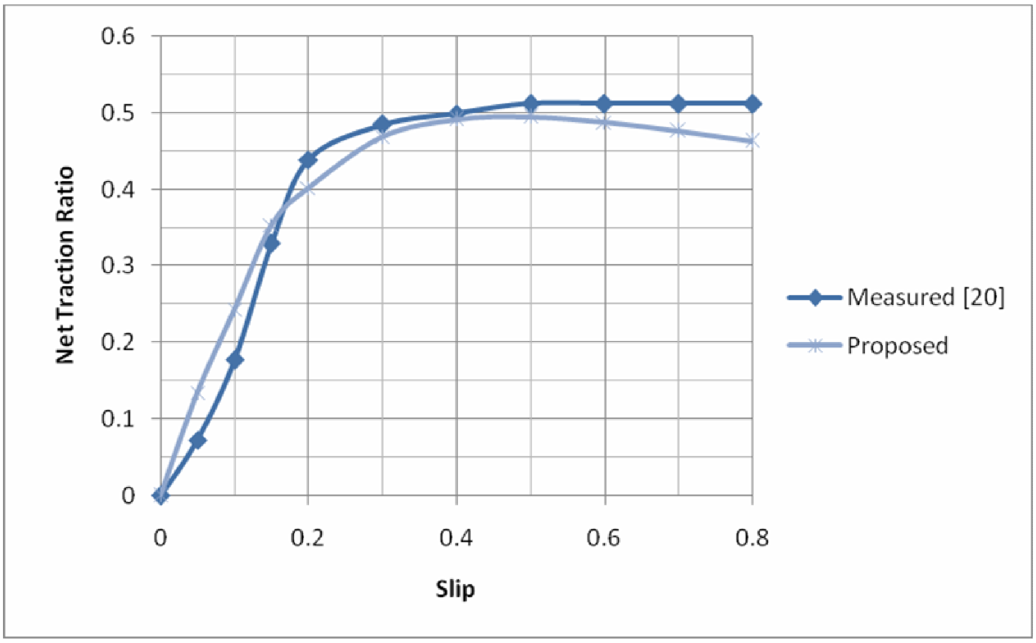

Fig. 10. Variation of net traction ratio with slip.

Appendix 1: Tire geometry from manufacture [27].

Type / Size	Low speed on soft sand				High speed								S.L.R	
1200-18	Inflation pressure		Max load		Inflation pressure		Max load		Section width		Overall diamter		Static Radius	
	Psi	kPa	kg	kN	Psi	kPa	kg	kN	mm	in	mm	in	mm	in
	17	**117.2**	**1850**	**18.14**	**80**	**551.6**	**2650**	**25.98**	**281**	**11.08**	**1081**	**42.56**	**475**	**18.72**
1250-20	Inflation pressure		Max load		Inflation pressure		Max load		Section width		Overall diamter		Static Radius	
	Psi	kPa	kg	kN	Psi	kPa	kg	kN	mm	in	mm	in	mm	in
	20	**137.9**	**1315**	**12.9**	**50**	**344.7**	**2000**	**19.61**	**284**	**11.38**	**1026**	**40.38**	**459**	**18.06**
750-16	Inflation pressure		Max load		Inflation pressure		Max load		Section width		Overall diamter		Static Radius	
	Psi	kPa	kg	kN	Psi	kPa	kg	kN	mm	in	mm	in	mm	in
	15	**103.4**	**620**	**6.08**	**58**	**399.9**	**950**	**9.13**	**208**	**9.2**	**785**	**30.9**	**353**	**13.8**
780-15	Inflation pressure		Max load		Inflation pressure		Max load		Section width		Overall diamter		Static Radius	
	Psi	kPa	kg	kN	Psi	kPa	kg	kN	mm	in	mm	in	mm	in
	15	**103.4**	**460**	**4.51**	**36**	**248.2**	**690**	**6.77**	**211**	**8.32**	**725**	**28.5**	**326**	**12.83**
900-13	Inflation pressure		Max load		Inflation pressure		Max load		Section width		Overall diamter		Static Radius	
	Psi	kPa	kg	kN	Psi	kPa	kg	kN	mm	in	mm	in	mm	in
	15	**103.4**	**685**	**6.72**	**35**	**241.3**	**960**	**9.41**	**234**	**9.2**	**800**	**31.5**	**351**	**13.8**