



UNIVERSITI PUTRA MALAYSIA

**MOTION RESISTANCE RATIO, NET TRACTION RATIO AND
TRACTIVE EFFICIENCY OF A RICELAND TYPE TYRE**

ELWALEED AWAD KHIDIR

FK 1999 17



**MOTION RESISTANCE RATIO, NET TRACTION RATIO AND
TRACTIVE EFFICIENCY OF A RICELAND TYPE TYRE**

By

ELWALEED AWAD KHIDIR

**Thesis Submitted in Fulfilment of the Requirements for the Degree of Master
of Science in the Faculty of Engineering
Universiti Putra Malaysia**

May 1999



Dedicated
to
My
Mother,
Brothers and Sisters



ACKNOWLEDGEMENTS

I wish to express my profound gratitude and sincere appreciation to Dr. Azmi Yahya, chairman of my supervisory committee for his invaluable guidance, constructive criticisms, suggestions, discussions and patience throughout the research work and during the preparation of this thesis. I am also much indebted and grateful to Assoc. Prof. Dr. Desa Ahmad and Assoc. Prof. Dr. Wan Ishak Wan Ismail, members of my supervisory committee, for their invaluable advice and guidance in supervising this dissertation.

I am especially indebted to Dr. Gizan Saleh for his guidance throughout and after his Advanced Statistical Methods course. I am also indebted to Dr. Faizal, Mr. A/Mutalib, Mr. Mutasim El Tayeb, Mr. Darius El Pebrian. I also acknowledge with gratitude Mr. Mohamad Rushdi, laboratory assistant of Machine Design Laboratory for his generous cooperation and unlimited helping. I also wish to thank Ir. Mesran Rasan, Mr. Mohamad Ikhsan, Mr. Mohamad Kamal Hashim, Mr. Suratman Sulaiman and Mr. Sahat Daud who have been very helpful especially in allowing the use of workshop facilities and developing the rig.



TABLE OF CONTENTS

		Page
	ACKNOWLEDGEMENTS	iii
	LIST OF TABLES	vii
	LIST OF FIGURES	xi
	LIST OF PLATES	xiv
	LIST OF ABBREVIATIONS	xv
	ABSTRACT	xvii
	ABSTRAK	xx
CHAPTER		
I	INTRODUCTION	1
	Objectives	4
II	LITERATURE REVIEW	6
	Soil Bins	6
	Traction Prediction	8
	Traction Mathematical Modeling	9
	Tyre Motion Resistance	15
	Soil-Tyre Forces System	17
	Dimensional Analysis Modeling	18
	Mobility Number	19
	Waterways Experiment Station (WES) Model	20
	Wismer and Luth (1974) Model	22
	Brixius (1987) Model	24
	Factors Affecting Tyre Traction	27
	Tyre Type	27
	Tyre Inflation Pressure	29
	Tyre Diameter	32
	Tyre Width	32
	Soil	33
	Lug Design	33
	Dynamic Load	35
III	MATERIALS AND METHODS	36
	Tyre Testing Facility	36
	Moving Carriage Assembly	38



	PERPUSTAKAAN	38
	UNIVERSITI PUTRA MALAYSIA	40
Carriage Driving Unit		38
Tyre Driving Unit		40
Pulling Tower		40
Soil Tank		40
Main Control Console		42
Data Acquisition System and Software		43
Carriage Speed Encoder		46
Tyre Rotation Encoder		46
Horizontal and Vertical Load Cells		47
Displacement Transducer		48
Software Program Commands		51
Test Tyre		53
Cone Penetrometer		53
Soil Preparation Equipment		54
Experimental Procedure for Tyre Motion Resistance Ratio		57
Tyre Dimensions		57
Equipment Setup		58
Test Procedure		61
Data Calculation and Analysis		61
Experimental Procedure for Tyre Net Traction Ratio		62
Tyre Dimensions		62
Wheel Numeric Determination		63
Equipment Setup		64
Test Procedure		64
Data Calculation and Analysis		65
Experimental Design		66
Experimental Model for Tyre Motion Resistance Ratio		67
Experimental Model for Tyre Net Traction Ratio		68
IV RESULTS AND DISCUSION		70
Tyre Motion Resistance Ratio		70
Tyre Dimensions		70
Analysis of Covariance		71
Regression Analysis		74
Moving Carriage Speed		80
Tyre Rotational Speed		82
Tyre Travel Reduction		84
Tyre Net Traction Ratio		87
Tyre Dimensions		87
Wheel Numeric Determination		90
Analysis of Covariance		93
Regression Analysis		97
Tractive Efficiency		109
V CONCLUSIONS		128



REFERENCES	132
APPENDIX	
A	Motion Resistance Ratio 137
B	Tyre Dimensions at Different Inflation Pressures 145
C	Net Traction Ratio..... 149
D	Samples of Torque Ratio Models with their Residuals .. 160
VITA	164



LIST OF TABLES

Table		Page
1	Dependent Gear-Soil Parameters	20
2	Independent Gear-Soil Parameters	21
3	Soil- Wheel Parameters (Wisner & Luth)	22
4	Soil- Wheel Parameters (Brixius)	25
5	Classification of Typical Agricultural Soils	54
6	Tyre Dimensions	70
7	ANOVA for Tyre Overall Diameter	71
8	Means for Tyre Overall Diameter and Rolling Radius	71
9	ANCOVA for Tyre Motion Resistance Ratio in Terms of Wheel Numeric	73
10	Mean and Adjusted Mean for Tyre Motion Resistance Ratio in Terms of Wheel Numeric	73
11	ANCOVA for Tyre Motion Resistance Ratio in Terms of Mobility Number	73
12	Mean and Adjusted Mean for Tyre Motion Resistance Ratio in Terms of Mobility Number	74
13	Regression Analysis for Tyre Motion Resistance Ratio in Terms of Wheel Numeric	75
14	Regression Analysis for Tyre Motion Resistance Ratio in Terms of Mobility Number	76
15	Comparison of the Predicted Tyre Motion Resistance Ratio with other Models	78
16	Tyre Characteristics for the Three Models	79
17	ANCOVA for Moving Carriage Speed	81
18	Mean and Adjusted Mean for Moving Carriage Speed	81



19	ANCOVA for Tyre Rotational Speed	82
20	Mean and Adjusted Mean for Tyre Rotational Speed	83
21	ANCOVA for Tyre Travel Reduction	85
22	Carriage Speed and Tyre Rotation at Different Inflation Pressures	88
23	ANOVA for Rolling Radius	88
24	Tyre Rolling Radius at Different Inflation Pressures	89
25	Tyre Dimensions.....	89
26	Cone Index Obtained by Rollers	91
27	Motion Resistance Ratio for Various Inflation Pressure and Wheel Numeric	92
28	Motion Resistance Ratio for Various Inflation Pressure and Mobility Number	92
29	ANCOVA for Tyre Net Traction Ratio in Terms of Wheel Numeric	94
30	Mean and Adjusted Mean for Tyre Net Traction Ratio in Terms of Wheel Numeric	94
31	ANCOVA for Tyre Net Traction Ratio in Terms of Mobility Number.....	96
32	Mean and Adjusted Mean for Tyre Net Traction Ratio in Terms of Mobility Number	96
33	Regression Analysis with Marquardt's Model	98
34	Regression Analysis with Logarithmic Model	99
35	ANCOVA for Tyre Rotational Speed	100
36	Mean and Adjusted Mean for Tyre Rotational Speed	100
37	ANCOVA for Moving Carriage Speed	101



38	Tyre Net Traction Ratio in Terms of Wheel Numeric	103
39	Tyre Net Traction Ratio in Terms of Mobility Number	105
40	Maximum Tractive Efficiency in Terms of Wheel Numeric	111
41	Maximum Tractive Efficiency in Terms of Mobility Number	113
42	Tractive Efficiency for the three Models at Wheel Numerics of 29 and 19	119
43	Tractive Efficiency for the three Models at Mobility Numbers of 39 and 26	119
44	Tyre Motion Resistance Ratio at 166 kPa Tyre Inflation Pressure	142
45	Tyre Motion Resistance Ratio at 193 kPa Tyre Inflation Pressure	143
46	Tyre Motion Resistance Ratio at 221 kPa Tyre Inflation Pressure	144
47	Tyre Dimensions at 221 kPa	145
48	Tyre Dimensions at 193 kPa	145
49	Tyre Dimensions at 166 kPa	145
50	Tyre Dimensions at 221 kPa	146
51	Tyre Dimensions at 193 kPa	146
52	Tyre Dimensions at 166 kPa	146
53	Tyre Dimensions at 193 kPa	147
54	Tyre Dimensions at 221 kPa	147
55	Tyre Dimensions at 166 kPa	147
56	Tyre Dimensions at 221 kPa	148
57	Tyre Dimensions at 166 kPa	148



58	Tyre Dimensions at 193 kPa	148
59	Net Traction Ratio at 166 kPa Tyre Inflation Pressure for Firm Soil	154
60	Net Traction Ratio at 193 kPa Tyre Inflation Pressure for Firm Soil	155
61	Net Traction Ratio at 221 kPa Tyre Inflation Pressure for Firm Soil	156
62	Net Traction Ratio at 166 kPa Tyre Inflation Pressure for Tilled Soil	157
63	Net Traction Ratio at 193 kPa Tyre Inflation Pressure for Tilled Soil	158
64	Net Traction Ratio at 221 kPa Tyre Inflation Pressure for Tilled Soil	159



LIST OF FIGURES

Figure		Page
1	Shear Deformation Diagram	10
2	Evaluation of Soil Parameter 'k' from a Typical Soil Shear Deformation Curve	12
3	Idealization of Shear-Deformation Diagrams	13
4	Forces Acting on a Driving Wheel	18
5	UPM's Traction Facility	37
6	Block Diagram of the Data Acquisition System	45
7	Procedure of Taking the Initial Reading	51
8	Procedure of Retrieving and Printing the Data	52
9	Tyre Motion Resistance Ratio	77
10	Tyre Motion Resistance Ratio for the Three Models	79
11	Moving Carriage Speed for Tyre Motion Resistance Ratio	81
12	Tyre Rotational Speed for Tyre Motion Resistance Ratio	83
13	Tyre Travel Reduction with Wheel Numeric	86
14	Tyre Travel Reduction with Mobility Number	86
15	Tyre Rotational Speed for Net Traction Ratio	101
16	Moving Carriage Speed for Net Traction Ratio	102
17	Tyre Net Traction Ratio for Wheel Numeric of 29	103
18	Tyre Net Traction Ratio for Wheel Numeric of 19	104
19	Tyre Net Traction Ratio for Mobility Number of 39	105
20	Tyre Net Traction Ratio for Mobility Number of 26	106



21	Net Traction Ratio for Mobility Number of 39 and Wheel Numeric of 29	108
22	Net Traction Ratio for Mobility Number of 26 and Wheel Numeric of 19	108
23	Tyre Tractive Efficiency for Wheel Numeric of 29	110
24	Tyre Tractive Efficiency for Wheel Numeric of 19	110
25	Tyre Tractive Efficiency for Mobility Number of 39	112
26	Tyre Tractive Efficiency for Mobility Number of 26	113
27	Tractive Efficiency Models in Terms of Wheel Numeric of 29 and Mobility Number of 39	117
28	Tractive Efficiency Models in terms Wheel Numeric of 19 and Mobility Number of 26	118
29	Tyre Net Traction Ratio at Nominal Inflation Pressure in Terms of Wheel Numeric	122
30	Tyre Tractive Efficiency at Nominal Inflation Pressure in Terms of Wheel Numeric	122
31	Tyre Net Traction Ratio at Nominal Inflation Pressure in Terms of Mobility Number	125
32	Tyre Tractive Efficiency at Nominal Inflation Pressure in Terms of Mobility Number	125
33	Tyre Net Traction Ratio at 193 kPa Inflation Pressure in Terms of Wheel Numeric	126
34	Tyre Tractive Efficiency at 193 kPa Inflation Pressure in Terms of Wheel Numeric	126
35	Tyre Net Traction Ratio at 193 kPa Inflation Pressure in Terms of Mobility Number	127
36	Tyre Tractive Efficiency at 193 kPa Inflation Pressure in Terms of Mobility Number	127
37	Marquardt's Torque Ratio Model for Wheel Numeric of 29 and Mobility Number of 39 at 193 kPa	160



38	Marquardt's Torque Ratio Model Residuals for Wheel Numeric of 29 and Mobility Number of 39 at 193 kPa	160
39	Torque Ratio Logarithmic Model for Wheel Numeric of 29 and Mobility Number of 39 at 193 kPa	161
40	Torque Ratio Logarithmic Model Residuals for Wheel Numeric of 29 and Mobility Number of 39 at 193 kPa	161
41	Marquardt's Torque Ratio Model for Wheel Numeric of 19 and Mobility Number of 26 at 193 kPa	162
42	Marquardt's Torque Ratio Model Residuals for Wheel Numeric of 19 and Mobility Number of 26 at 193 kPa	162
43	Torque Ratio Logarithmic Model for Wheel Numeric of 19 and Mobility Number of 26 at 193 kPa	163
44	Torque Ratio Logarithmic Model Residuals for Wheel Numeric of 19 and Mobility Number of 26 at 193 kPa	163



LIST OF PLATES

Plate		Page
1	Moving Carriage of the Soil Bin Facility	39
2	Moving Carriage Driving Unit	39
3	Test Tyre Driving Unit	41
4	The Tower	41
5	Soil Tank	42
6	Main Control Console	44
7	Data Acquisition System	44
8	Carriage Speed Encoder Location	49
9	Tyre Rotation Encoder Location	49
10	Horizontal and Vertical Load Cells	50
11	Displacement Transducer	50
12	Soil Compactor	55
13	Roller for Preparing Soil of Cn at 19	56
14	Roller for Preparing Soil of Cn at 29	56
15	Soil Cone Penetrometer	59
16	Soil Loosening	59
17	Soil Leveling	60
18	Inflation Pressure Determination	60

LIST OF ABBREVIATIONS

<i>A</i>	tyre contact area, cm ²
<i>a</i>	constant depends on tyre flexibility, dimensionless
<i>Bn</i>	mobility number, dimensionless
<i>B</i>	tyre width, cm
<i>c</i>	soil cohesion, N/cm ²
<i>CI</i>	cone index, N/cm ²
<i>Cn</i>	wheel numeric, dimensionless
<i>Cs</i>	carriage speed, m/s
<i>d</i>	tyre unloaded diameter, cm
<i>d_{rim}</i>	tyre rim diameter, cm
<i>F</i>	maximum tractive force, N
<i>G</i>	sand penetration resistance gradient, N
<i>H</i>	tractive force, N
<i>h</i>	unloaded tyre section height, cm
<i>k</i>	deformation modulus, cm
<i>k_φ</i>	frictional moduli of deformation, kN/m ⁿ⁺²
<i>k_c</i>	cohesive moduli of deformation, kN/m ⁿ⁺¹
<i>L</i>	tyre contact length, cm
<i>LR</i>	tyre loaded radius, cm
<i>Nc</i>	clay-tyre numeric, dimensionless
<i>Ns</i>	sand-tyre numeric, dimensionless
<i>Nt</i>	tyre rotational speed, rpm



n	index, dimensionless
P	net traction, N
P_c	tyre carcass pressure, N/cm ²
P_i	tyre inflation pressure, N/cm ²
Q	torque, N cm
R_0	rolling radius, cm
s	travel reduction (slip), dimensionless
TE	tractive efficiency, %
TF	towed force, motion resistance or rolling resistance, N
UR	tyre unloaded radius, cm
u	constant depends on tyre flexibility, dimensionless
V_a	tyre actual velocity, m/s
V_t	tyre theoretical velocity, m/s
W	tyre vertical load, N
Z	sinkage, cm
τ	shear stress, N/cm ²
σ	normal stress, N/cm ²
ϕ	soil friction angle, degree
α	shear deformation, cm
δ	tyre deflection, cm

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the degree of Master of Science.

MOTION RESISTANCE RATIO, NET TRACTION RATIO AND TRACTIVE EFFICIENCY OF A RICELAND TYPE TYRE

By

ELWALEED AWAD KHIDIR

May 1999

Chairman: Azmi Yahaya, Ph. D.

Faculty: Engineering

A study was conducted to determine the accuracy of Wismer-Luth and Brixius equations in predicting the tyre motion resistance ratio, net traction ratio and tractive efficiency of a Riceland type tyre. The tyre was tested on a sandy clay loam soil in an indoor UPM tyre traction testing facility. The experiment was conducted by running the tyre in two modes; towing mode for the formulation of tyre motion resistance ratio equation and driving mode for the formulation of tyre net traction ratio and tractive efficiency equations.

A total of ninety test runs were involved in the tyre motion resistance ratio determinations at three selected inflation pressures (i.e. 221, 193 and 166 kPa) and selected wheel numerics ranging between 0 to 70. From the analysis of covariance (ANCOVA) it was found that both inflation pressure and wheel numeric has significant effect on the tyre motion resistance ratio. Regression analysis was also conducted to determine the closeness of fit for Wismer-Luth and Brixius equations



in predicting the motion resistance ratio of the tested tyre. Finally, 3 new logarithmic models for the tyre motion resistance ratio were formulated. The 193 kPa inflation pressure revealed a lower tyre motion resistance than the nominated pressure (i.e. 221 kPa) and the 166 kPa.

For the tyre net traction ratio and tractive efficiency determinations, 126 test runs were conducted in a combination consisting of three selected inflation pressures (i.e. 221, 193 and 166 kPa) and two wheel numerics (i.e. 19 and 29) representing two extreme types of soil strength under different levels of travel reduction ranging between 0 to 40%. Regression analysis was conducted to determine the prediction equation describing the tyre torque ratio. Marquardt's method used by Wismer-Luth for predicting non-linear equation was found not suitable in predicting the torque ratio of the tested tyre for its low coefficient of determination and inadequacy. The logarithmic model was found to be suitable in predicting the torque ratio. From the analysis of covariance (ANCOVA) the mean effect of travel reduction, tyre inflation pressure and wheel numeric were found to be highly significant whereas the interaction of inflation pressure and wheel numeric was not significant. The 193 kPa inflation pressure was the best, among the three inflation pressures used, in getting higher net traction ratio and higher maximum tractive efficiency.

Finally, two models were formulated for the tyre net traction ratio; one in terms of wheel numeric and travel reduction and the other in terms of mobility

number and travel reduction, to describe the tested tyre performance at different soil strengths. It can be concluded that Wismer-Luth and Brixius models cannot be made common to all agricultural tyres due the differences in their characteristics of width to diameter ratio, deflection to section height ratio, rolling radius to diameter ratio and tyre type.



Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains.

NISBAH RINTANGAN GULING, NISBAH TUKISAN BERSIH DAN KECEKAPAN TUKISAN SEBUAH RODA JENIS TANAH SAWAH

Oleh

ELWALEED AWAD KHIDIR

Mei 1999

Pengerusi : Azmi Yahaya, Ph. D.

Fakulti : Kejuruteraan

Kajian telah dijalankan untuk menentukan kejituan persamaan Brixius dan Wismer-Luth dalam meramalkan nisbah rintangan guling, nisbah tukisan bersih dan kecekapan tukisan bagi tayar jenis sawah. Ujian telah dijalankan dengan menggunakan kemudahan makmal ujikaji tukisan tayar di UPM pada tanah jenis loam liat berpasir. Ujikaji telah dijalankan dalam dua mod; mod tunda bagi pembentukan persamaan nisbah rintangan gulingan tayar dan mod pacuan bagi pembentukan persamaan nisbah tukisan bersih dan kecekapan tukisan.

Sebanyak 90 ujian telah dijalankan yang melibatkan penentuan nisbah rintangan guling tayar pada tiga pilihan tekanan tayar (iaitu 221, 193, 166 kPa) dan pilihan bagi pekali roda diantara antara 0 hingga 70. Keputusan daripada analisis kovarian (ANCOVA) menunjukkan tekanan tayar dan pembilang roda mempunyai kesan nyata pada nisbah rintangan guling tayar. Analisis regresi dijalankan bagi menentukan kejituan persamaan Wismer-Luth dan Brixius



meramalan nisbah rintangan guling tayar. Jesteru itu, tiga model logaritma baru telah diterbitkan bagi nisbah rintangan guling tayar. Sebanyak 126 ujian telah dijalankan bagi penentuan nisbah tukisan bersih dan kecekapan tukisan dalam kombinasi tiga pilihan tekanan tayar (iaitu 221, 193, 166 kPa) dan dua pekali roda (iaitu 19 dan 29) yang mewakili dua jenis kekuatan tanah yang berbeza pada peringkat pengurangan pergerakan tayar diantara 0 hingga 40 peratus. Analisis regresi dijalankan bagi mendapatkan persamaan yang dapat menerangkan nisbah kilas tayar. Kaedah Marquardt yang digunakan untuk meramal persamaan tak lurus oleh Wismer-Luth didapati tidak tepat untuk nisbah tork bagi tayar yang diuji memandangkan pekali penentuannya adalah rendah dan tidak kesesuaian. Model logaritma didapati amat tepat meramal nisbah tork tayar.

Daripada analisis kovarian (ANCOVA), kesan purata pengurangan pergerakan tekanan tayar dan pekali roda didapati mempunyai kesan nyata yang tinggi, manakala interaksi antara tekanan tayar dan pekali roda adalah tidak berkesan. Tekanan tayar pada 193 kPa didapati menunjukkan kesan yang terbaik berbanding dengan dua tekanan lain yang diuji bagi mendapatkan nisbah tukisan bersih dan kecekapan tukisan yang maksimum.

Akhir sekali, dua model yang telah dapat diterbitkan bagi nisbah tukisan bersih tayar; satu berdasarkan pekali roda dan pengurangan pergerakan tayar dan yang satu lagi berdasarkan nombor mobiliti dan pengurangan pergerakan tayar untuk menerangkan prestasi tayar yang diuji pada kekuatan tanah yang berbeza.

Ianya dapat disimpulkan bahawa model Wismer-Luth dan Brixius tidak boleh digunakan pada semua jenis tayar pertanian disebabkan perbezaan ciri-ciri nisbah lebar dengan diameter, nisbah pesongan dengan tinggi keratan, nisbah jejari guling dengan diameter dan jenis tayar.

CHAPTER I

INTRODUCTION

Tractors are widely used in farms that perform most of the agricultural field operations. As energy from fossil fuel sources becomes more expensive, the efficient utilization of energy resources becomes a major concern to agricultural production systems. The farm tractors consume approximately 20% of the total onfarm energy requirements (Heichel, 1976).

Tractor power is utilized by transmitting the engine power both through the driving wheels as traction to provide the drawbar power required for draught implements, and through the power take-off shaft - as well as the hydraulic system to provide mobile support for the attached machines. Of these principal ways the least efficient and most used method is the drawbar. Engine power can be converted to drawbar power only if the drive wheels develop traction (Brian, 1988; Liljedahl *et al.* 1989).

Research results throughout the world show that from 20 to 55% of the energy delivered to the drive wheels of the tractors is wasted in the traction elements. This energy is not only wasted but the resulting soil compaction



created by a portion of this energy may be detrimental to crop production. This loss of energy by the pneumatic tyre has prompted researchers to search for operational parameters that could improve tractive efficiency (Burt *et al.* 1983).

An understanding of the basic characteristics of the interaction between the running gear and the ground is essential to the study of the performance characteristic and handling the behavior of ground vehicles (Wong, 1993). The running gear of a ground vehicle is generally required to fulfill the following functions:

1. support the weight of the vehicle
2. cushion the vehicle over surface irregularities
3. provide sufficient traction for driving and braking
4. provide adequate steering control and directional stability.

Pneumatic tyres can perform these functions efficiently, thus they are exclusively used in road vehicles and are also widely used in off-road vehicles. The study of the mechanics of pneumatic tyres therefore is of fundamental importance to the understanding of the performance and characteristics of ground vehicles. Two basic types of problem in the mechanics of tyres are of special interest to vehicle engineers; one is the mechanics of tyres on hard surfaces and the other is the mechanics of tyres on deformable surfaces, which is of prime importance to the study of off-road vehicle performance.