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APPENDIX REPORT No 5

MODELLING OF THE WHEEL AND TYRE

1. TYRE AND SOIL CONTACT

SURVEY ON TYRE CONTACT AREA AND GROUND PRESSURE MODELS
FOR STUDYING THE MOBILITY OF FOREST TRACTORS

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MODELLING OF THE WHEEL AND TYRE

1. TYRE AND SOIL CONTACT

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1. INTRODUCTION

1.1 Tractor specification, problems related to the concept of ground pressure

When selecting a suitable tractor configuration for a certain task different characteristics of the vehicles are compared. Specifications, such as engine power, mass, load capacity etc., on which the productivity estimates are based, are usually reliable enough. One characteristic, ground pressure, is used to assess the suitability of the vehicle from the environmental point of view.

Tyre contact pressure, or nominal ground pressure is the nominal tyre load divided by the tyre contact area. Tyre contact area is calculated using a simple formula (see Chapter 3.1): tyre diameter multiplied by tyre width. (Mikkonen & Wuolijoki 1975, Metsätalousrenkaiden... (No year)).

The first problem arising is that the tyre inflation pressure is not included into the calculation method. Tyre inflation pressure plays, however, an important role in mobility and rut formation (Löfgren 1991, Granlund & Andersson 1997).

The second problem arises from the fact, that the model gives unrealistic small tyre contact pressure values, the tractor is hardly capable to cope with no-go situation, and the rut formation is already excessive high, because it assumes that around 30% of the wheel radius is bogged into the soil.

In this report the concept of ground pressure is studied based on a literature survey, in order to find out which factors should be emphasised when selecting environmentally more effective vehicles.

The calculations are available in EXCEL-file:**ECOCONTACTP.XLS**

1.2 Terms and symbols

WHEEL, models based on rigid wheel geometry and theory
TYRE, models aimed at taking into consideration some features of a flexible tyre
HARD SURFACE, surface with extremely high modulus of elasticity, a theoretical plane
SOFT GROUND: medium with elastic and/or plastic deformations

Wheel, Rigid wheel

A	Footprint area, m^2
b	Wheel width, Tyre (section) width, m
r	Wheel radius, m
d	Wheel diameter, Tyre diameter, m
W	Wheel load, kPa

Tyre, Pneumatic wheel

δ	Deflection, m
A	Footprint area, m^2,
C_O	Spring rate
G	Ground pressure index, kPa
a	Aspect ratio
b_c	Contact width, m
b_w	Tyre tread width, m
h	Section height, m
l_{AX}	Axle base, m
l_c	Contact length, m
d_{RIM}	Rim diameter, m
p	Contact pressure, Ground pressure, kPa
p_0	Conditional pressure, kPa

p_i	Tyre inflation pressure, kPa
r_c	Tyre transversal radius, m
r_l	Loaded radius, m
W_N	Nominal wheel load, kPa
W	Wheel load, kPa

MMP	Mean maximum pressure, kN/m^2, kPa

W_{TW}	Vehicle weight , N
m	Number of axles
b	Wheel, tyre or track width m
c	Track link profile factor, footprint area/(p·b)
p	Track link pitch, m
d	Wheel diameter, road wheel diameter, m
l_p	Road wheel base, m
h	Tyre section height, m
T	Tyre tread factor
S	Constant for proportionality
w	Total number of vehicle wheels

Unloaded radius (r)

Rigid wheel or cases, when a flexible tyre is expected to behave as a rigid wheel

$$r = \frac{d}{2} \tag{1.2.1}$$

Loaded radius (r_l)

Loaded radius is obtained by measuring the distance of the axle centre of a pneumatic tyre from the rigid surface.

Deflection (δ)

difference between unloaded and loaded radius:

$$d = r - r_l \tag{1.2.2}$$

Section height (h)

$$h = \frac{d - d_{RIM}}{2} \tag{1.2.3}$$

Aspect ratio, (a)

$$a = \frac{h}{b} \tag{1.2.4}$$

$$a = \frac{d - d_{RIM}}{2 \cdot b} \tag{1.2.5}$$

2. TYRE AND SOIL INTERFACE

Tyre and soil interface can be interpreted with many ways depending on the analyses of the forces involved. Two most simple terms are contact area and contact surface, see Figure 2.1.

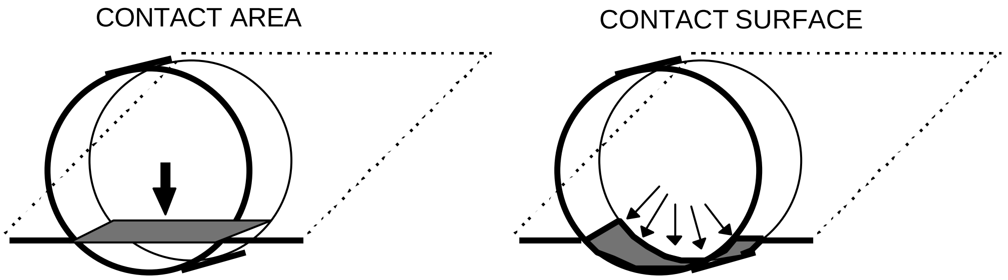

Figure 2.1. Contact area and contact surface

2.1 Footprint area

2.1.1 Measuring of the footprint area

In the bearing capacity analysis of a static wheel the loading force is vertical. Therefore the vertical projection of the supporting surface (contact surface), *footprint area*, is exact enough for simple models. Footprint area can be measured by pulling the tyre against the soil surface with a certain wheel load (W). The contact line with the soil is marked with painting or chalk, the tyre is lifted off and the footprint area (A) is measured using an appropriate technique.

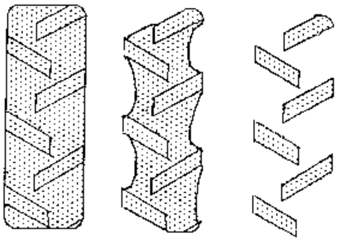

Figure 2.2. Idealised, real and effective surface of contact on soft soil. (From Abeels 1994)

The measuring of the footprint of a tyre with lugs presents a certain problem, see Figure 2.2. Generally, also the area between lugs, even if not in full contact with the soil, specially on harder surfaces, is included in footprint area. For more exact analysis, effective area, e.g. the lug area supporting the load, is measured. For example, for estimating the contact pressure, the stress is concentrated on supporting medium under the lug, and the effective surface may be the best estimate for the footprint area. The shear stress due to wheel momentum is also partially generated into the soil between lugs, and therefore effective surface may be the best estimate for evaluating the footprint area. Idealised footprint is some kind of overestimate, but can be used for different models, which are based on average forces. It is, however, possible also to develop models for real and effective footprint areas or contact surfaces based on idealised footprint area.

2.1.2 Modelling of the contact area

Contact area models can be empirical, semi-empirical or theoretical depending on the method used.

Theoretical models

Rigid wheel on hard surface

In theory, the footprint of a rigid wheel on hard surface is a line, equal to the width of the tyre. Because the contact length is close to zero, $l_c \approx 0$, footprint area is close to zero also, $A \approx 0$. This means, that in practice, the footprint area of a rigid tyre on hard surface becomes very small, and the contact pressure is high.

Pneumatic tyre on hard surface

Pneumatic tyre deflects always somewhat, and the theoretical contact length becomes as follows, see Figure 2.3.

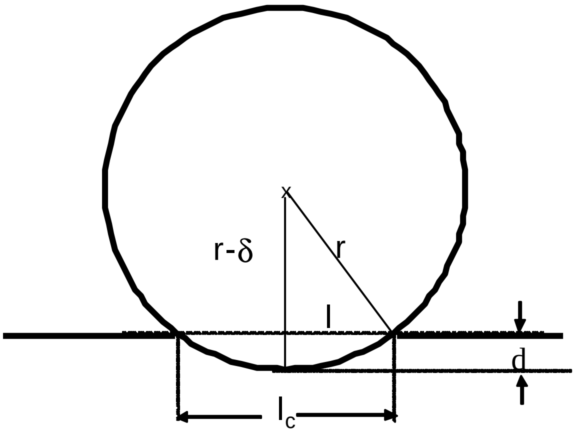

Figure 2.3. Contact length of a flexible tyre

$$l = \sqrt{r^2 + \left(r - d\right)^2} \qquad (2.1.1)$$

and further the contact length of the tyre

$$l_c = 2 \cdot \sqrt{d \cdot d - d^2} \qquad (2.1.2)$$

The corresponding contact width is

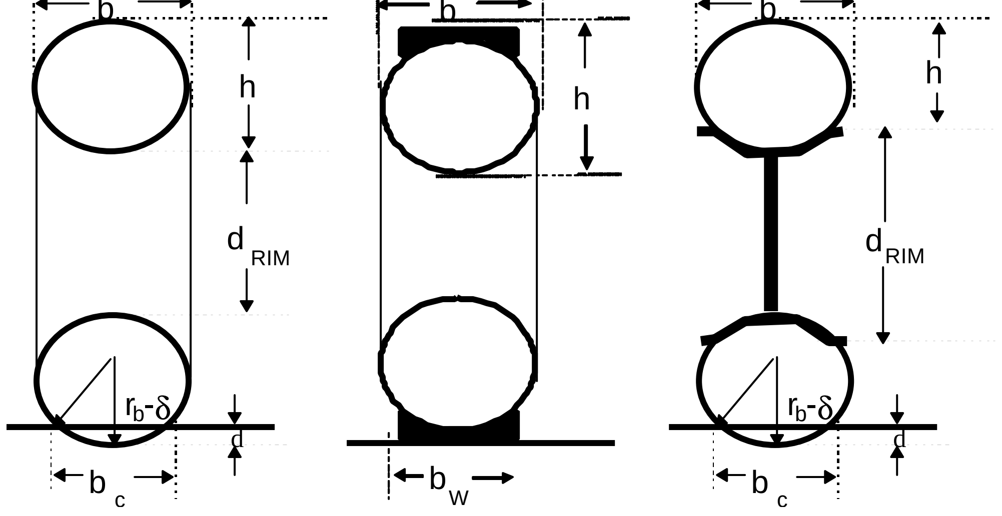

Figure 2.4. Contact width and section height of a flexible tyre

$$b_c = 2 \cdot \sqrt{2 \cdot r_b \cdot d - d^2} \qquad (2.1.3)$$

where

b_c Contact width, m
r_b Tyre transversal radius, m
δ Deflection, m

The problem is, which tyre transversal radius should be used. For 1960 - 1970 cross belt tyres with aspect ratio near 1 the transversal radius is

$$r_b = \frac{h}{2} \qquad (2.1.4)$$

For forest tractor tyres with aspect ratio 0.5 … 0.7 and the widthwise transformation is small, it is reasonable to use

$$r_b = \frac{b}{2} \qquad (2.1.5)$$

or even longer radius.

Flexible tyre on rigid plane models have developed Ziani et Biarex (1990).

Flexible tyre on soft ground

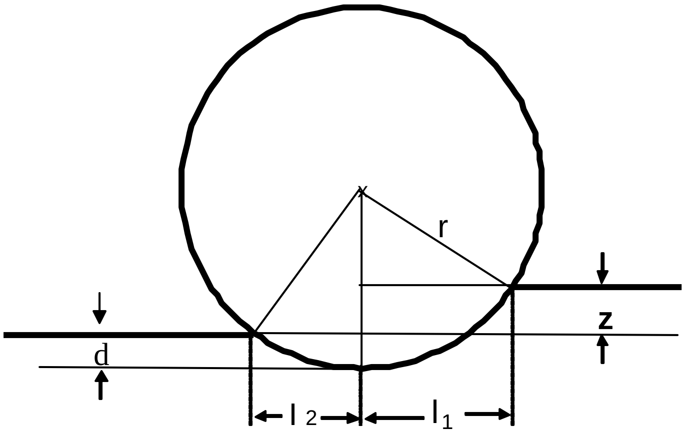

Figure 2.5. Flexible tyre on soft ground

The contact lengths l_1 and l_2 can be calculated based on tyre geometry, Fig. 2.5:

$$l_1 = \sqrt{r^2 - (r - z - d)^2} \tag{2.1.6}$$

$$l_2 = \sqrt{r^2 - (r - d)^2} \tag{2.1.7}$$

$$l_c = l_1 + l_2 \tag{2.1.8}$$

$$l_c = \sqrt{d \cdot (z + d) - (z + d)^2} + \sqrt{d \cdot d - d^2} \tag{2.1.9}$$

Schwanghart (1990) has developed models for flexible tyre on soft ground.

Rigid wheel on soft ground

The third case, a flexible tyre with great modulus of elasticity compared to the soil can be described with Equations (2.6)-(2.9) with $\delta=0$.

2.2 Tyre footprint shape

Tyre footprint shape depends on the tyre construction, inflation pressure, wheel load and the properties of the ground. On hard surface, under narrow, large diameter tyres with high inflation pressure the contact shape is elliptical. With broader tyres the shape is more rounded. A general model for tyre footprint area is

$$A = c \cdot l_c \cdot b_c \tag{2.2.1}$$

where c is shape parameter. The value of the constant c is

circle and ellipse $c = \frac{\pi}{4} = 0.785$

square and rectangle $c = 1$

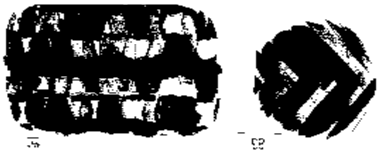

Figure 2.6. Tyre footprint forms (Grecenko 1995)

The form of the footprint is generally between circle and rectangle, and the estimate for c lies between 0.8 and 0.9.

Upadhyaya et Wulfsohn (1990) presents an ellipse model for footprint:

$$\frac{x^2}{c^2} = \frac{y^2}{\left(\frac{c}{b}\right)^2} \qquad (2.2.2)$$

where

c longer axle, m

b shorter axle, m

Hallonborg (1996) proposed a superelliptic model:

$$\frac{x^n}{a^n} + \frac{y^n}{b^n} = 1 \qquad (2.2.3)$$

The form of the contact area depends on the soil and tyre properties, see Figure 2.7.

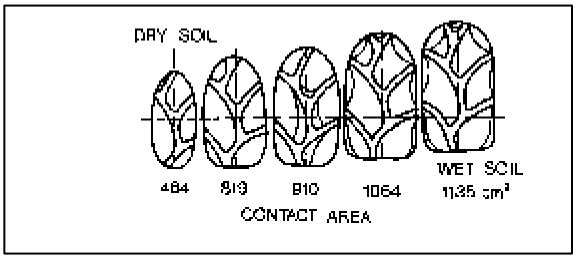

Figure 2.7. Tyre footprint on different soil moisture conditions (Hallonborg 1996)

2.3 Empirical models for tyre footprint area

The empirical models are based on models, where the observed footprint area is dependent variable and independent variables are some tyre and soil parameters. Commonly used tyre parameters are inflation pressure, tyre diameter and width or tyre stiffness modulus. Soil parameters are penetration resistance or modulus of elasticity and its components.

2.4 Tyre contact profile

The real contact surface or contact profile are difficult to model. The contact surface is three dimensional, describing the deformation in x- y and z-planes. Commonly used tools are FEM-method, or integrals over the different planes. General solutions are based on contact profiles using spiral or equivalent rigid wheel, using a larger hypothetical wheel radius r_p, see Figure 2.8.

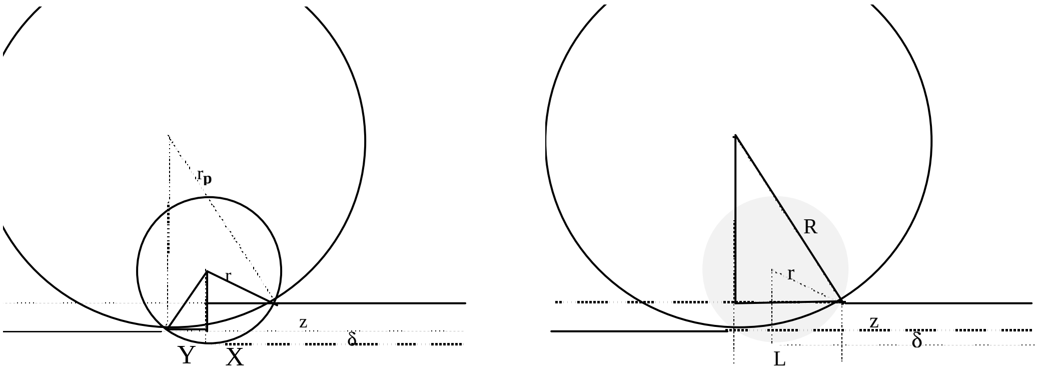

Figure 2.8. Equivalent rigid wheel model

$$X = \sqrt{r^2 - (r - z - d)^2} \qquad (2.4.1)$$

$$Y = \sqrt{r^2 - (r - d)^2} \qquad (2.4.2)$$

$$L = X + Y \qquad (2.4.3)$$

$$R^2 = (R - z)^2 + L^2 \qquad (2.4.4)$$

$$R^2 = R^2 - 2 \cdot R \cdot z + z^2 + L^2 \qquad (2.4.5)$$

$$R = \frac{z^2 + L^2}{2 \cdot z} \qquad (2.4.6)$$

The equivalent wheel modelling, virtual wheel, *surrogate wheel*, has been developed by IKK, the University of the Federal Armed Forces of Germany (Schmid 1995, Lach 1996). The problem lies in the fact, that the radius of equivalent wheel *(surrogate wheel*) depends on the properties of the wheel and soil, and it is not known beforehand, but needs iterative calculations to be found.

More comprehensive modelling of contact surface and 3-D modelling is left out of the scope of the paper. 3-D model is presented for example by Wulfsohn et Upadhyaya (1992a, 1992b).

2.5 Contact pressure

The contact pressure of a pneumatic tyre on hard surface depends on the tyre construction and inflation pressure. Karafiath et Nowatsky (1978) gives the following model:

$$p = c_i \cdot p_i + p_c \qquad (2.5.1)$$

where

p	tyre contact pressure, kPa
c_i	tyre stiffness constant
	c1 = 0.6 high pressure tyres
	c1= 1 low pressure tyres
p_i	tyre inflation pressure, kPa
p_c	contact pressure of the empty tyre (p_i = 0), kPa

3. TYRE CONTACT AREA MODELS

3.1 Nominal Ground Pressure, NGP

The tyre contact area is based on a theoretic calculation, based on 15% sinkage. Model is recommended in the Nordic forestry researches (Mikkonen & Wuolijoki 1975). The same model is used by NOKIAN Renkaat (Metsätalous-renkaiden... (No year)). Therefore it can be considered as some kind of a “standard model” for calculating the tyre contact area and ground pressure.

Tyre

$$A = b \cdot r \qquad (3.1.1)$$

Flexible track

$$A = (0.72 \cdot r_1 + 0.53 \cdot r_2 + l_{AX}) \cdot b \qquad (3.1.2)$$

A	tyre contact area, m²
b	tyre width, m
r	unloaded radius, m
r_1	unloaded radius of tyre 1, m
r_2	unloaded radius of tyre, m
l_{AX}	axle base, m

The model gives some kind of a maximal contact area, and thus leads to a hypothetical minimum ground pressure, because it can be reached at the situation, where 30% of the unloaded radius is under the soil surface level, as seen from Figure 3.1.

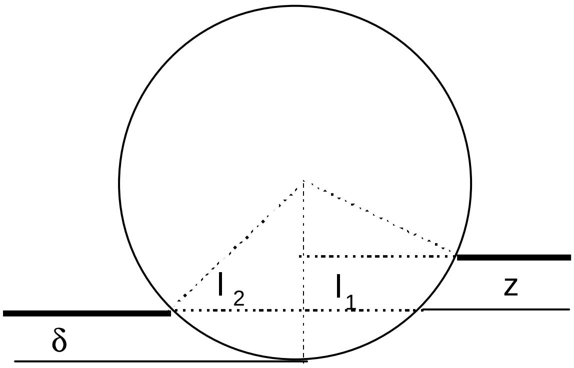

Figure 3.1. Tyre geometry for the Swedish formula

$$l_c = 1.42 \cdot 0.87 \cdot r = 1.235 \cdot r \tag{3.1.3}$$

$$l_1 = \frac{1.42}{2} \cdot r = 0.71 \cdot r \tag{3.1.4}$$

$$l_2 = (1.235 - .071) \cdot r = 0.5254 \cdot r \tag{3.1.5}$$

Based on the calculated contact lengths one can calculate, that the deflection of the tyre becomes:

$$d = 0.149 \cdot r \tag{3.1.6}$$

and the sinkage

$$z = 0.147 \cdot r \tag{3.1.7}$$

which means, that 30% of the unloaded radius is under the soil surface. The model assumes the following tyre width:

$$b_c = 1.02 \cdot b \tag{3.1.8}$$

The suitability of the formula for assessing the contact pressure for forest tyres is discussed in Appendix 1.

The Equation (3.1.1) is identical and Equation (3.1.2) and is close to **Nominal Ground Pressure** (NGP) equations. NGP is still widely used as a trafficability indicator for wheeled and tracked vehicles.

NGP formula presented for a tracks, Eq(3.1.2) or its modification for a bogey axle (Eq. 3.1.9) is not suitable for estimating the soil contact pressure of different wheel or track configurations.

$$A = b \cdot (1.25 \cdot r + l) \tag{3.1.9}$$

Saarilahti & Anttila (1999) studied the rut depth of 6 and 8- wheeled forwarders, of which some were fitted with flexible tracks. The neglect of the influence of tracks improved the prediction power or the models, see Figure 3.1.

$$N_{CI} = \frac{b \cdot (1.25 \cdot r + l) \cdot CI}{W} \qquad N_{CI} = \frac{b \cdot d \cdot CI}{W} \cdot \sqrt{\frac{d}{h}} \cdot \frac{1}{1 + \frac{b}{2 \cdot d}}$$

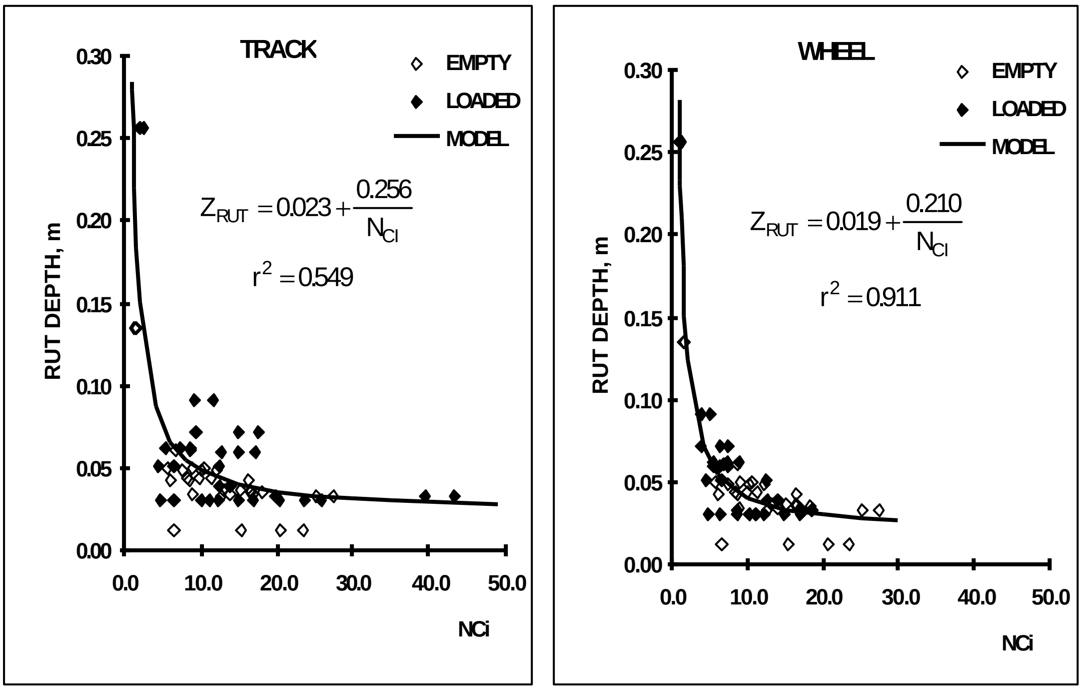

Figure 3.1 Rut depth model developed using rigid plate contact area model (TRACK) **and pneumatic wheel model** (WHEEL). **(Saarilahti & Anttila 1999)**

Littleton & Hetherington (1987) studied the MMP under metal plate track and concluded, that the MMP was close to the pressure based on the contact area of one track plate, see Figure 3.2. The MMP model is thus

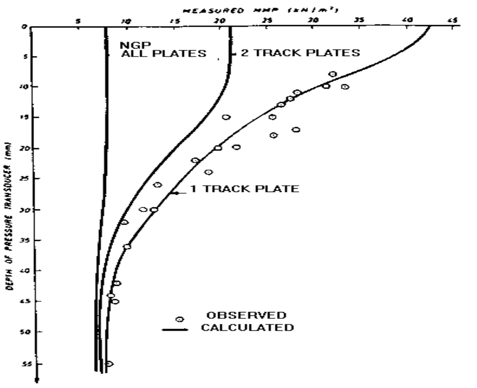

Figure 3.2 Variation of measured MMP with depth (Littleton & Hetherington 1987)

$$MMP = \frac{W}{2 \cdot m \cdot b \cdot p} \qquad (3.1.10)$$

where

MMP is mean maximum pressure, kPa

m	number of axles
b	track width, m
p	track plate length, m

3.2 *Schwanghart (1990)*

Schwanghart (1990) gives an empirical model for estimating the ground pressure of agricultural tyres

$$A = 0.77 \cdot b \cdot l_c \tag{3.2.1}$$

$$l_c = \sqrt{d \cdot (z + d) - (z + d)^2} + \sqrt{d \cdot d - d^2} \tag{3.2.2}$$

where

A	footprint area, m^2
b	tyre width, m
l_c	tyre contact length, m
d	tyre diameter, m
z	sinkage, m
δ	tyre deflection, m

$$b_c = b + c \cdot \frac{W}{W_N} \tag{3.2.3}$$

c	constant, 0.03 ... 0.05

An empirical model for loaded tyre:

$$p = 45 + 0.32 \cdot p_i \tag{3.2.4}$$

p	contact pressure, kPa
p_i	tyre inflation pressure, kPa

$$\delta = 0.8 \cdot \frac{W}{C_O} \tag{3.2.5}$$

C_O	spring rate

3.3 *Komandi (1990)*

The empirical model for agricultural tyres constructed by Komandi (1990)

$$A = \frac{c \cdot W^{0.7} \cdot \sqrt{\frac{b}{d}}}{p_i^{0.45}} \tag{3.3.1}$$

A is	tyre contact area, m^2
c	constant from Table 1
W	wheel load, kN
b	tyre width, m
d	tyre diameter, m
p_I	inflation pressure, kPa

Table 3.1 Constant c for different substrates in Komandi's model (3.3.1) (Komandi 1990)

Soil	Constant c for model (3.3.1)
Rather bearing soil	0.30 - 0.32
Sandy field	0.36 - 0.38
Loose sand	0.42 - 0.44

N.B. The constant c=0.175 seems to apply rather well for the estimation of the contact pressure under forestry tyres.

3.4 Silversides & Sundberg (1989) and Kemp (1990)

Silversides, C. R. & Sundberg, U. (1989 p. 113) assume, that 10% of the wheel load is supported by the side walls and give the following model:

$$A = \frac{0.90 \cdot W}{p_i} \qquad (3.4.1)$$

where

A	tyre contact area, m^2
W	wheel load, kN
p_i	tyre inflation pressure, kPa

Kemp (1990) assumes the support of side walls to zero, hence tyre contact pressure is equal to inflation pressure, and the contact area is:

$$A = \frac{W}{p_i} \qquad (3.4.2)$$

3.5 Grecenko (1995)

Grecenko (1995) presents an overview on the modelling of the footprint area and presents empirical models:

$$A = 1.57 \cdot (d - 2 \cdot r_l) \cdot \sqrt{d \cdot b} \tag{3.5.1}$$

$$A = \pi \cdot \delta \cdot \sqrt{d \cdot b} \tag{3.5.2}$$

$$A = c \cdot d \cdot b \tag{3.5.3}$$

c constant from Table 2.

Table 3.2 Constant c for Grecenko's footprint area model, Eq.(3.5.3)

Tyre and soil type	c
Hard tyre, hard ground	0.175
Flexible tyre (20% deformation), soft ground	0.245
Hard tyre, soft ground	0.270

$$A = 0.245 \cdot \left(\frac{W}{W_N}\right)^{\frac{2}{3}} \cdot d \cdot b \tag{3.5.4}$$

$$A = 1.57 \cdot \left(\frac{W}{W_N}\right)^{\frac{2}{3}} \cdot (d - 2 \cdot r_l) \cdot \sqrt{d \cdot b} \tag{3.5.5}$$

$$A = 2 \cdot \left(\frac{W}{W_N}\right)^{\frac{2}{3}} \cdot (d - 2 \cdot r_l) \cdot (d - d_{RIM}) \tag{3.5.6}$$

$$A = 1.65 \cdot \left(\frac{W}{W_N}\right)^{\frac{2}{3}} \cdot b \cdot \left[r_l \cdot (d - 2 \cdot r_l)^2\right]^{\frac{1}{3}} \tag{3.5.7}$$

He also draws conclusion on several papers. Also Sharma & Pandey (1996) present an overview over the tyre models of different authors.

3.6 Krick (1969)

Several authors have referred to Krick's tyre models:

$$A = 8 \cdot d \cdot h \tag{3.6.1}$$

$$A = 2 \cdot (d - 2 \cdot r_l) \cdot (d - d_{RIM}) \tag{3.6.2}$$

$$A = 5.3 \cdot h^2 \cdot d \cdot \left(\frac{p_i}{W} \cdot d \cdot b \right)^{0.8} \qquad (3.6.3)$$

Pillai & Fielding (1986) model is also often referred to:

$$A = 1.85 \cdot d^{\frac{2}{3}} \cdot b \cdot r^{\frac{1}{3}} \qquad (3.6.4)$$

3.7 Lyasko (1994)

The models presented by Lyasko (1994) are based on the tyre research carried out in Soviet Union. He also presents the “universal characteristics of a tyre”, Figure 3, the dependence of tyre deflection/tyre load of tyre deflection/tyre inflation and carcass pressure.

$$l_c = c_3 \cdot \sqrt{d \cdot \delta - \delta^2} \qquad (3.7.1)$$

$$c_3 = \frac{23}{ABS\left(\frac{d}{b} - 3.5 \right) + 11.9} \qquad (3.7.2)$$

$$b_c = 2 \cdot \sqrt{\frac{b+h}{2.5} \cdot \delta - \delta^2} \qquad (3.7.3)$$

$$A = \frac{\pi}{4} \cdot l_c \cdot b_c \qquad (3.7.4)$$

$$\delta = \frac{c_2 \cdot W}{2 \cdot (p_a + p_0)} + \sqrt{\left[\frac{c_2 \cdot W}{2 \cdot (p_a + p_0)} \right]^2 + c_1 \cdot W} \qquad (3.7.5)$$

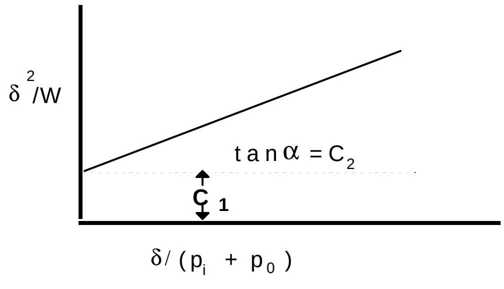

Figure 3.2 “The universal characteristics of a tire”

$$\frac{\delta^2}{W} = c_1 + \frac{c_2 \cdot \delta}{p_i + p_0} \tag{3.7.6}$$

can also be presented in the following form:

$$W = \frac{p_i + p_0}{\frac{c_1 \cdot (p_i + p_0)}{\delta^2} + \frac{c_2}{\delta}} \tag{3.7.7}$$

p_0	Conditional pressure, kPa
p_i	Inflation pressure, kPa

The estimate for the tyre section height:

$$h = 0.77 \cdot b^{0.89} \tag{3.7.8}$$

It seems rational, however, to use either tyre width b, or apply the model 3.7.9. specially for broad forestry tyres on softer soils.

$$b_c = 2 \cdot \sqrt{\frac{b + 0.77 \cdot b^{0.89}}{2.5} \cdot \delta - \delta^2} \tag{3.7.9}$$

3.8 Godbole et al. (1993)

Godbole et al. (1993) presents the following models:

$$l_c = 2 \cdot \sqrt{d \cdot d} \tag{3.8.1}$$

$$b_l = 2 \cdot \sqrt{h \cdot d} \qquad (h=b) \tag{3.8.2}$$

$$A = p \cdot d \cdot \sqrt{d \cdot h} \qquad (h=b) \tag{3.8.3}$$

$$d = h \cdot 0.67 \cdot \left(\frac{p_i \cdot d \cdot b}{W} \right)^{-0,8} \qquad (h=b) \tag{3.8.4}$$

LARGE AGRICULTURAL TYRES

$$d = h \cdot 0.54 \cdot \left(\frac{p_i \cdot d \cdot h}{W} \right)^{-0,79} \qquad \text{(h=b)} \qquad (3.8.5)$$

SMALL AGRICULTURAL TYRES

$$d = h \cdot 1.05 \cdot \left(\frac{p_i \cdot d \cdot h}{W} \right)^{-1.24} \qquad \text{(h=b)} \qquad (3.8.6)$$

3.9 Dwyer (1984)

Dwyer (1984) recommends Ground pressure index, based on WES-formula, to be used as a tyre characteristics:

$$G = \frac{W}{b \cdot d} \cdot \sqrt{\frac{h}{\delta}} \cdot \left(1 + \frac{b}{2 \cdot d} \right) \qquad (3.9.1)$$

$$A = \frac{W}{G} \qquad (3.9.2)$$

3.10 Ziani & Biarez (1990)

Ziani et Biarez (1990) give the following formulae for calculating tyre contact properties:

$$A = \frac{\pi}{4} \cdot b_c \cdot l_c \qquad (3.10.1)$$

$$l_c = 2 \cdot \sqrt{z \cdot (2 \cdot r - z)} \qquad (3.10.2)$$

$$b_c = 2 \cdot \sqrt{z \cdot (2 \cdot r_b - z)} \qquad (3.10.3)$$

b_c	contact width, m
l_c	contact length, m
r	tyre (longitudinal) radius, m
r_b	tyre (transversal) radius, m
z	sinkage, m

3.11 Febo (1987)

Febo (1987) measured the characteristics of modern wide agricultural tyres and developed the following semiempirical models for hard surface contact area:

$$l_c = 2 \cdot \sqrt{d} \cdot \delta^{j} \qquad (3.11.1)$$

j	empirical constant
	theoretical 0.5
	standard tractor tyre 0.41
	flexible, worn out 0.40
	wide tyre, with lugs 0.44

The values used in simulations in this paper
flexible tyre 0.40
forestry tyre, 0.44

$$b_c = b_w \cdot (1 - \exp^{-k \cdot d}) \qquad (3.11.2)$$

b_w	contact width, m
k	empirical constant
	standard tyre 33
	flexible, worn out 18
	wide tyre with lugs, 30

flexible tyre, 20
forestry tyre, 33

for high inflation pressure forestry tyres the value of 36 is more suitable

$$A = \frac{\pi}{4} \cdot l_c \cdot b_c \qquad (3.11.3)$$

3.12 Steiner (1979)

The empirical models for agricultural tyres presented by Steiner (1979) are:

Radial tyre

$$p_m = 267.7 + 0.575 \cdot p_i + 1.1 \cdot W - 16.0 \cdot d \qquad (3.12.1)$$

Cross ply

$$p_m = 112.8 + 0.665 \cdot p_i + 0.88 \cdot W - 40.0 \cdot d \qquad (3.12.2)$$

p_m	average contact pressure, kPa
p_i	tyre inflation pressure, kPa
W	wheel load, kN
d	tyre diameter, m

3.13 Mean Maximum Pressure, MMP

The following definitions are used in the MMP-equations.

MMP	mean maximum pressure, contact pressure, kN/m^2
W_{TW}	vehicle weight, kN
m	number of axles
b	tyre breadth, track width, m
c	track link profile factor, footprint area/($l_p \cdot b$)
d	tyre diameter, road wheel diameter, m
δ	tyre deflection on hard ground, m
h	tyre section height, m
k_1	constant, 9.1 tai 7.9 depending on inflation pressure
K_1	constant, Table 3.13.
K_2	constant, Table 3.13.
l_p	track link pitch, m
p_t	track pitch, m
S	proportionality constant
T	tread factor, Table 3.13.

Rowland (1972) developed a method for assessing the *Mean maximum pressure*, (**MMP**) for different cross county tyres and tracks on soft soils. Larminie (1988,1992) has developed the method further. The models based on MMP and WES-method are used, for example, in the British Army mobility models. The actual maximum contact pressure is, however, higher than calculated using Rowland's method (Wong 1994, 1995). Wong has developed a mathematical method, NTVPM-86, for calculating the contact pressure of tracks for fast moving tracked vehicles.

The original Rowland (1972) models:

Tracked vehicles, metal road wheels, for fine grained soils (clays, cohesive soils)

$$\mathrm{MMP} = \frac{1.26 \cdot W_{TW}}{2 \cdot m \cdot b \cdot \sqrt{d \cdot p_t}} \tag{3.13.1}$$

Tracked vehicles, pneumatic road wheels

$$\mathrm{MMP} = \frac{0.50 \cdot W_{TW}}{2 \cdot m \cdot b \cdot \sqrt{d \cdot \delta}} \tag{3.13.2}$$

Cross-country tyres

$$\text{MMP} = \frac{1.18 \cdot W_{TW}}{2 \cdot m \cdot b \cdot \sqrt{d \cdot h}} \qquad (3.13.3)$$

Conventional tyre, MMP for moist clay soils

$$\text{MMP} = \frac{3.3 \cdot W_{TW}}{2 \cdot m \cdot b \cdot d \cdot \sqrt{\frac{\delta}{h}}} \qquad (3.13.4)$$

Conventional tyre, MMP for moist clay soils

$$\text{MMP} = \frac{k_1 \cdot W_{TW}}{2 \cdot m \cdot b \cdot d} \qquad (3.13.5)$$

k_1= 9.1 high inflation pressures, used on roads
k_1= 7.9 low inflation pressures, used on terrain

Larminie (1988) proposed some standards for mobility requirements of military vehicles based on MMP. He published the following models for MMP calculations:

Tracked vehicles, metal road wheels, for fine grained soils (clays, cohesive soils)

$$\text{MMP} = \frac{1.26 \cdot W_{TW}}{2 \cdot m \cdot c \cdot b \cdot \sqrt{d \cdot l_p}} \qquad (3.13.6)$$

Wheels on fine-grained cohesive soils

$$\text{MMP} = \frac{K_1 \cdot W_{TW}}{2 \cdot m \cdot b^{0.85} \cdot d^{1.15} \sqrt{\frac{\delta}{h}}} \qquad (3.13.7)$$

Table 3.3 Constant K_1 for model (3.13.7)

Number	Proportion of axles driven						
of axles	1	3/4	2/3	3/5	½	1/3	1/4
2	3.65				4.40		
3	3.90		4.35			5.25	
4	4.10	4.44			4.95		6.05
5	4.32			4.97			
6	4.6		5.15		5.55	6.20	

If differential locks are in use, then
MMP = MMP · 0.98 for 4x2 vehicles
MMP = MMP · 0.97 for 4x4 vehicles

For wheels on dry coarse grained frictional soils, sand soils

$$MMP = \frac{S \cdot T \cdot W_{TW}}{2 \cdot m \cdot b^{1.5} \cdot d^{1.5} \cdot \frac{\delta}{h}} \qquad (3.13.8)$$

where

S constant of proportionality, use S=0.6
T tread factor, see Table 3.13.2

Table 3.4 Constant T, Tyre tread factor, for models (3.13.8 and 3.13.11)

Tyre tread	Constant T
Smooth tyre	1.0
Road tyre	1.4
Road/CC tyre	2.8
Earth mover tread	3.3

Later Larminie (1992) presented improved models for MMP. One of the important modifications was the replacement of the form factor δ/h by δ/d.

Wheeled vehicle on fine grained soils, cohesive soils

$$MMP = \frac{K_2 \cdot W_{TW}}{2 \cdot m \cdot b^{0.85} \cdot d^{1.15} \sqrt{\frac{\delta}{d}}} \qquad (3.13.9)$$

Table 3.5. Constant K_2 for model (3.13.9)

Number	Proportion of axles driven						
of axles	1	3/4	2/3	3/5	½	1/3	1/4
2	1,83				2,20		
3	1,95		2,17			2.62	
4	2,05	2,22			2,48		3,02
5	2,16			2,48			
6	2,30		2,57		2,77	3,10	

Wheeled vehicle on coarse grained soils (sands, frictional soils)

$$\mathrm{MMP} = \frac{S \cdot T \cdot \mathrm{W_{TW}}^{1.3}}{2 \cdot \mathrm{m} \cdot \mathrm{b}^{1.5} \cdot d^{1.5} \cdot \frac{d}{d}} \qquad (3.13.10)$$

Tyre tread factor T from Table 3.4. and S from Table 3.6.

Table 3.6. Constant S for model 3.13.10.

Axles driven	Constant S
All wheel drive	0.31
4x2	0.37
6x4	0.35
8x6	0.34
8x4	0.38

> ***Note**: For an unknown reason the model 3.13.10 seems to give unrealistic values, and the values seem more realistic if multiplied by 0.1. More realistic values are obtained by using the earlier Larminie's (1988) earlier model (3.13.8).*

Belt tracks with pneumatic tyres

$$\mathrm{MMP} = \frac{0.50 \cdot \mathrm{W_{TW}}}{2 \cdot \mathrm{m} \cdot \mathrm{b} \cdot \sqrt{\mathrm{d} \cdot \delta}} \qquad (3.13.11)$$

Wheeled vehicle with different wheel sizes on cohesive soils

$$\mathrm{MMP} = \frac{\mathrm{K}}{2 \cdot \mathrm{m}} \cdot \left[\frac{\mathrm{W_1}}{\mathrm{b_1}^{0.85} \cdot \mathrm{d_1}^{1.15} \sqrt{\frac{\delta_1}{\mathrm{d_1}}}} + \cdots + \frac{\mathrm{W_i}}{\mathrm{b_i}^{0.85} \cdot \mathrm{d_i}^{1.15} \sqrt{\frac{\delta_i}{\mathrm{d_i}}}} \right] \qquad (3.13.12)$$

Twinned wheels

Sandy soils

Replace factor 2·m by the total number of wheels w

Clay soils

Substitute the factor 2m by $\frac{2 \cdot \mathrm{m} + \mathrm{w}}{2}$, where w is the total number of twinned wheels

Half track vehicles

For half track vehicles use K value of 1.66.

Differential locks

If differential locks are in use the equivalent MMP is improved:

for 4x2 vehicles $MMP \cdot 0.98$

4x4 vehicles $MMP \cdot 0.97$

6x6 vehicles $MMP \cdot 0.97$

Rowland (1972 p. 379) concludes the experience gained on the mobility of the Second World War military vehicles as follows, Table 3.13.6. Some kind of limiting value for soft soils is thus MMP=170 kPa. Note, that the MMP under the foot of a man is about 50 kPa.

Table 3.7. Mobility of the Second World War II military vehicles. (Rowland (1972)).

MMP, kPa	Observed mobility
Over 400	*unsuitable for the soft ground role*
Over 300	*short lived*
Substantially above 200	*substantially above 200 kPa have been significantly affected by bogging, whilst vehicles below this limit have been little troubled*
Under 170	*noted for good mobility*

Larminie (1988) gives the following model for determining trafficability limit, go/no-go situation, on moist cohesion soils (fine grained and clay soils)

$$CI = 0.827 \cdot MMP \tag{3.13.13}$$

where

CI Rating cone index, kPa

MMP Mean maximum pressure

The CI should pass the values given in Table 3.13.8

Table 3.8. Minimum CI for the intensity of the traffic

Number of pass	1	2	5	10	25	50
Multiply One pass CI by	1	1.2	1.53	1.85	2.35	2.8
Nb^x		0.26	0.26	0.26	0.26	0.26

Littleton & Hetherington (1987) found out that the MMP was independent on the road wheel diameter, and can be estimated based on the contact surface of one track segment (width (b) x length (p)). They present a model for mean maximum pressure, Eq(3.13.14). for a full track vehicle.

$$\mathrm{MMP} = \frac{\mathrm{W}}{2 \cdot \mathrm{m} \cdot \mathrm{b} \cdot \mathrm{p}} \qquad (3.13.14)$$

Referring to Maclaurin's (1997) proposal to replace the MMP by a new go/nogo parameter, Limiting Cone Index, $\mathrm{CI_L}$, Hetherington (2001) questions the use as a simple specification of trafficability. After his field measurements the observed MMP proposed by Maclaurin's models are underestimates, and Rowland's original equations give estimates closer to observed. Limiting cone index is the cone index of the weakest soil, which a vehicle can pass. It is to be noted, that Maclaurin has based his tests on wheel and track performance tests, and not on soil pressure gauge measurements.

The Maclaurin's (1997) $\mathrm{CI_L}$ equations are

For wheels

$$\mathrm{CI}_{\mathrm{Lwheel}} = \frac{1.85 \cdot \mathrm{W_w}}{2 \cdot \mathrm{n} \cdot \mathrm{b}^{0.8} \cdot \mathrm{d}^{0.8} \cdot \delta^{0.4}} \qquad (3.13.15)$$

For tracks

$$\mathrm{CI}_{\mathrm{Ltrack}} = \frac{1.63 \cdot \mathrm{W_w}}{2 \cdot \mathrm{n} \cdot \mathrm{b} \cdot \mathrm{e} \cdot \mathrm{p}^{0.5} \cdot \mathrm{d}^{0.5}} \qquad (3.13.16)$$

where

$\mathrm{CI_{Lwheel}}$	limiting cone index for wheels
$\mathrm{CI_{Ltrack}}$	limiting cone index for tracks
$\mathrm{W_W}$	vehicle total weight, kN
n	number of axles, number of road wheels per side
b	(inflated, unloaded) tyre width, track width, m
d	(inflated, unloaded) tyre diameter, m
δ	tyre deflection when loaded, m
p	track plate length, m
e	track link area ratio

3.14 Keen & Craddock (1997)

Keen & Craddock (1997) developed the measuring technique of the deflection, and found out, that the latter term of contact length (l_2) can be estimated by the model

$$l_2 = 2.9 \cdot d \qquad (3.14.1)$$

They present an empirical model for the contact area for wide low pressure tyres:

$$A = 0.78 \cdot b_{RUT} \cdot \left(\sqrt{(\delta + z) \cdot (2 \cdot r - \delta - z)} + 2.9 \cdot \delta \right) \qquad (3.14.2)$$

b_{RUT} rut width, m

3.15 Koolen (1992)

Koolen studied (Koolen et al. 1992, Heij & Koolen 1994) wheel soil stresses, and concluded, that the stress at the contact area, contact pressure, is twice the tyre inflation pressure

$$p = 2 \cdot p_i \qquad (3.15.1)$$

This means, that the contact pressure is close to MMP.

3.16 Ziesak & Matthies (2001)

Ziesak & Matthies (2001) studied forestry tyres on a hard surface under different loads and recorded the contact area and developed an empirical tyre contact area model for the the average contact pressure. They concluded that the contact pressure cannot be calculated simply by dividing the wheel load by the observed contact area and developed a pressure zone model based on the fact, that the soil pressure under deformable tyre is not uniform, see Figure 3.3. The contact pressure is thus some kind of average maximal contact pressure.

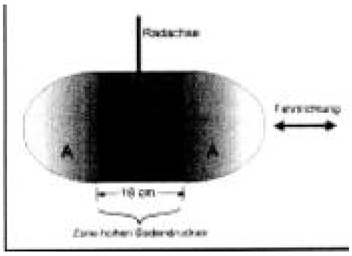

Figure 3.3 Tyre contact pressure zones (Ziesak & Matthies 2001)

The empirical Ziesak & Matthies (2001) **tyre contact pressure** model for forestry tyres is, Eq(4.16.1)

$$\begin{aligned} p_c = & -3947 + 0.000452 \cdot \frac{W \cdot PR \cdot p_i}{b \cdot d} + 29.4 \cdot \ln\left(\frac{W}{9.81}\right) - \frac{4239}{p_i} - 253.3 \cdot d^2 - \frac{1149.5}{b} \\ & - 2911.8 \cdot \ln(1000 \cdot b) + 1807 \cdot b \cdot d + \frac{1.295 \cdot W}{b \cdot d} - 0.009 \cdot W^2 - \frac{7117.3}{PR} - 440.6 \cdot \ln(PR) \\ & + \frac{1144.4}{h} + 3845 \cdot \ln(h \cdot 1000) - \frac{2.26 \cdot b}{1000} \cdot \left[\left(\frac{1000 \cdot d}{2} \right)^2 - (500 \cdot d - 1000 \cdot h)^2 \right] \end{aligned}$$

(3.16.1)

The developed **tyre contact area** model is, Eq(4.16.2)

$$A = 282.6 + 3769 \cdot b + 2369 \cdot d - 257.2 \cdot PR - 2.291 \cdot p_i + 18.41 \cdot W - 2895 \cdot b \cdot d - \frac{7788.5}{W}$$

$$+ 7.46 \cdot PR^2 + 17 \cdot \frac{p_i}{W} + 2768.5 \cdot \frac{W}{p_i} \tag{3.16.2}$$

p_c	mean contact pressure, kPa
W	wheel load, kN
p_i	inflation pressure, kPa
PR	ply rating
b	tyre width, m
d	tyre diameter, m
h	tyre carcass height, m

3.17 Boling (1985)

Boling (1985) refers to some older farm tractor studies and gives the following model for tyre contact pressure model

$$p_c = 40 + p_i \tag{3.17.1}$$

The tyre contact area can be calculated based on contact pressure.

3.18 Söhne (1969)

Söhne’s (1969) study is one of the older, frequently referred studies on farm tractor tyre contact area

$$A = 2 \cdot b \cdot \sqrt{d \cdot z} \tag{3.18.1}$$

4. COMPARISON OF THE MODELS

4.1 Tyre soil contact

Different models are compared in Figures 4.1 and 4.2. The reference tyre is a forwarder tyre 700/50-26.5, 16 ply tyre with 400 kPa inflation pressure. Tyre dimensions are b=0.700 m and d=1.330 m. Wheel load is 35 kN. If available, bearing soil constant has been used, and the soil cone index is put to1000 kPa. For comparison also NGP **(NGP)** and Limiting cone index **(CI)** values are presented in Figures 4.1 and 4.2. Tyre contact area, footprint area calculated using different models is presented in Figure 4.1.

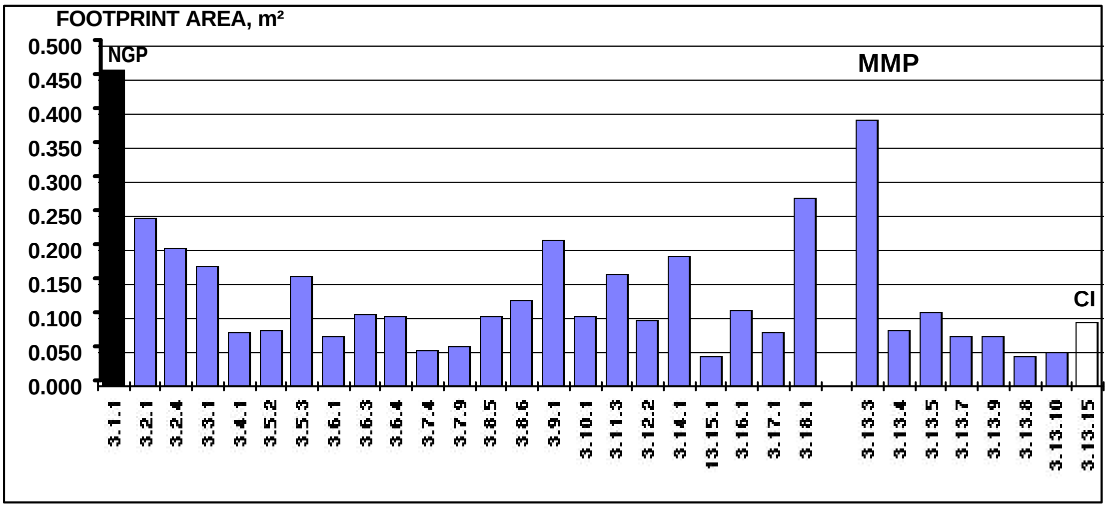

Figure 4.1 Footprint area calculated using different tyre models

The outcome of the tested models differs largely, and the "correct" footprint area is difficult to judge. However, the NGP seems to give too high footprint area estimates compared to the other models.

Table 4.1. Models used in Figures 4.1. and 4.2.

No	Equation	Reference	No	Equation	Reference
Contact pressure and area models					
1	3.1.1	Swedish Formula	13	3.8.5	Godbole & al (1993)
2	3.2.1	Schwanghart (1990)	14	3.8.6	-"-
3	3.2.4	-"-	15	3.9.1	Dwyer (1984)
4	3.3.1	Komandi (1990)	16	3.10.1	Ziani & Biarez (1990)
5	3.4.1	Silversides & (1989)	17	3.11.3	Febo & Pessina (1987)
6	3.5.2	Grecenko (1995)	18	3.12.2	Steiner (1979)
7	3.5.3	-"-	19	3.14.1	Keen & Craddock (1997)
8	3.6.1	Krick (1994)	20	3.15.1	Koolen et al. (1992)
9	3.6.3	-"-	21	3.16.1	Ziesak & Matthies (2001)
10	3.6.4	-"-	22	3.17.1	Boling (1985)
11	3.7.4	Lyasko (1994)	23	3.18.1	Söhne (1969)
12	3.7.9	-"-			
Mean maximum pressure models					
1	3.13.3	Cross country tyre	5	3.13.9	Cohesive soils
2	3.13.4	Cohesive soils	6	3.13.8	Dry friction soils
3	3.13.5	Conventional, cohesive	7	3.13.10	Dry friction soils
4	3.13.7	Cohesive soils	8	3.13.15	Limiting CI, Maclaurin

In Figure 4.2 different models are compared based on the tyre contact pressure.

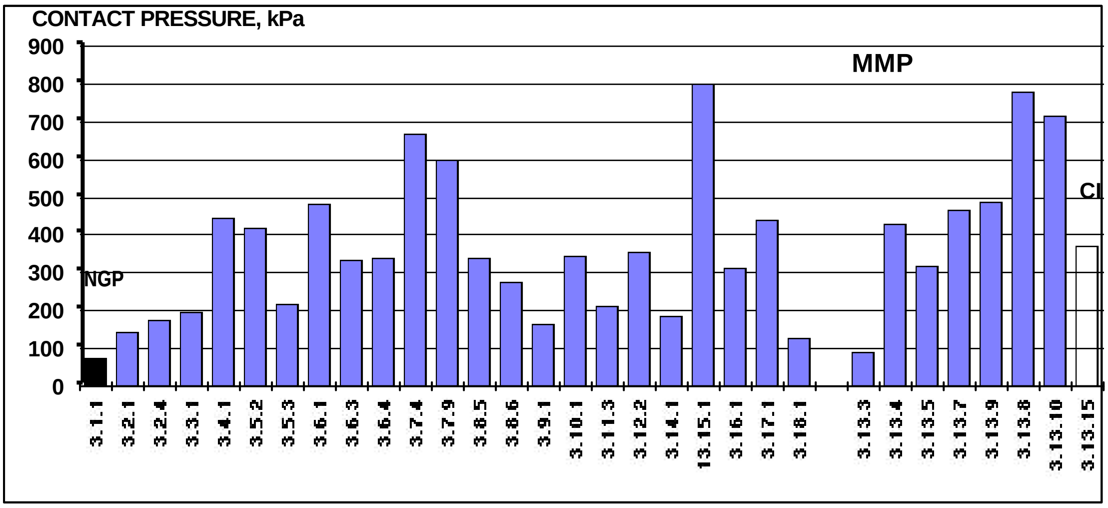

Figure 4.2 Comparison of the calculated tyre contact pressure using different models

The models give values from 80 to 880 kPa, and the NGP model seems to give very low values, about the same size as an old cross-country tyre MMP-model (3.1.3). The deflection of the cross-country tyre is, however, quite different from the forwarder tyre.

4.2 Track soil contact

As the report is concentrated on tyre-wheel interaction, tracked vehicles are not largely analysed. It is, however, important to notice, that the NGP-formula for tracks, Eq. (3.1.2) cannot be used for evaluating the footprint area or soil contact pressure for a wheeled forest tractor tandem axles fitted with flexible tracks. As an example the following Table 4.2.

Table 4.2. Track contact area and contact pressure after NGP-model (Eq. 3.1.2) and MMP-formula for tracked vehicle with pneumatic road wheels (Eq. 3.13.2)

Model	NGP	MMP
Contact pressure, kPa	43	130
Footprint area, m^2	1.634	0.268

Different track contact pressure models, all based on MMP concept, are compared in Figure 4.3. For comparison also NGP **(NGP)** and Limiting cone index **(CI)** values are also presented in Figure 4.3.

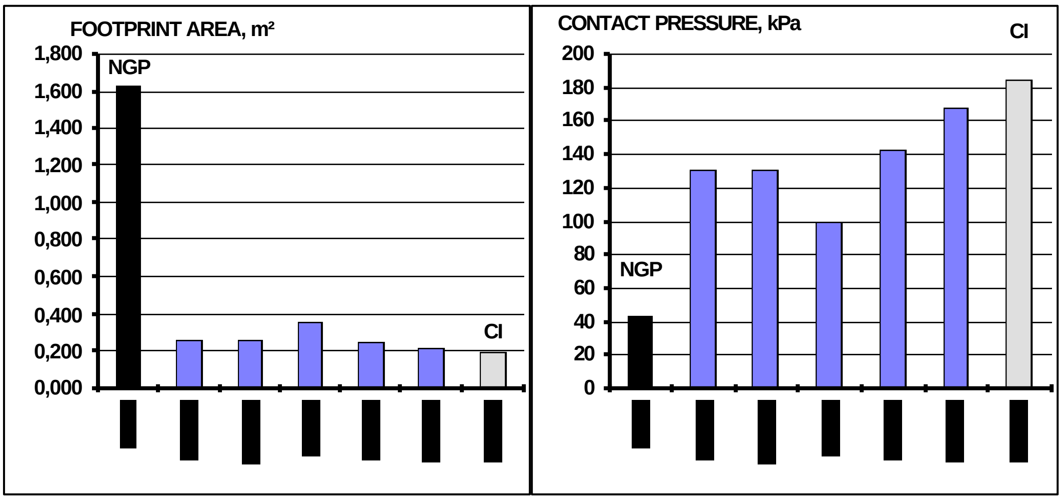

Figure 4.2. Comparison of the track contact area and contact pressure models.

Table 4.3. MMP-formulae used in comparison calculus.

No	Model	Application	No	Equation	Application
1	3.1.2	NGP, Swedish formula	5	3.13.6	Metal tracks, cohesive
2	3.13.2	Pneumatic road wheels	6	3.13.14	Metal tracks, cohesive
3	3.13.11	Belt tracks, pneumatic	7	3.13.16	Limiting CI, Maclaurin
4	3.13.1	Metal tracks			

4.3 Influence of different factors on tyre contact pressure

Two models were selected for studying the influence of different factors on contact pressure. The results are presented together with the NGP values in order to visualise the difference between “true” contact pressure and a calculated indice.

1) Ziesak & Matthies (2001) model, Eq(3.16.1), is developed from an empirical data on modern forest tractor tyres
2) Maclaurin’s (1997) Limiting Cone Index model, Eq(3.13.15), is some kind of a MMP model based on military vehicle field tests

The two completely different models gave rather similar results, and therefore they can be considered as “the best estimates” for forest tractor tyre contact pressure on harder surfaces.

The calculations are based on 14 ply forest tractor tyres with 0.600 and 0.700 m width, 1.330 m diameter, 0.300 m tyre section height and 400 kPa tyre inflation pressure. Tyre deflection is calculated using the following average forest tractor tyre deflection model. Eq(4.1), see the Appendix Report No. 6, Tyre stiffness and deflection.

$$d = 0.001 \cdot (0.365 + \frac{170}{p_i}) \cdot W \qquad (4.1)$$

A certain correction has been made when studying the influence of ply rating assuming that the deflection is larger under tyres with less plies.

4.3.1 Influence of tyre inflation pressure

Under the normal full wheel load, 40 kN, tyre contact pressure seems to be somewhat lower than the tyre inflation pressure, see Figure 4.3. At low inflation pressure (100 kPa) the contact pressure is already high, over 200 kPa, indicating rather stiff tyre carcass. At normal working pressure[1] (400-450 kPa) the contact pressure is close to inflation pressure, around 300-400 kPa.

At the same inflation pressure the tyre contact pressure seems to be somewhat lower under broader tyre.

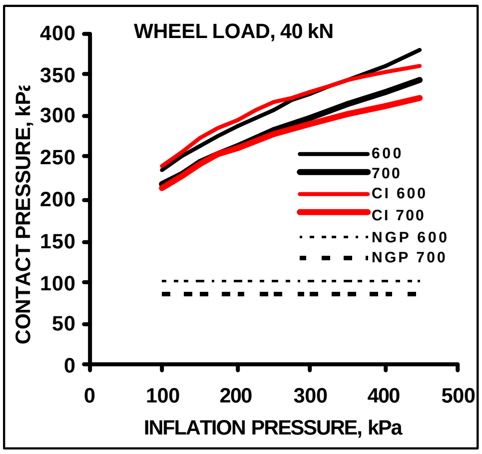

Figure 4.3 Effect of inflation pressure on tyre contact pressure

4.3.2 Effect of wheel load on tyre contact pressure

Wheel load increases rather linearly the tyre contact pressure, as seen from Figure 4.4. The “true” contact pressure is more than four times higher than Nominal Ground Pressure, as seen from Figure 4.4.

Under empty forwarder wheel (< 20 kN wheel load) the contact pressure is around 300 kPa, and under the loaded wheel (40 kN wheel load) the contact pressure is around 400 kPa, of the same magnitude than the inflation pressure.

The both models give rather similar contact pressures for loaded wheels, and the difference for empty tractor is also rather small. This

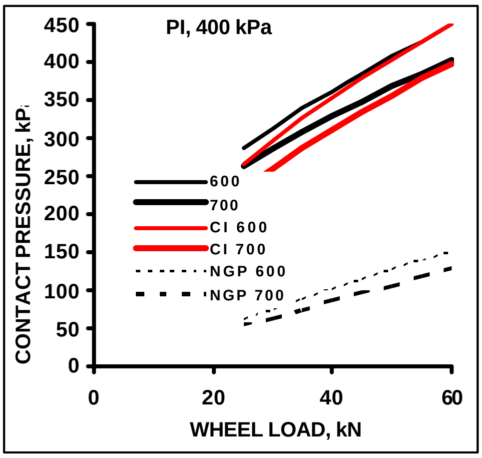

Figure 4.4 Effect of the wheel load on tyre contact pressure

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[1] In the Finnish forestry

encourages to recommend these two models to be used as “reference models” for comparing different machines fitted with different wheel configurations, as they seem to be the most logical models for forestry tyres found in literature.

4.3.3 Influence of tyre width on tyre contact pressure

The influence of tyre width on contact pressure seems to be somewhat more complicated than, for example, that of the inflation pressure or tyre diameter, see Figure 4.5. One reason may be the fact, that tyre contact pressure under a plate is higher under centerline than on sides, and the average contact pressure depends on the measuring technique and calculation procedure. At least the interpolation of the Ziesak & Matthies model for larger diameter and narrower tyres seems to differ somewhat from the simpler Maclaurin model. For normal tractor tyres, 600-700 mm wide with 1300 mm diameter the models give similar results and the both models can therefore be used for normal forwarders, but may give biased estimates for special tractor tyres.

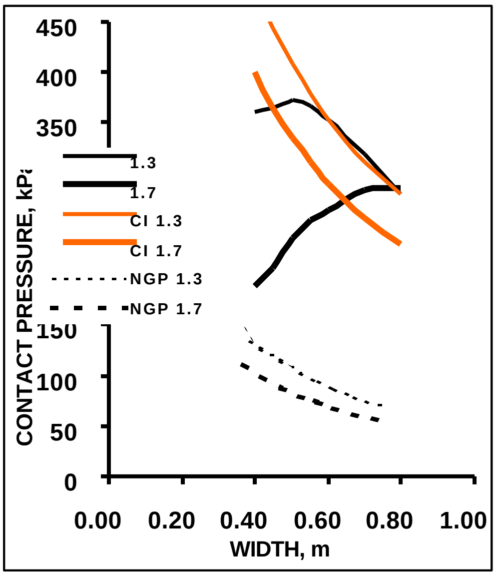

Figure 4.5 Influence of tyre width on contact pressure

4.3.4 Influence of wheel diameter on tyre contact pressure

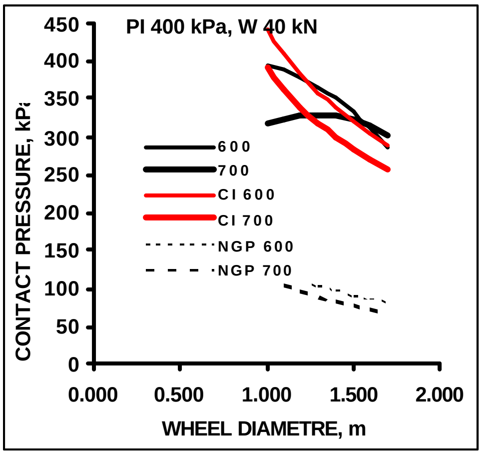

Figure 4.6 Effect of diameter on tyre contact pressure

Tyre contact pressure under large diameter wheel is lower than under a small one as seen from Figure 4.6 The tendency is the same for the both models, but a certain difference can be detected. After the Ziesack & Matthies model the increase in diameter does not affect the contact pressure for larger tyres, even for the narrow tyres the increase in diameter reduces the contact pressure. After Mclaurin’s model the increase in diameter decreases the contact pressure independently on the tyre width. The discrepancy between models have less influence for everyday analysis, because large diameter (1.6 m) tyre is generally narrow (0.5 -0.6 m), and small diameter tyre (1.3 m) is wide (0.6 – 0.7 m).

4.3.5 Effect of tyre structure on contact pressure

As expected, the stiffer tyre with high number of plies generates higher contact pressure, see Figure 4.7. Again the two models seems to match well, but it must be kept in mind, that the Maclaurin model uses deflection as an input variable. The true deflection of tyres with different ply ratings was not available, but only an educated guess.

The more wear resistant tyre with several plies generates higher contact pressure, which, as a rule is considered environmentally more damaging.

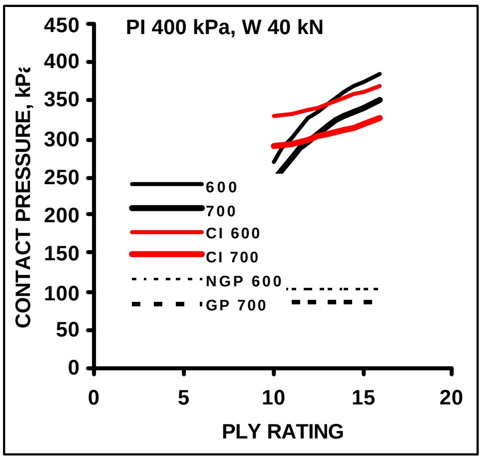

Figure 4.7 Effect of tyre structure on contact pressure

4.4 Comparison of tyre contact pressure models

The following six tyre contact pressure models have been taken for a closer comparison:

1) Contact pressure model derived from Silversides & Sundberg's (1989) tyre contact area model, Eq(3.4.1), model 4.2. The results are marked as S&S in Figure 4.9.

$$p = 1.11 \cdot p_i \tag{4.2}$$

where

p is	tyre contact pressure, kPa
p_i	tyre inflation pressure, kPa

2) Ziesak & Matthies (2001) tyre contact pressure model, Eq(3.16.1). The results are marked as Z&M in Figure 4.9.

3) Ground pressure index based on Maclaurin's (1997) limiting cone index model, Eq(3.13.15), Eq(4.3). The results are marked as Z&M in Figure 4.9.

$$p = \frac{W}{b^{0.8} \cdot d^{0.8} \cdot d^{0.4}} \qquad (4.3)$$

4) Nominal Ground pressure, NGP, Eq(3.1.1). The results are marked as NGP in Figure 4.9.

5) Based on virtual wheel contact length model Eq(2.4.1 to 2.4.3) and tyre width, Eq(4.4). The results are marked as VIRTUAL in Figure 4.9.

$$p = \frac{W}{\frac{p}{4} \cdot b \cdot l_c} \qquad (4.4)$$

6) Ground pressure model developed from Komandi's (1990), Eq(3.3.1) contact area model, Eq(4.5). The results are marked as Komandi in Figure 4.9.

$$p = \frac{W^{0.3} \cdot p_i}{c \cdot \sqrt{\frac{b}{d}}} \qquad (4.5)$$

For the constant **c** the following model was developed by allocating a certain arbitrary CI value for each soil bearing class presented in Table 3.1., see Figure 4.8. The developed c-model is, Eq(4.6)

$$c = \frac{9.5}{\sqrt{CI}} \qquad (4.6)$$

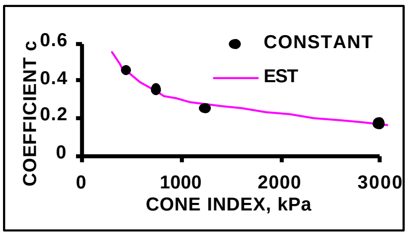

Figure 4.8 Constant c as a function of Cone Index

The used tyre characteristics are:

W= 36 kN
d=1.330 m
b=0.700 m
p_i=400 kPa

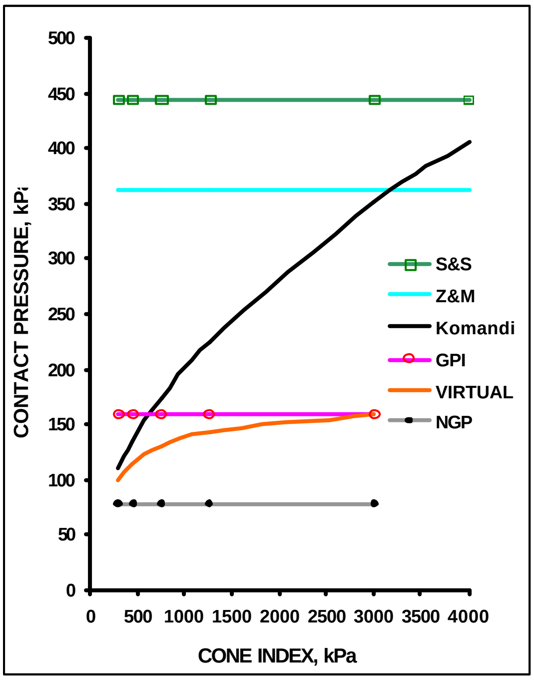

Figure 4.9 Contact pressure as a function of Cone Index using different models

The comparison of the different models is depicted in Figure 4.9. There are three models where the soil properties or wheel sinkage are not used as input variables, and they lead to a constant soil contact pressure. Two of them (S&S and Z&M) assume a hard surface with minimal sinkage. They are thus some kinds of maximal contact pressure values. The other two models (NGP and GPI) give some kinds of minimum contact pressure values, as they consider the situation where the wheel has already a noticeable sinkage, about 25% for GPI and 30% for NGP, close to the no-go situation. The model based on Komandi's (1990) approach estimates the true contact area on different soil bearing capacity conditions. It seems to behave logically, as on low bearing soils is it close to the NGP and GPI pressure estimates, and for bearing soil it matches with hard surface models Z&M and S&S. The Komandi model gives thus some kind of "average contact pressure on true contact area". The behaviour of virtual wheel contact model gives hints on the "average contact pressure over the whole contact surface". On harder surfaces it matches well with the GPI and on sensitive soils when the wheel sinkage begins to play a remarkable role in stead of tyre deflection in the formation of contact surface, the pressure begins to approach the NGP value.

As a conclusion it can be said, that the models can be used in different wheel soil models, but not giving a certain true ground truth value, but a set of relative values to support more correct wheel/site matching decisions.

5. CONCLUSIONS AND RECOMMENDATIONS

Currently used method, NGP, for calculating tyre contact area and ground pressure can be considered misleading, because it gives unrealistically low ground pressure values. The values can be used only in rough comparison of some rather similar machines, but cannot be used for selecting environmentally better machine solutions.

There is not any simple model, which can be shown to be reliable and valid for all the purposes. The problem has its origins from the fact that the real pressure and force distribution in soil depends on the form and structure of the loading surface. Many models are originally based on rigid plate theories, which are applicable for foundations. The pressure distribution under a flexible surface and dynamic load differs from that of the rigid static one, and the theory also becomes more complicated. There are already rather sophisticated calculation methods, but they demand larger resources: adequate computer facilities and programs, higher mathematical and programming skills, and adequate know how on soil properties and soil models.

Simpler models can, however, be used for developing acceptable models for wheel soil interaction. Models based on **maximum pressure** evaluation are more appropriate in evaluating the **soil damages**. **Contact area** models seems more reliable for evaluating the mobility, such as **thrust, pull and rolling resistance**.

Because the immediate adaptation of the 3-D tyre mathematical models seems unrealistic, it is still worth of improving the line of semi-empirical models, based on observed tyre contact area on forest soil under forestry tractors using forestry tyres.

NGP is one tyre variable, which can be used for rapid evaluation between some alternatives, with rather similar tyre configurations at a constant tyre inflation pressure. The NGP formula, proposed for tracked vehicle is completely misleading, if applied for a forest tandem axle fitted with belt track.

MMP, even having a large number of formulas to be chosen, has an advantage, that it takes into account more tyre variables, and gives more reliable information for decision making. It has an advantage, that wheeled and tracked drive lines can be compared with a certain accuracy, even rather a heavy critique has been presented by Hetherington (2001). Both the Ziesak & Matthies (2001) and Maclaurin (1997) models seem useful for estimating the tyre contact pressure under forest tractor tyres.

Dwyer's proposal to use G-variable, related to the same tyre characteristics as MMP, has the advantage, that it is directly related to Wheel Numerics. It has the disadvantage, that it cannot be applied for tracked vehicles. As a Wheel Numeric takes into account also one soil variable, Wheel Numeric as such, can be used as an selection criterium. Ground pressure and tyre footprint area, are not indispensable variables for machine and method selection between wheeled vehicles. Also it is possible to develop some semiempirical general models, based on existing literature, giving adequately exact estimates to compare machines with rather different tyre configurations.

Literature

Abeels, P. F. J. 1994. Mechanisation of the forest operations and impacts on the environment. Interactive workshop and seminar FORSITRISK, soil, tree, machine interactions. Feldafing, Federal Republic of Germany, 4-8. July 1994. Joint Committee on Forest Technology, Management and Training, IUFRO Div. P3.08.0. 24 p.

Anttila, T. 1998. Metsämaan raiteistumisen ennustaminen WES-menetelmää käyttäen. University of Helsinki, Department of forest resource management. Publications 17. 53 p. ISBN 951-45-8025-7

Boling, I. H. 1985. How to predict soil compaction from agricultural tires. Journal of terramechanics 22(4):205-226

Dwyer, M. J. 1984. Tractive performance of wheeled vehicles. Journal of Terramechanics, 21(1):19-34

Febo, P. 1987. Contact area tests of a new wide section agricultural tyre. Proceedings of the 9th International ISTVS Conference, Barcelona, Spain, 31 August-4 September 1987. I:236-243

Godbole, R., Alcock, R. & Hettiaratchi, D. 1993. The prediction of tractive performance on soil surfaces. Journal of Terramechanics 30(6):443-459.

Grandlund, P. & Andersson, G. 1997. Möt våren med CTI. Studier av virkesfordon utrustade med CTI våren 1997. Looking forward to spring with CTI. A study on timber haulage vehicles equipped with CTI, spring 1997. The Forestry Research Institute of Sweden, SkogForsk. Redogörelse nr 2. 26 p.

Grecenko, A. 1995. Tyre footprint area on hard ground computed from catalogue value. Journal of Terramechanics 32(6):325-333.

Hallonborg, U. 1996. Super ellipse as tyre-ground contact area. Journal of Terramechanics 33(3):125-132.

Heij, W. & Koolen, A. J. 1994. Stress transmission in forest soils and the reinforcing effect of roots. Interactive workshop and seminar FORSITRISK, soil, tree, machine interactions. Feldafing, Federal Republic of Germany, 4-8. July 1994. Joint Committee on Forest Technology, Management and Training, IUFRO Div. P3.08.0. 10 p.

Hetherington, J. G. 2001. The applicability of the MMP concept in specifying off-road mobility for wheeled and tracked vehicles. Journal of terramechanics 38(2):63-70.

Littleton, I. & Hetherington, J. G. 1987. The study of parameters which affec tracked vehicle ground pressures on dry sand. Proceedings of the 9th ISTVS Conference, Barcelona, Spain, 31 August-4th September 1987. I:213-220.

Karafiath, L. L. & Nowatzki, E. A. 1978. Soil mechanics for off-road vehicle engineering. Trans. Tech. Publications, Series on rock and soil mechanics 2:5. 515 s.

Keen, A. & Craddock, S. 1997. A method for determining the tyre-soil contact of a rolling tyre by using the dynamic measurement of the radial and tangential tyre deflection. Proceedings of the 7th ISTVS European Conference, Ferrara, Italy 8-10.10.1997: 139-146.

Kemp, H. R. 1990. Climbing ability of four-wheel-drive vehicles. Journal of Terramechanics 27(1):7-23.

Komandi, G. 1990. Establishment of soil-mechanical parameters which determine traction on deforming soil. Journal of Terramechanics 27(2):115-124.

Koolen, A. J. P., Lerink, D.A. g., Kurstjens, J. J. H., van der Akker & Arts, W. B. M. 1992. Prediction of aspects of soil-wheel systems. Soil and Tillage Research 24: 381-396.

Krick, G. Radial and shear stress distribution under rigid wheels and pneumatic tyres operating on yielding soils with consideration of tyre deformation. Journal of Terramechanics 6(3):73-98.

Lach, B. 1996. The influence of tire inflation pressure - a comparison between simulation and experiment. In: Off road machines and vehicles in theory and practice. Proceedings of the 1st International Conference, Wloclaw, Poland. September 23-24, 1996. 265-272.

Larminie, J. C. 1988. Standards for the mobility requirements of military vehicles. Journal of Terramechanics 25(3):171-189.

Larminie, J. C. 1992. Modifications to the mean maximum pressure system. Journal of Terramechanics 29(2):239-255.

Löfgren, B. 1991. Lägre lufttryck ger mindre spårdjup. Skogsarbeten resultat Nr 23. 4 p.

Littleton, I & Hetherington, J. G. 1987. The study of parameters which affect tracked vehicle ground pressures on sand. Proceedings of the 9th International ISTVS Conference, Barcelona, Spain. 31 August- 4 September 1987. I:213-220.

Lyasko, M., I. 1994. The determination of deflection and contact characteristics of a pneumatic tire on a rigid surface. Journal of Terramechanics 31(4):239-242.

Maclaurin, E. B. 1990. The use of mobility numbers to describe the in-field tractive performance of pneumatic tyres. Proceedings of the 10th International ISTVS Conference, Kobe, Japan, August 20-24, 1990. I: 177-186.

Maclaurin, E. B. 1997. Proposed revisions to MMP based on the tractive performance trials with single pneumatic tyres and a modular track system. DERA/LS/TR970122/1. DERA, Chertsey, UK.

Mikkonen, E. & Wuolijoki, E. 1975. Pikatestausten suoritustekniikka. The technique of short term testing. Metsätehon katsaus 9. 5 p.

Metsätalousrenkaiden tekninen käsikirja. No year. Nokian Renkaat Oy. Nokia. 15 s.

Pillai, P. S. & Fielding-Russel, G. S. 1986. Empirical equation for tire footprint area. Rubber Chem. Tech. 59(1):155-159

Rieppo, K. 1997. Metsäkoneiden telin liikedynamiikasta ja pintapaineiden määrittämisestä. Metsätehon raportti 23. 18 s.

Rowland, D. 1972. Tracked vehicle ground pressure and its effect on soft ground performance. Proceedings of the 4th ISTVS Conference, Stockholm-Kiruna April 24-28, 1972. I:353-384

Saarilahti, M. & Anttila, T. 1999. Rut depth model for timber transport on moraine soils. Proceedings of the 13th International conference of the ISTVS, Munich, Germany, September 17-17, 1999: 29-37

Schwanghart, H. 1990. Measurement of contact area, contact pressure and compaction under tires in soft soil. Proc. 10th ISTVS Conf, Kobe Aug 20-24, 1990. I:193-204

Sharma, A. K. & Pandey, K. P. 1996. A review on contact area measurement of pneumatic tyre on rigid and deformable surfaces. Journal of Terramechanics 33(5):253-264

Silversides, C. R. & Sundberg, U. 1989. Operational efficiency in forestry. Vol 2. Practice. Kluver Academic Publishers, Dortrecht/Boston/London. 169 p. ISBN 0-7923-0063.

Schmid, I. C. 1995. Interaction of the vehicle and terrain results from 10 years research at IKK. Journal of Terramechanics 32(1):3-27.

Steiner, M. 1979. Analyse, Synthese und Berechnungsmetoden der Triebkraft-Schlupf-Kurve von Luftreifen auf nachgiebigen Boden. M.E.G., Technische Universität München, Lehrstuhl für Landmaschinen. No 33.

Söhne, W. 1969. Agricultural engineering and terramechanics. Journal of terramechanics (4):9-18.

Terrängmaskinen 1981. Del 2. Forskningsstiftelsen Skogsarbeten, Stockholm. 461 p. ISBN 91-7614-012-1

Upadhyaya, S. K. & Wulfsohn, D. 1990. Relationship between tyre deflection characteristics and 2-D tyre contact area. Transaction of the ASAE 33(1):25-30.

Wong, J. Y. 1994. On the role of mean maximum pressure as an indicator of cross-country mobility for tracked vehicles. Journal of Terramechanics 31(3):197-213.

Wong, J. Y. 1995. Application of the computer simulation model NTVPM-86 to the development of a new version of the infantry fighting vehicle Ascod. Journal of Terramechanics 32(1):53-61.

Wulfsohn, D. & Upadhyaya, S. K. 1992a. Determination of dynamic three-dimensional soil-tyre contact profile. Journal of terramechanics 29(4/5):433-464.

Wulfsohn, D. & Upadhyaya, S. K. 1992b. Prediction of traction and soil compaction using three-dimensional soil-tyre contact profile. Journal of terramechanics 29(6):541-564.

Ziani, F. & Biarez (1990). Pressure sinkage relationship for tyres on very loose sand. Journal of Terramechanics 27(3):167-177.

Ziesak, M. & Matthies, D. 2001. Untersuchen zur last- und innendruckabhängigen Aufstandsfläche von Forstspezialreifen. KWF, Forsttechnische Informationen, FTI 9+10/2001:104-110.