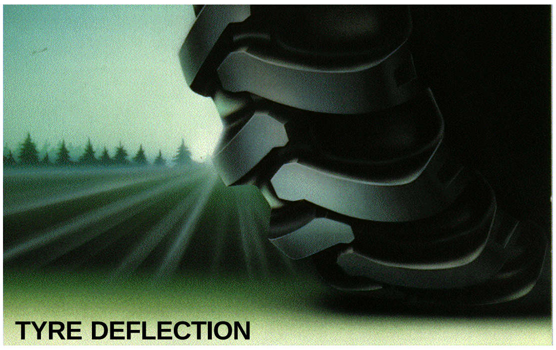
DEVELOPMENT OF A PROTOCOL FOR ECOEFFICIENT WOOD HARVESTING ON SENSITIVE SITES (ECOWOOD)

Quality of Life and Management of Living Resources Contract
No. QLK5-1999-00991
(1999-2002)

PROJECT DELIVERABLE D2 (Work Package No. 1) on

SOIL INTERACTION MODEL

APPENDIX REPORT No 6



MODELLING OF THE WHEEL AND TYRE

2. TYRE STIFFNESS AND DEFLECTION

SURVEY ON TYRE DEFLECTION MODELS FOR STUDYING THE MOBILITY OF FOREST TRACTORS

M. Saarilahti [1)]

[1)]University of Helsinki, Department of Forest Resource Management

May 2002

MODELLING OF THE WHEEL AND SOIL

2. TYRE STIFFNESS AND DEFLECTION

1. INTRODUCTION 5
2. TYRE STIFFNESS 5
3. DEFLECTION MODELS 6
  3.1 Deflection models presented by different authors 6
  3.2 Deflection models developed from Nokia tyre data 6
  3.3 Forestry tractor tyres 6
  3.4 Agriculture tractor tyres 8
  3.5 Other tyres 8
4. OPTIMAL TYRE INFLATION PRESSURE 9
5. INFLUENCE OF TYRE DEFLECTION ON TYRE PERFORMANCE 10
  5.1 Influence of tyre deflection on mobility 10
    5.1.1 Influence of tyre deflection on rolling resistance 11
    5.1.2 Influence of tyre deflection on drawbar pull 12
    5.1.3 Influence of tyre deflection on thrust 12
  5.2 Influence of tyre deflection on rut depth and soil compaction 13
6. CONCLUSIONS 15
  Literature 15

List of Tables

Table 3.1.Linear model coefficients for forestry tractor tyre deflection model.................. 7
Table 3.2. Coefficients for logarithmic agriculture tractor tyres.. 8

List of Figures

Figure 3.1. Constant b_δ as a function of tyre inflation pressure for Nokia forest tractor tyres.. 7
Figure 3.2. Military tyre deflection as a function of tyre load and inflation pressure (Schmid 1995)... 9
Figure 4.1. Optimal tyre inflation pressure as a function of tyre load, application of Eq.(3.5). Average load and inflation pressure for different tyre types marked with rectangles. 10

Symbols

K_t	tyre stiffness, kN/m
K_c	carcass stiffness, kN/m
p_i	inflation pressure, Pa
K_p	inflation pressure depencece modulus, kN/m·Pa
K_p	inflation pressure dependent modulus, kN/m·kPa
b	tyre section width, m
d_{RIM}	rim diameter, m
A	age, a
δ	deflection, m
W	wheel load, kN
K	load factor, $K=1.1$
P	tyre inflation pressure, kPa
b_{RIM}	rim width, m (from tyre catalog)
b	tyre width, m (tyre designation)
d_{RIM}	rim diameter, m (tyre designation)

1. INTRODUCTION

One of the most important tyre properties is the modulus of elasticity, the relation between the applied force and tyre deformation. The elasticity of tyre is expressed using the *spring constant* (C_o). The spring constant depends on the tyre materials, number of layers (*ply*), construction (*cross or belt tyre*), tyre inflation pressure (p_i) and tyre dimensions (d, b)

2. TYRE STIFFNESS

Lines ja Murphy (1991) studied the tyre stiffness and give the general model for tyre stiffness, Eq.(2.1)

$$K_t = K_c + p_i \cdot K_p \tag{2.1}$$

where

K_t is	tyre stiffness, kN/m
K_c	carcass stiffness, kN/m
p_i	inflation pressure, kPa
K_p	inflation pressure dependence modulus, kN/m·Pa

For agriculture tractor tyres the inflation pressure modulus is, Eq(2.2):

$$K_p = 527 \cdot b \cdot d_{RIM} \tag{2.2}$$

where

K_p	inflation pressure dependent modulus, kN/m·kPa
b	tyre section width, m
d_{RIM}	rim diameter, m

For a stationary tyre, a comprehensive model for tyre stiffness modulus, which also takes into account the wear of the tyre, is as follows:

$$K_t = 172 - 69.69 \cdot d_{RIM} + 5.6 \cdot A + 5.27 \cdot b \cdot d_{RIM} \cdot p_i \tag{2.3}$$

where

K_t is	tyre stiffness, kN/m
d_{RIM}	rim diameter, m
A	age, a
b	tyre section width, m
p_i	inflation pressure, Pa

Tyre stiffness decreases as a function of speed. Because of rather low velocities in timber terrain transport the effect of the speed can be neglected.

3. DEFLECTION MODELS

3.1 Deflection models presented by different authors

Wulfsohn et al. (1988) give the following model for an 18.4-38 agricultural tyre

$$\delta = 0.02 + 0.006 \cdot W - 1.35 \cdot W \cdot p_i \cdot 10^{-5} \tag{3.1}$$

3.2 Deflection models developed from Nokia tyre data

The general form of the model for forest tractor tyres is, Eq(3.1).

$$\delta = a_\delta + b_\delta \cdot W \tag{3.1}$$

Nokian renkaat Oy[1] has published graphs on the tyre deflection for some agriculture and forestry tractor tyres. Linear tyre deflection models (Eq. (3.1)) have been developed from this data. Linear models may give for some tyres somewhat too large a deflection under smaller loads, when the tyre carcass stiffness begins to influence.

Coefficients $\mathbf{a}_d$ and $\mathbf{b}_d$ are given in Table 3.1.

For agricultural tractor tyres a logarithmic model fits better, Eq. (3.2)

$$d = 0.121 \cdot \frac{W^{0.476}}{p_i^{0.570}} \tag{3.2}$$

3.3 Forestry tractor tyres

The correlation between the tyre inflation pressure and constant $\mathbf{b}_d$ for 16 ply tyres is presented in Figure 3.1. Constant $\mathbf{a}_d$ is independent on inflation pressure, but may be specific for different tyre construction. Data is not adequate, however, to establish the constant values for different tyres.

The best model developed from the available material is (Eq (3.3)):

$$d = 0.008 + 0.001 \cdot \left(0.365 + \frac{170}{p_i} \right) \cdot W \tag{3.3}$$

where

---

[1] Nokia Tyres Ltd

δ is deflection, m
p_i inflation pressure, kPa
W wheel load, kN

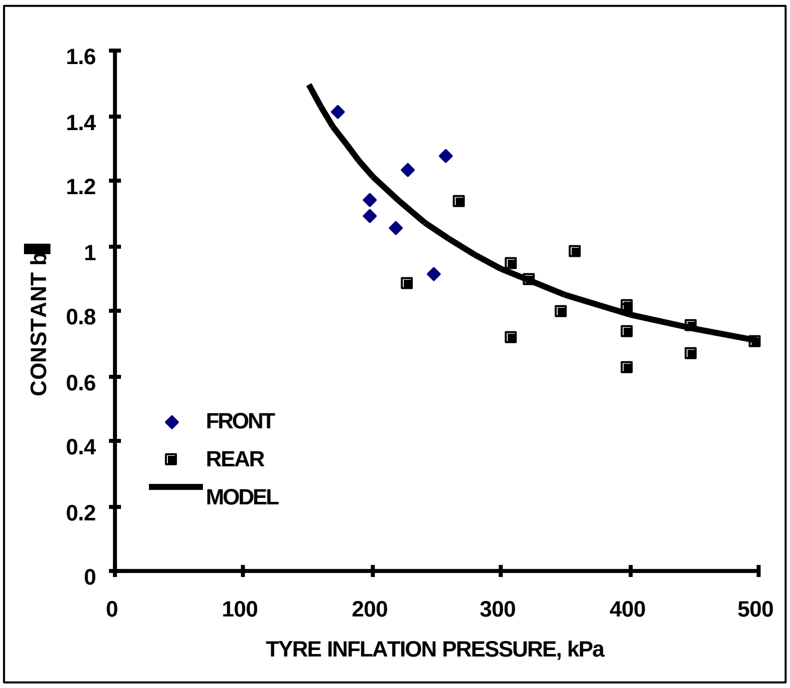


Figure 3.1. Constant b_δ as a function of tyre inflation pressure for Nokia forest tractor tyres.

Table 3.1.Linear model coefficients for forestry tractor tyre deflection model

Designation	Pattern	Ply	$p_{i,}$ kPa	b, m	d, m	h, m	**a**$_d$	**b**$_d$
Front wheels								
23,1-26			200	0.610	1.600	0.470	0.015	1.11
23,1-26			260	0.610	1.600	0.470	0.014	1.29
600/65-34	TRS	14	175	0.592	1.644	0.385	0.004	1.43
600/65-34	TRS	14	**230**	0.592	1.644	0.385	0.002	1.25
700/55-34			200	0.601	1.634	0.385	0.006	1. 16
700/55-34			220	0.601	1.634	0.385	0.008	1. 07
700/55-34			250	0.601	1.634	0.385	0.011	0. 93
Rear wheels								
17,5/25			500	0.420	1.280	0.323	0.006	0.72
17,5/25			450	0.420	1.280	0.323	0.006	0.77
17,5/25			400	0.420	1.280	0.323	0.006	0.82
17,5/25			325	0.420	1.280	0.323	0.005	0.91

600/55-26.5	ELS	16	270	0.611	1.333	0.330	0.005	1.15
600/55-26.5	ELS	16	360	0.611	1.333	0.330	0.004	1.00
600/55-26.5	ELS		350	0.601	1.333	0.330	0.009	0.81
600/55-26.5	ELS		400	0.601	1.333	0.330	0.010	0.75
600/55-26.5	ELS		450	0.601	1.333	0.330	0.010	0.68
700/45-22.5			310	0.700	1.150	0.289	0.003	0.96
700/45-22.5			400	0.700	1.150	0.289	0.003	0.83
700/50-26.5			230	0.700	1.333	0.330	0.007	0.90
700/50-26.5			310	0.700	1.333	0.330	0.009	0.73
700/50-26.5			400	0.700	1.333	0.330	0.008	0.64

3.4 Agriculture tractor tyres

The coefficients for logarithmic agricultural tractor tyre model are given in Table 3.2.

Table 3.2. Coefficients for logarithmic agriculture tractor tyres

Designation	Pattern	Ply	p_{i}, kPa	b, m	d, m	h, m
Front wheels						
Rear wheels	Radial					
13.6R38	TR	8	250	0.338	1.554	0.294
13.6R38	TR	8	200	0.338	1.554	0.294
13.6R38	TR	8	160	0.338	1.554	0.294

3.5 Other tyres

For comparison, the deflection of a military tyre is depicted in Figure 3.1. The corresponding model is:

$$d = 0.01 + (0.0007 + \frac{0.302}{p_i}) \cdot W \tag{3.4}$$

Deflection of a military tyre is nearly twice the deflection of a forest tractor tyre.

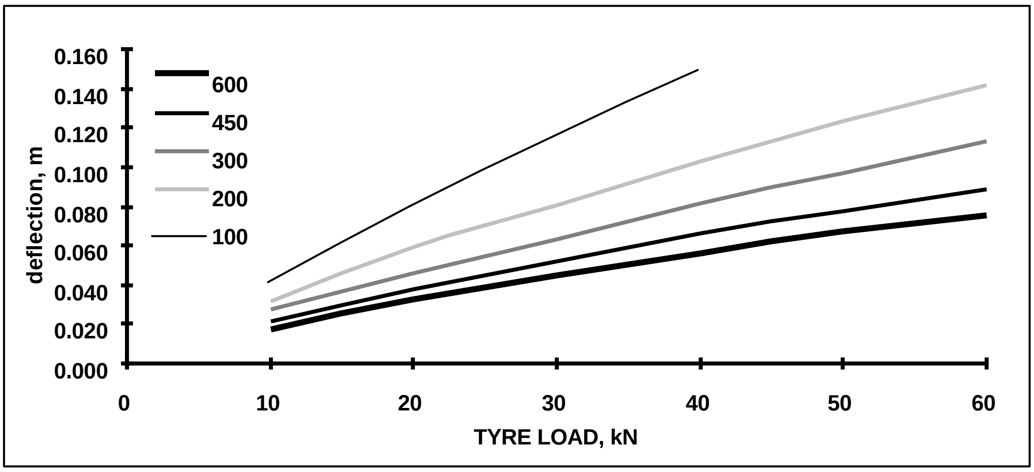


Figure 3.2. Military tyre deflection as a function of tyre load and inflation pressure (Schmid 1995)

4. OPTIMAL TYRE INFLATION PRESSURE

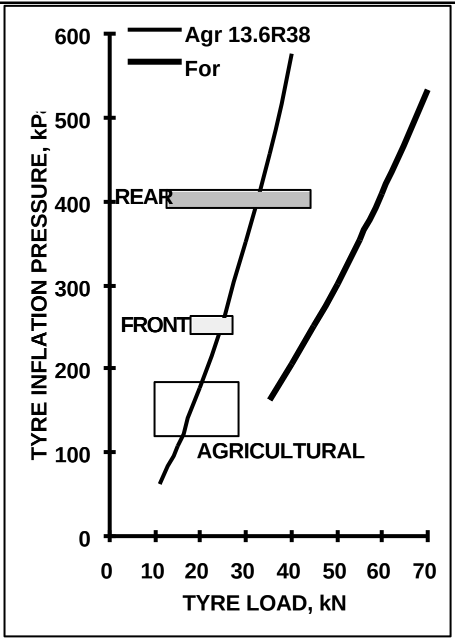


Figure 4.1. Optimal tyre inflation pressure as a function of tyre load, application of Eq.(3.5). Average load and inflation pressure for different tyre types marked with rectangles.

Too high a deflection increases rolling resistance on bearing soils, tyre temperature and the wearing of tyre. Inflation pressure has also a remarkable influence on tyre performance (Lee & Kim 1997). They give a model for optimising the tyre inflation pressure, based on the recommendations of JIS-norms.

$$P = 98.1 \cdot \left[\frac{W}{58 \cdot K \cdot b'^{1.39} \cdot (d_{RIM} + b')} \right]^{1.71}$$

(3.5)

$$b' = \frac{b}{143.3} \cdot \left[180 - SIN^{-1}\left(\frac{b_{RIM}}{b} \right) \cdot \frac{180}{p} \right]$$

(3.6)

where

W	tyre load, kN
K	load factor, K=1.1
P	tyre inflation pressure, kPa
b_{RIM}	rim width, m (from tyre catalog)
b	tyre width, m (tyre designation)
d_{RIM}	rim diameter, m (tyre designation)

In Figure 4.1. the Equation (3.5) is used for studying the optimal inflation pressure for different tyre loads. It is evident, that the optimum tyre inflation pressure is relatively high for larger loads. Current tyre types are not optimal from the environmental point of view because they demand high inflation pressure.

5. INFLUENCE OF TYRE DEFLECTION ON TYRE PERFORMANCE

Because the WES-method is proposed as the main frame of reference of the Project, the tyre performance analyses are mainly based on the WES concept and models. Tyre performance is composed of two aspects: tyre mobility and soil trafficability, where the tyre/soil interface, contact area and contact pressure play the gouverning factor. If the soil bearing capacity is low, high contact pressure breaks the soil causing large soil deformation increasing the rolling resistance and decreasing the thrust.

5.1 Influence of tyre deflection on mobility

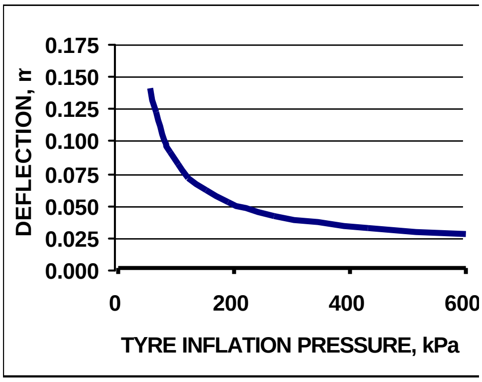


Figure 5.1. Tyre deflection as a function of tyre inflation pressure for the reference tractor

Influence of tyre deflection on mobility is somewhat discussed also in Appendix Report No 3. Influence of tyre deflection on rolling resistance is visualised using different WES models, see Appendix Report No2. The reference wheel is a loaded forwarder wheel, d=1.330, b=0.610 m and W= 40 kN. Soil penetration resistance, CI= 500 kPa, which is close to the mobility limit. On the low bearing soils the influence of deflection is assumed to play rather a remarkable role. The tyre deflection is assumed to vary from 0.01 to 0.14 m, see Figure 5.1. The normally used tyre inflation pressure (in the Finnish conditions) is 420-450 kPa, and the calculated tyre deflection is 0.032 m. From Figure 5.1. it can be seen, that the deflection becomes noticeable larger only, if the tyre inflation pressure is < 100 kPa.

5.1.1 Influence of tyre deflection on rolling resistance

The influence of tyre deflection on rolling resistance on rather a low bearing soil (CI=5000 kPa) is depicted in Figure 5.2. Note, that all the models do not contain deflection as an input variable. There is quite a large difference between the models, but a certain conclusion can be drawn: the soil (500 kPa) begins to break down if the deflection becomes smaller than about 0.04 m because the rolling resistance begins to climb up drastically towards smaller deflections. It is evident, that for sensitive sites the increase of deflection decreases the rolling resistance, thus improving the mobility.

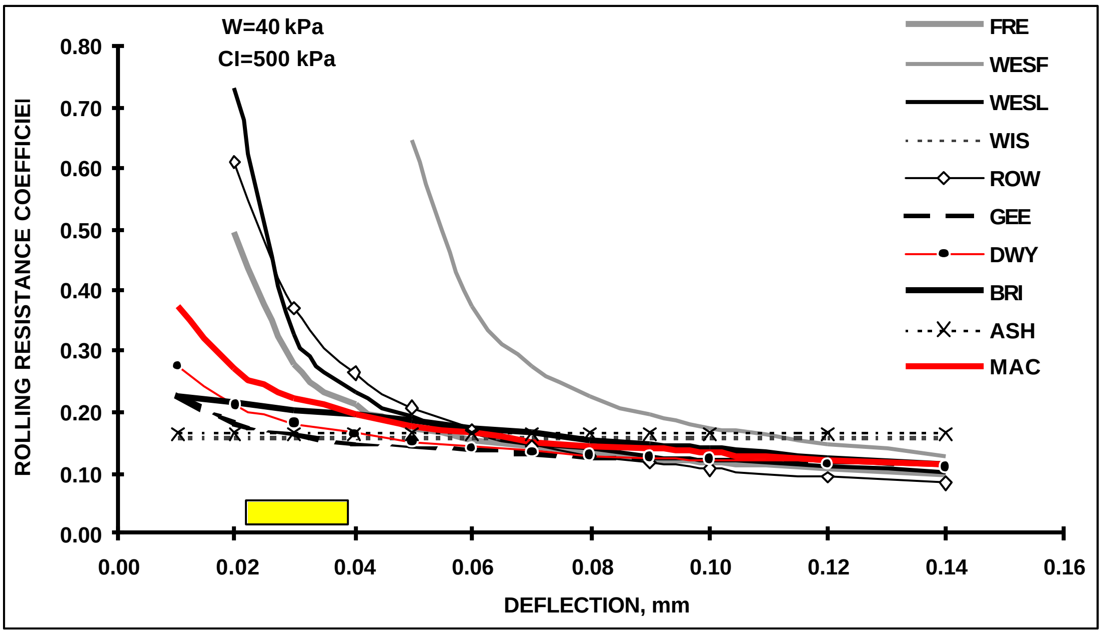


Figure 5.2 Influence of tyre deflection on rolling resistance calculated using different WES models (Models: see Appendix Report 2)

5.1.2 Influence of tyre deflection on drawbar pull

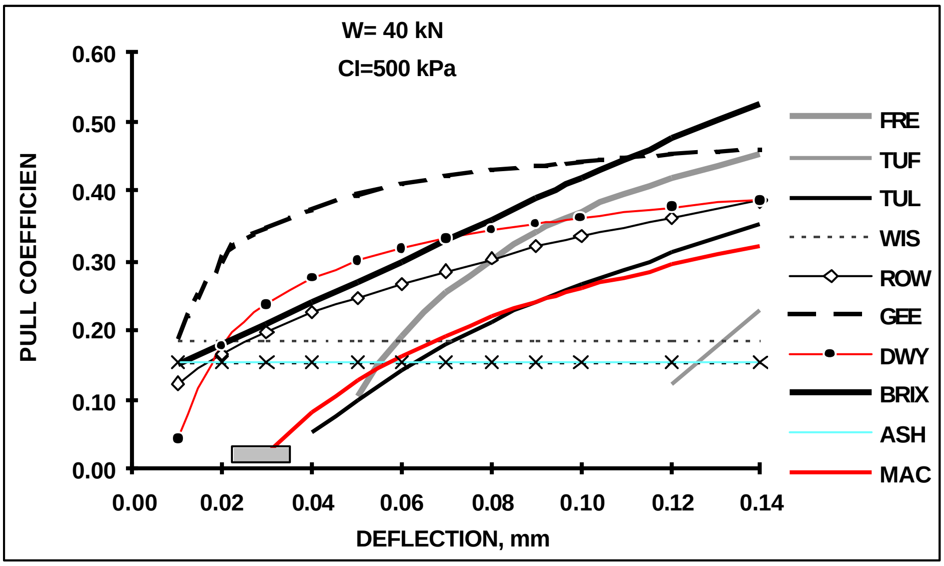
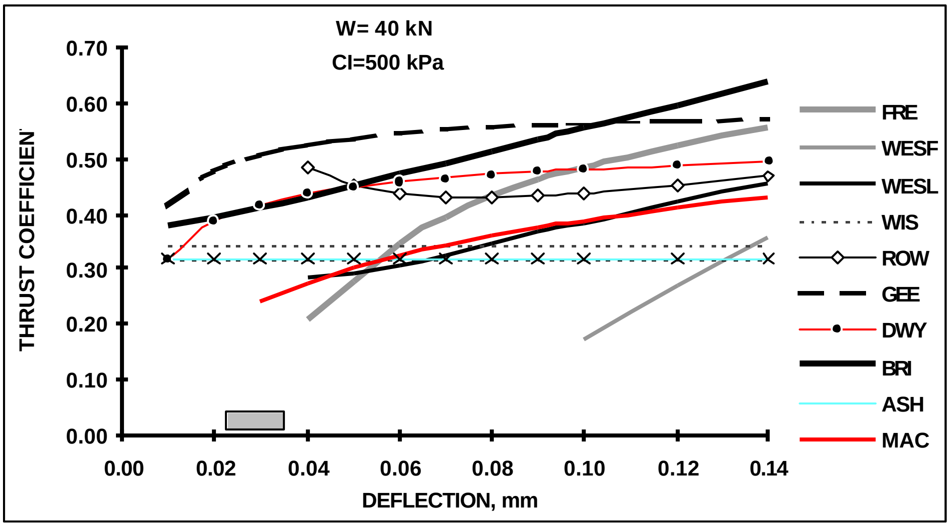


Figure 5.3. Influence of tyre deflection on drawbar pull

Net thrust, drawbar pull is rather a good mobility index, high pull indicating good mobility. In Figure 5.3. the drawbar pull as a function of deflection is depicted. The outcomes of the different models vary considerably, but some models containing the tyre deflection-input seems to give 0 pull near the 0.04 m deflection, but after some models even 0.02 m deflection seems acceptable to develop adequate pull.

5.1.3 Influence of tyre deflection on thrust

As a rule, the increase in tyre deflection increases somewhat the thrust and improves the mobility as seen from the Figure 5.4. The increase in improvement of the thrust is rather linear, due to the assumed increase in length of the contact area.



5.2 Influence of tyre deflection on rut depth and soil compaction

In Finland, tyre inflation pressure in forwarders is high, usually over 400 kPa (Anttila 1999), higher than recommended by the tyre manufacturers, 360…400 kPa. Both the contractor's experience and tyre manufacturers' recommendations (Metsätalousrenkaiden....) suggest high tyre inflation pressure. In the literature, however, low inflation pressure is recommended, specially for low bearing soil conditions. It is therefore important to develop tyre models in order to compare different tyre solutions without costly field test.

A rut depth simulation model based on WES-tyre model, on Maclaurin's (1990) sinkage model and on Anttila's (1998) rut depth model. The model is tested against Löfgren's (1991) field data. Löfgren studied the rut depth using different two forwarders with varying tyre inflation pressures and load sizes.

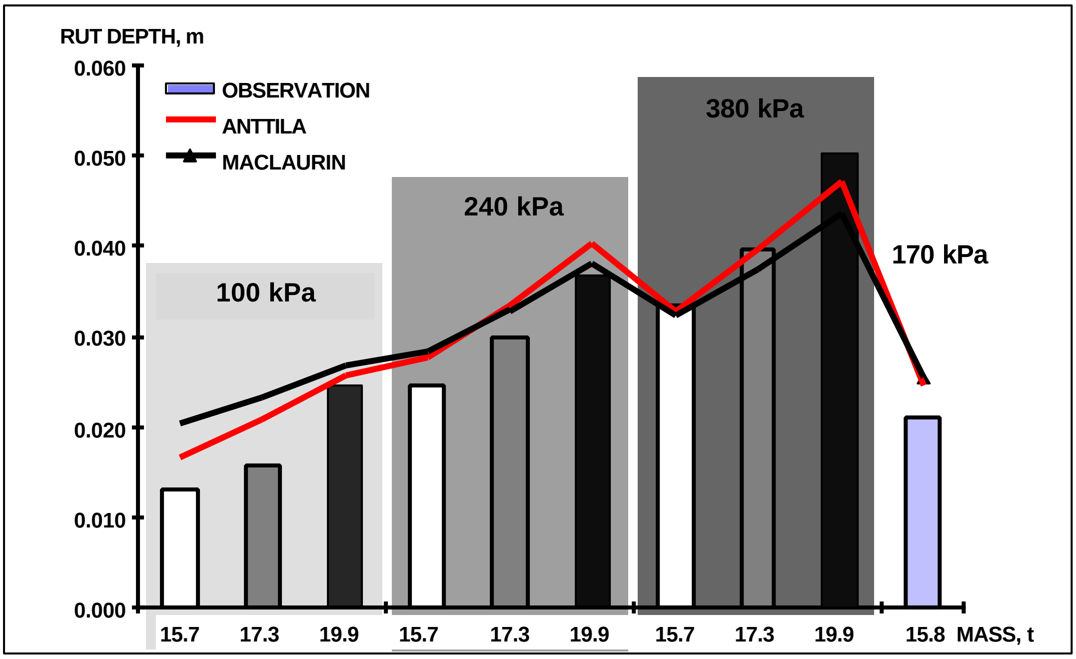


Figure 5.5. Testing of the rut depth models

As expected, the deepest rut comes after the heaviest load and the highest inflation pressure. The influence of the inflation pressure is more significant than the load size, because the smallest load with the highest inflation pressure causes deeper rut than the highest load with lower inflation pressure. The results, both empirical and calculated, lead to the same conclusion. The models are acceptable at least for the simulations, and reliable enough for the information to screen out better and poorer alternatives. More field tests are needed to test how reliable are the results at absolute level.

The rut depth estimates for soil with different bearing capacity (penetration resistance) are simulated using different tyre width, inflation pressure and load size (wheel load). The admissible rut depth, 0.1 m is based on the recommendations of the Finnish Board of Forestry **Tapio**. After the recommendations the logging is classified as "good" if the rut depth of 0.1 m does not exceed 5% of the total length of the total skid trail length and "acceptable", if the percentage is less than 5 -10% of the total length. The simulations are based on a 1020 mm diameter rear wheel of a tandem axle forwarder.

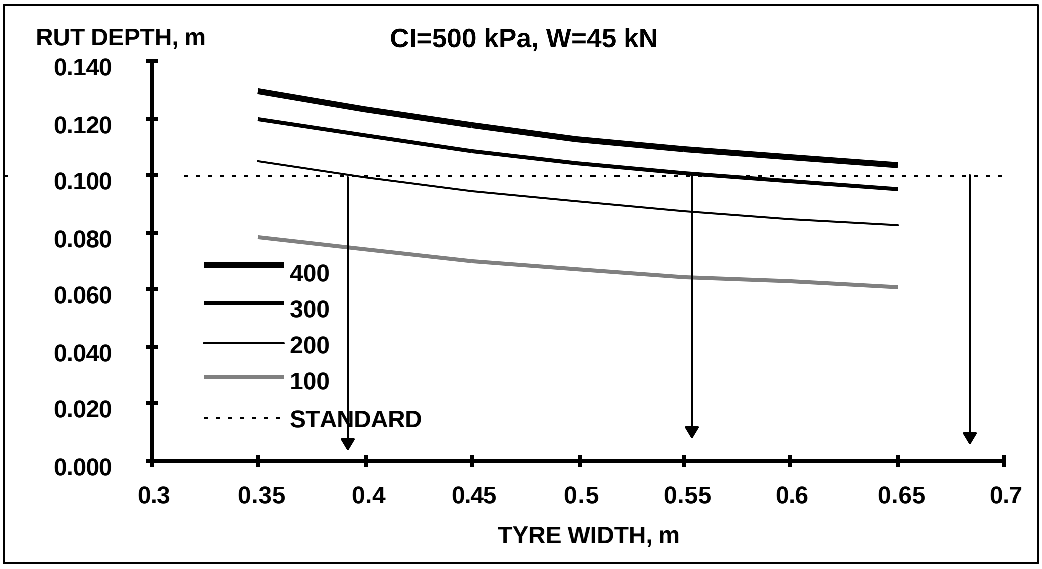


Figure 5.6. Rut depth as a function of tyre width with different tyre inflation pressures

With low tyre inflation pressure (100 kPa) even the narrowest tyre (b=0.30 m) is acceptable, because the rut depth stays under 0.1 m. If the tyre inflation pressure increases up to 200 kPa, then the tyre width should be of 0.400 m. High tyre pressure, 400 kPa demands already nearly 700 mm tyres. Tyre inflation pressure has thus a paramount effect on tractor's environmental properties.

The calculations lead to the conclusion, that it is difficult to give general recommendations concerning the tyre width or inflation pressure, because the rut depth increases rapidly after a certain bearing capacity limit. The problem is accentuated in Finland, where the local variation in bearing capacity is remarkable. On bearing sites the risk of tyre damage is remarkable when using low inflation pressure. On low bearing sites the damage to the environment becomes the problem when using inflated tyres.

6. CONCLUSIONS

If all the other factors are unchanging, the increase in tyre deflection improves the mobility and decrease the soil rutting. This means, that a more flexible tyre is, in theory, better than a stiffer one, when about the same tyre construction is used. The conclusions drawn from WES-model simulation does not permit, however, comparing for example belt or bias tyres, under which the pressure development is different.

Literature

Anttila, T. 1998. Metsämaan raiteistumisen ennustaminen WES-menetelmällä. University of Helsinki, Department of Forest Resource Management. Publications No. 17. 53 p. ISBN 951-45-8025-7

Lee, D. R. & Kim, K. U. 1977. Effect of inflation pressure on tractive performance of bias tires. Journal of Terramechanics. 34(3):187-208.

Lines, J. A. & Murphy, K. 1991. The stiffness of agricultural tractor tyres. Journal of Terramechanics. 28(1):49-63

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

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.

Schmid, I. C. 1995. Interaction of vehicle and terrain results from 10 years research at IKK. Journal of terramechanics 32(1):2-26

Wulfsohn, S.K., Upadhyaya, S. K. & Chancellor, W. J. 1988. Tractive characteristics of radial ply and bias ply tyres in California. Journal of terramechanics 25(2):111-134