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

Quality of Life and Management of Living Resources Contract
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PROJECT DELIVERABLE D2 (Work Package No. 1) on

SOIL INTERACTION MODEL

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EXCECUTIVE SUMMARY

SOIL INTERACTION MODEL

The prerequisite for ecoefficient wood harvesting is an appropriate planning method, which permits the evaluation of the operational and socio-economic costs and outcomes for the planned actions in advance. Operational planning is becoming computerised, which implies that the planning programs and algorithms are reliable enough to lead to acceptable decisions. Too simplistic models and decision-making rules may lead to the selection of incorrect alternatives. Improved models and modelling techniques are needed in order to fit together the scattered knowledge on wheel soil interaction and its consequences to the operations, environment and society.

The report is based on 8 state of the art reports presented in Appendix Reports No. 1 to 8. and supported by three software manuals, where the data have been collected into interactive submodels, Appendix Reports No. 9 –11, see Table 1.

The objectives of the project *"To develop a protocol for ecoefficient wood harvesting on sensitive sites that matches the machines to the site...."* can be achieved when the two elements, machine and site, meet the environmental and economical criteria on three hierarchical levels:

- wheel-soil
- machine-terrain
- transport-environment

In each level the soil and wheel properties are to be known or modelled. In terramechanics, different soil mechanics theories are applied into the modelling of the wheel-soil interface and wheel performance.

> In the **WES-method** the soil penetration resistance is measured using a standard cone penetrometer. This is rather a simple operation, and the analysis of the results is easy.
>
> In the **Bekker-method** the soil constants are calculated from plate sinkage test results. The test arrangements and the analysis of the results are more complicated than in the WES-method.
>
> The **mathematical method,** based on soil strength tests, demands the most resources in measuring the soil parameters, and seems more appropriate for scientific programmes than for field applications.

Soil modelling can be based simply on site identification and classification. The main features of the coarse soil classes are:

- Friction soils: changes in water content have small variation in trafficability. Soil density affects largely on trafficability. Repetitive loading often improves the trafficability.
- Cohesive soils: trafficability is poor in wet conditions, but improves significantly towards drier conditions. Soils often have higher initial strength, and the trafficability worsens as a function of the number of passes, due to deterioration of cohesive bounds.

- Peaty soils, organic soils have as a rule very poor trafficability due to high water content and low dry density.

Soil bearing capacity can be assessed using different testing methods, and the soil parameters are also dependent on the loading conditions. In forestry, the soil bearing capacity is usually considered as the maximum allowable wheel contact pressure. Different soil engineering models allow the evaluation of the soil bearing capacity, and the vane tester and the penetrometer also permit assessment of some soil parameters to be used as soil variables in the modelling of the wheel-soil interaction. Soil bearing capacity, shear strength and penetration resistance are dependent on soil moisture, dry density and particle size distribution, but developing universal models seems difficult, because both frictional and electro-chemical forces are involved in the formation of the soil strength. Another problem arises due to the problems related in assessing the contact pressure of a tractor wheel.

The main problem in the modelling of a pneumatic wheel consists of assessing the contact area, because this depends on the elasticity of the tyre and the soil. An additional problem comes from the fact that, the tyre-soil contact surface is flexible, and the pressure distribution depends on the loading conditions. There are a large number of studies on tyre contact area, but most of them give only a maximum or minimum contact pressure. Nominal Ground Pressure can be considered as a minimum contact pressure attainable in near no-go situations, when soil rutting is already unacceptable for environmental reasons. Different empirical models developed from tests on hard surfaces give the contact pressure in minimal rutting conditions. Different Ground Pressure Indexes can be used in tyre/soil evaluation to screen out the sensitive sites.

Tyre dimension and structure can be considered as constants, but load size and tyre inflation pressure are alterable within a work site. Smaller load and/or lower inflation pressure reduces the contact pressure, and therefore can be considered as a means to minimise the environmental risks. Unfortunately using smaller loads reduces the productivity, and lower inflation pressure shortens the tyre technical life, thus adding to the operational costs.

Rolling resistance, the horizontal force resisting the movement of the wheel, is due to the soil deformation. The larger the rolling resistance, the larger the rutting caused, and hence less acceptable from an environmental point of view. There are several WES-models for evaluating the rolling resistance, and they can be used in assessing the trafficability of the site or mobility of a machine. Another mobility parameter, thrust, is essential for machine-site matching. Semi-empiric WES models can be used in comparing the mobility of different machines under different loading conditions on sensitive sites.

Macro terrain parameters i.e. slope and aspect, and some features of micro terrain parameters such as obstacles, can be assessed directly from available maps. Some additional data on obstacle height and density may be needed and can be obtained from field inventories. There are already good terrain classification schemes to be used for developing operation protocol, but developing more comprehensive surface profiling methods are still needed.

Soil macro and micro terrain parameters are needed for estimating the different resisting forces the machine must overcome when moving on a certain site. The older models took into consideration rolling resistance only, but obstacle and winding resistance models must be added into programming of ecoefficiency of forwarders.

From the environmental point of view the modelling of soil damage, soil compaction and rutting is of primary importance, because the reduction of pore space decreases the root formation, and deep ruts cut the roots of growing trees and serve as water collection drains adding to the erosion risk. The development of wheel, tractor and cycle pass rutting and compaction models is therefore needed to serve in the machine/site selection.

Table 1. List of Appendix Reports

Appendix	File	Name	Content
	Terrain classification		
1	**ECO010.DOC**	**Dynamic terrain classification**	Survey on possibilities to improve the current terrain classification
	Evaluation of the WES-method in assessing the trafficability of terrain and the mobility of forest tractors		
2	**ECO021.DOC**	**1. WES-mobility models**	Literature search on empirical WES-models
3	**ECO022.DOC**	**2. Comparison of the different WES-models**	Different WES-models presented and compared using a reference forwarder wheel
4	**ECO023.DOC**	**3. Interpretation and application of the results**	The use of the mobility and trafficability models in assessing the ecoefficiency of the transport method
	Modelling of the wheel and soil		
5	**ECO031.DOC**	**1. Tyre and soil contact**	Survey on tyre contact area and ground pressure for studying the mobility of forest tractors
6	**ECO032.DOC**	**2. Tyre stiffness and deflection**	Survey on tyre deflection models for studying the mobility of forest tractors
7	**ECO033.DOC**	**3. Tyre/soil models predicting rut formation and soil compaction**	Survey on soil deformation for studying the mobility of forest tractors
8	**ECO034.DOC**	**4. Forest soil properties**	Survey on forest soil properties and soil compaction for studying the mobility of forest tractors
	Software manuals		
9	ECOMODEL.DOC	**Ecomodel**	Visual Basic program for machine site matching
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SOIL INTERACTION MODEL

CONTENT

List of Tables

List of Figures

Symbols

τ	shear strength, kN/m² (kPa)
γ	soil density, kg/m^3
ϕ	soil internal friction, °
δ	tyre deflection, m
γ	soil density, kg/m^3
α	trajectory angle, °
μ_O	obstacle resistance coefficient
μ_P	pull coefficient
μ_T	thrust coefficient
A	tyre footprint area, contact area, m²
a	acceleration, m/s^2
a	soil specific multipass coefficient
A	tyre contact area, m²
a_{max}	limiting vertical acceleration, m/s^2
a_n	multipass coefficient for the nth wheel pass
b	(inflated, unloaded) tyre width, track width, width of loading surface m
C	soil cohesion, kN/m^2 , kPa
C1, C2, C3, C4	constant to be estimated depending upon soil type
CI_{Ltrack}	limiting cone index for tracks
CI_{Lwheel}	limiting cone index for wheels
C_r	Clay ratio, (clay/other components)
d	(inflated, unloaded) tyre diameter, m
d	travel distance, m
e	track link area ratio
E_P	potential energy, J
F_A	air resistance, N
F_D	steering resistance, winding resistance, N
F_O	obstacle resistance, N
F_P	drawbar pull, N
F_R	rolling resistance, N
F_S	slope resistance, N
F_T	total resisting force, kN
g	gravity acceleration, 9.81 m/s²
g	soil dry density, kg/m³
H	v. Post humification class (Used in Nordic countries)
h	obstacle height, m
k	soil deformation modulus
k	specific coefficient depending on tractor’s driveline configuration, energy loss factor
k_{driver}	driver constant
L	load size, m³
m	tractor mass or wheel mass, kg
MC	moisture content, % dry weight
MC	soil moisture content, % (w/w)
n	number of axles, number of road wheels per side
n	number of loadings
n	soil deformation exponent
N_c, N_ϕ, N_γ	soil bearing coefficients (cohesion, friction, and weight)
NGP	nominal ground pressure, kPa
p	load, kPa

P	productivity, m³/s
P	rated engine power, kW
p	track plate length, m
p_c	tyre contact pressure, kPa
p_i	inflation pressure, kPa
P_{NET}	net power on driveline, kW
q	penetration resistance, kPa
Q	wheel torque, Nm
Q_u	soil bearing capacity, ultimate bearing capacity, kPa (kN/m²)
R	decomposition percent, % (Standard of the USSR)
r	wheel radius, m
r_1	radius of the wheel, m
r_2	radius of the obstacle, m
r_l	tyre loaded radius, m
ϕ	soil internal friction
T	thrust, kN
t	cycle time, s
t_f	distant independent times (loading, unloading, personal etc), s
W	wheel load, kN
w	water content of peat, %
v	ground speed, m/s
W	wheel load, kN
v_1	empty velocity, m/s
v_2	loaded velocity, m/s
v_{max}	maximal attainable
W_W	vehicle total weight, kN
W_W	vehicle total weight, kN
v_x	horizontal velocity, x-plane, m/s
v_z	vertical velocity, x-plane, m/s
z	rut depth, sinkage, m
z_1	rut depth after first pass, m
z_2	estimated rut depth after 2nd pass without no prior soil disturbance, m
z_n	rut depth after nth load, m
z_{n-1}	rut depth after n-1th pass, m

1. INTRODUCTION

1.1 Background

The prerequisite for ecoefficient wood harvesting is an appropriate planning method, which permits the evaluation of the hard and soft economy of the planned operations. Hard economy in this context means the planning phases where the machine and other operation cost and productivity figures are worked out. Soft economy in this context means the planning phases where the socio-economic costs and outcomes of the operation are evaluated.

Operational planning and control is becoming computerised. This implies that the planning programs and algorithms are reliable enough to give acceptable outcomes. Too simple decision making rules may lead to the selection of wrong alternatives, especially when comparing new solutions with old ones, if the programs try to extrapolate old experience linearly to new challenges. Therefore, better models and modelling techniques are needed in order to bring together the scattered knowledge on wheel soil interaction and its consequences to the environment and society. This report concentrates mainly on basic modelling of the wheel-soil interaction. Costing and socio-economic modelling is the subject of the other reports.

1.2 Reports

The main report "**Soil interaction model**" is based on 8 state of the art reports presented in Appendix Reports No. 1 to 8. Three software manuals support the report; where the data have been collected into interactive submodels, Appendix Reports No. 9 –11, see Table 1.1.

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1.3 Structure of the modelling

The objectives of the project:

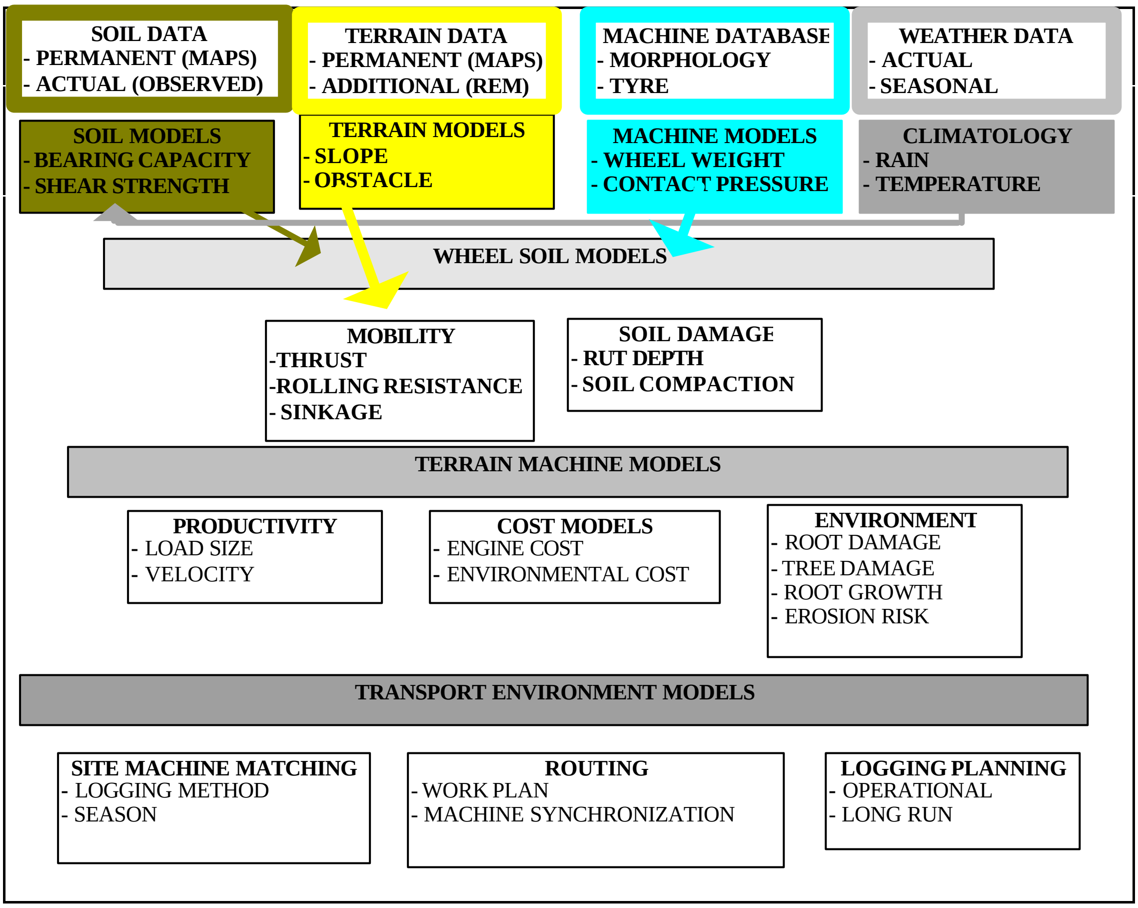
> ***"To develop a protocol for ecoefficient wood harvesting on sensitive sites that matches the machines to the site...."***

serve as a frame of reference to the paper. The matching of the two elements, machine and site, must meet the environmental and economical criteria. The modelling has to include all the three levels of:

- wheel-soil
- machine-terrain
- transport-environment.

This is only possible by developing interactive submodels, each of which can be updated with increasing experience. The main structure is as depicted in Figure 1.1.

Figure 1.1 Data and model structure



The current phase of modelling is based partially on the old terrain classification and partially on the new computer based GIS-technique. Therefore the modelling is adaptable, so that each submodel can be rewritten, when better models are developed.

When developing soil and terrain description and modelling, it should be kept in mind that the trafficability is not the only field of application, but that also the primary data should be useful for other different activities (Löffler 1979) e.g.

- wood production, soil as a growing medium
- the susceptibility to soil compaction and soil movements, (erosion, landslides)
- the workability of the soil, tool-soil system, planting, reforestation
- the engineering properties of a soil, soil-road system

In this report however, the main emphasise is put on the trafficability and the susceptibility to compaction.

1.4 Frame of reference

In the simplest wheel-soil and machine-terrain models only 'black-box' models developed from empirical data have been applied in describing the wheel or tractor performance in given conditions. The models are applicable only to similar tractors and soil conditions, for which data have been collected, and therefore cannot be extrapolated into other type of machines or conditions. Therefore more scientific tools are needed for developing mobility models for sensitive soils.

In terramechanics, different soil mechanics theories are applied into modelling the wheel-soil interface and wheel performance. Three different frames of reference based on soil mechanics can be distinguished (see Figure 1.2).

- **WES-method**, based on semi-empiric modelling of wheel performance and on measuring soil penetration resistance
- **Bekker method**, based on elasticity theory and on plate sinkage tests
- **Mathematical methods**, based on plasticity theory, and on soil mechanical strength parameters

Each of the approaches is based on identification of soil properties. In the simplest models the performance of the machinery is studied on "typical soils". The approach is applicable for large, homogenous sites.

In the **WES-method,** the soil penetration resistance is measured using a standard cone penetrometer. This is rather a simple operation, and the analysis of the results is easy.

In the **Bekker-method,** the soil constants are calculated from plate sinkage test results. The test arrangements and the analysis of the results are more complicated than in the WES-method.

The **mathematical method,** based on soil strength tests, demands the most resources in measuring the soil parameters and seems more appropriate for scientific programmes than for field applications.

The main frame of reference for the wheel-soil modelling is the WES-method due to its simplicity. Naturally, subprograms based on WES-models can be replaced by more scientific calculations, if more relevant soil properties and interaction models are available.

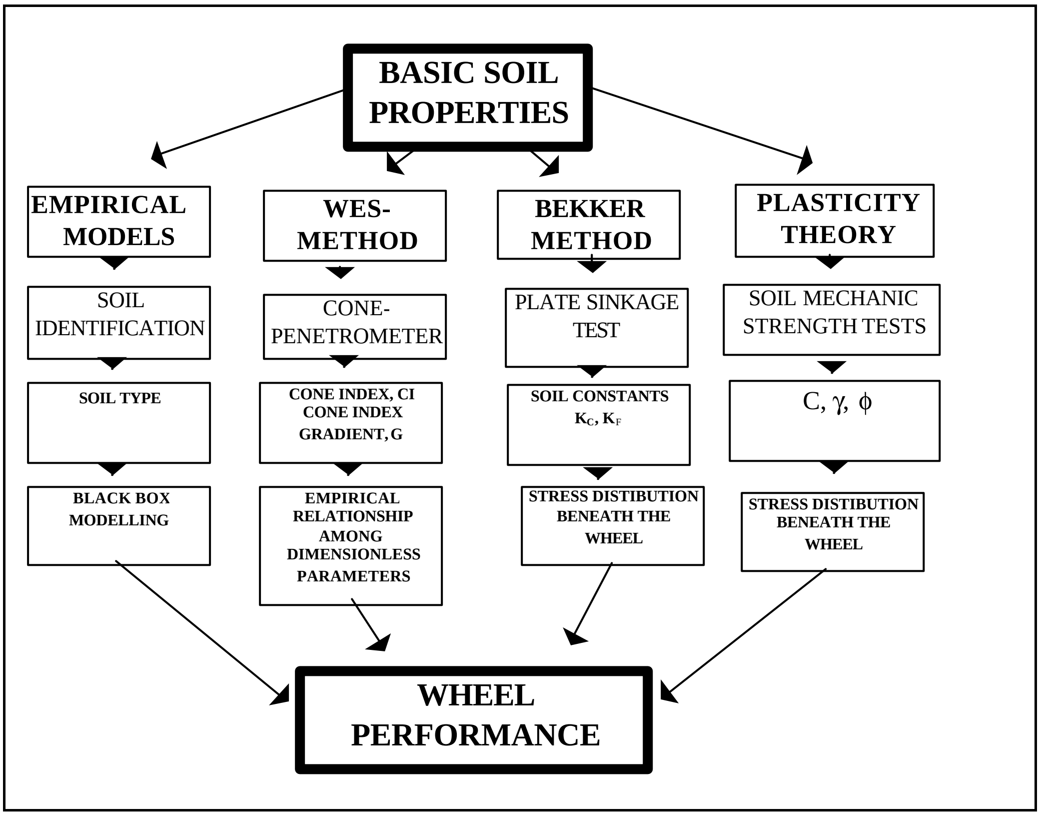


Figure 1.2 Schemes of various approaches to the problem of wheel performance (Adopted from Karafiath, 1971)

2. WHEEL-SOIL MODELLING

2.1 *Trafficability of soil, and mobility of the wheel*

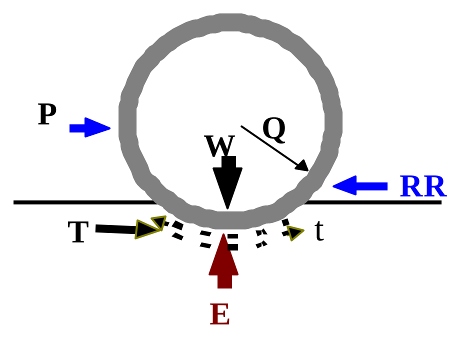


Figure 2.1. Forces in the wheel-soil interface

The trafficability of the soil depends on its capacity to resist the forces put on it by a rolling wheel or a moving track. In Figure 2.1. a simple wheel-soil model is visualised. The wheel weight (W) loads the soil and mobilises the soil bearing (E) forces. The wheel sinks to a certain depth, where the wheel load and soil bearing capacity are in balance.

The wheel sinkage causes rolling resistance (RR), a force resisting the forward movement of the wheel.

The wheel torque (Q) generates a turning momentum along the tyre perimeter, and develops strain into the soil. The horizontal forward force, thrust (T), can be used to overcome the resisting force of rolling resistance, and to generate a pull (P). The maximum thrust, some kind of surface friction force, depends on the shear strength (τ) of the soil.

In the simplest models, two types of forces, vertical load/bearing capacity and horizontal thrust/resistance to movement are to be evaluated for assessing the trafficability of the soil and the mobility of the machine.

2.2 SOIL MODELLING

2.2.1 Soil identification

Soil data can be collected from geological maps, if available. Currently, adequately detailed soil maps are seldom available, and therefore a more general soil classification must be used.

The basic criterion in soil classification schemes is soil particle distribution. There are different soil classification schemes, both international and national. Also, there exist different special classifications for different engineering, military or agricultural ventures. In most cases some kind of conversion between soil classifications can be made, and therefore most of the information available from existing maps or databases can be exploited.

For the purpose of the study the main classification from the geological point of view is the origin and the structure of the soils. Generally three types can be distinguished:

- **alluvial soils**, which are often deep deposits of rather homogenous soil particles
    - fine grained soils, clay soils, cohesive soils
    - coarse grained soils, sandy soils, friction soils
- **moraine soils**, which are mixtures of particles of different size. Moraine soils are often shallow because the rock bottom is near the surface
- **organic soils**

Different soil classification schemes are presented, and the following existing classifications are of practical use for the purposes of the study:

- NSR classification (Eriksson *et al* 1978), which is convenient for Nordic soils. USCS (Unified Soil Classification System), which has been adopted by the U.S. Army Corps of Engineering and is widely used and universally applicable. Also, ASAE has adopted this classification.

In terramechanics, the main distinction is made between friction and cohesive soils, because the typical behaviour under the wheel load differs. The main features of cohesive and friction soils are as given in Table 2.1.

Table 2.1 Main trafficability features of friction and cohesion soils

Friction soil	**Cohesion soil**
Changes in water content have small variation in trafficability	When wet very poor trafficability, but increases rapidly toward drier conditions
Soil density plays a remarkable role in trafficability	Soil moisture plays a remarkable role in trafficability
Trafficability increases under repetitive loading up to a certain strength	Trafficability worsens after soil disturbance, and the soils have only residual strength

2.2.2 Soil bearing capacity

2.2.2.1 Assessing the soil bearing capacity

There are different definitions for soil bearing capacity depending on the soil testing and modelling method. The proposal for IUFRO terrain classification standards (von Segebaden et al (1967)) concludes “the *bearing capacity of the ground in the unfrozen condition is recorded in kilopounds per sq. centimetre as determined by a method. There are no generally accepted methods at present*”. No standard method has been adopted ever since.

In forestry, soil-bearing capacity is usually considered as the maximal allowable wheel contact pressure. The actual wheel contact pressure however, is difficult to assess, because the true contact area depends on tyre and soil properties. In most cases the soil bearing capacity must be taken as some kind of guideline only.

In the WES-method, the soil bearing capacity is linked directly to the soil penetration resistance, and Cone Index can be considered as an indicator of bearing capacity.

In soil engineering the ***sinkage*** of the footing i.e. the wheel or track, is used as an output variable, and different soil bearing models are developed using different soil parameters as input variables.

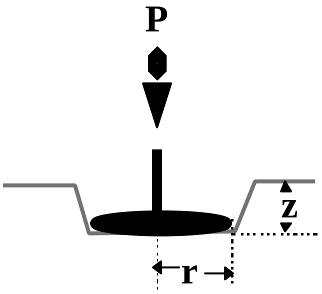


Figure 2.2 Measuring of the E-modulus

In elasticity theory the soil bearing capacity is measured using the circular plate-loading test (see Figure 2.2). In road construction, where the material properties are well defined and the layer structure known, the modulus of Elasticity (E-modulus) is used as the soil-bearing variable.

$$E = \frac{1.5 \cdot P \cdot r}{z} \qquad (2.1)$$

There are different standard methods for measuring the E-modulus, but they are difficult to apply in field tests in forestry, mainly due to the large counterweight needed to load the plate. As the plasticity theory only applies fully to homogeneous soils, where the pressure bulb is spherical, in practice the E-modulus depends also on the diameter of the plate.

The Bekker-method (Bekker, 1969) uses the concept of flotation as a description of soil bearing capacity. The Bekker method is based on elasticity theory, in which the load-sinkage relation is measured using round plates with different diameters. The soil constants are determined from the load/sinkage curve. The simple model for flotation is based on measuring the soil deformation modulus and soil deformation exponent.

$$z = k \cdot p^{\frac{1}{n}} \qquad (2.2)$$

where

z is	sinkage, m
k	soil deformation modulus
p	load, kPa
n	soil deformation exponent

Because the diameter of the plate influences the load/sinkage relation, Bekker introduced the cohesion and friction components into the basic sinkage model:

$$k = \frac{k_C}{b} + k_f \qquad (2.3)$$

and the sinkage model, “flotation” becomes:

$$z = \sqrt[n]{\frac{p}{\frac{k_C}{b} + k_\phi}} \qquad (2.4)$$

The cohesion component is mainly dependent on the soil cohesion, which is affected by the soil clay content and moisture. The friction component, related to friction angle of the soil (ϕ), depends on the compaction degree (bulk density), particle diameter distribution and form, and also somewhat on moisture, and can be modelled based on soil parameters. Modelling of the cohesion and friction component is difficult, and demands large numbers of plate tests in different soil and moisture conditions. Because the k_C and k_ϕ are related to soil cohesion (C), and internal friction angle (ϕ), some general modelling is possible.

In plasticity theory the ultimate bearing capacity is calculated using three different soil constants, which depends on soil internal friction, Figure 2.3.

$$Q_t = C \cdot N_c + g \cdot z_0 \cdot N_f + \frac{b}{2} \cdot g \cdot N_g \qquad (2.5)$$

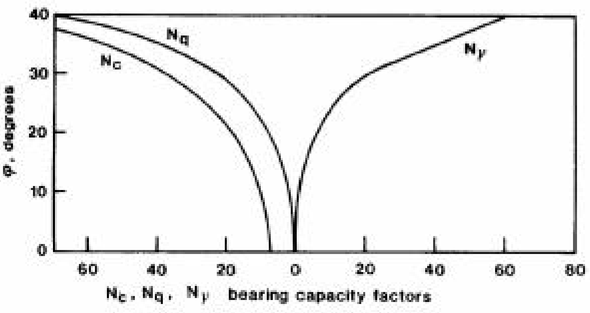


Figure 2.3 Dependence of soil bearing capacity factors on soil friction angle

where

Q_u	ultimate bearing capacity, kN/m³
C	soil cohesion, kN/m³
N_c, N_ϕ, N_γ	soil bearing coefficients, (cohesion, friction, and weight),
z_0	sinkage, m
γ	soil weight, kN/m³
b	width of loading surface, m

Karafiath and Nowatzky (1978) have developed the terramechanical applications of the plasticity theory, and they are widely used in FEM- simulation.

2.2.2.2 Soil bearing capacity modelling

Because the soil bearing capacity is largely dependent on soil cohesion and soil internal friction, some modelling of soil bearing capacity can be based on soil cohesion and friction models.

For friction soils the bearing capacity as such is not the limiting factor, but the shear strength. The wheel must develop enough friction between the tyre and soil in order to overcome the rolling resistance and other resistance forces, which grow high under deeper sinkage in loose soils.

For cohesion soils the bearing capacity is (Saarilahti, 1978)

$$Q_u = 2 \cdot C \tag{2.6}$$

where

Q_u is soil bearing capacity, kPa (kN/m²)
C soil cohesion, kPa

which means that the contact pressure can be twice the soil cohesion, e.g. for example soil shear strength measured by vane tester.

2.2.2.3 Empirical values for estimating the soil bearing capacity

In the Table 2.3 (next page) the bearing capacity values of different soils have been collected from different authors. For comparison, the following Ground pressure index values (see Appendix Report No. 1) are given for a 12 t forwarder with a 10 t full load. A tyre inflation pressure of 400 kPa is used in the modelling (Table 2.2).

Table 2.2 Tyre ground pressure index for the reference forwarder

Tyre	Load size			
Width	1	¾	1/2	¼
M	Ground pressure index, kPa			
0.600	192	172	154	133
0.700	167	157	136	117

Based on the apparent ground pressure under the wheel and the bearing capacity of the different soil types, the following rough sensitivity classification can be made (see Table 2.3).

For the Finnish peatlands, see the literature survey on site bearing capacity in Appendix 1. As a rule most of the undrained Finnish peatlands belong to the restricted class, being unsuitable for wheeled forwarder traffic.

Table 2.3 Soil bearing capacity after different authors and the corresponding soil sensitivity estimate for forwarder traffic

Soil description	Bearing capacity, kPa		Rough sensitivity Class
	Source 1)	Source 2)	
Moraine, dry	400 – 800		No
Moraine, moist, fine	200 – 500		Slightly
Moraine, moist, granular	300 – 600		No
Gravel, fine		500	No
Gravel, dry	300 – 700	200 - 600	No
Gravel, moist	400 – 800		No
Sand, dry	150 – 250	200	Very
Sand, moist	300 – 500	400	No
Clay, dry	400 – 1200	400	No
Clay, moist	200 – 300	200	Rather
Clay, wet	50 – 150	100	Restricted
Alluvial soils		50	Restricted
Peatland, wooded	40 – 70		Restricted
Peatland, open	10 – 40	20	Restricted
Snow, virgin	10 - 30		Depends on thickness
Snow, old, -10 C	50 – 100		Depends on thickness
Snow, compressed, -10 C	200 – 500		No
Snow, hard packed, -10 C	400 – 800	900	No
Ice	1000 – 2000		Depends on the ice thickness

1) Hyvärinen & Ahokas (1975) 2) Ragot (1976)

2.2.3 Soil shear strength and deformation modulus

Soil shear strength is of prime importance when developing thrust models for estimating the mobility. Soil deformation modulus in connection with shear strength permits the development of slip models for tyre-soil interaction.

The shear strength of the soil follows Coulomb's classical formula:

$$\tau = C + p \cdot \tan\phi \tag{2.7}$$

where:

τ is	shear strength, kPa
C	soil cohesion, kPa
p	load, kPa
ϕ	soil internal friction, °

It can be seen that in pure cohesion soils ($\phi=0$), the shear strength consists of cohesion; and in pure friction soils (C=0), the soil strength depends on soil internal friction angle (ϕ), and the load. The thrust coefficient can be estimated based on internal friction angle, because it is close to the tan(ϕ).

2.2.3.1 Shear strength of friction soils

Soil internal friction angle can be estimated based on soil compaction degree, granulometry and particle forms.

Table 2.4 Soil internal friction angle for friction soils (Helenelund 1974)

A. Influence of the soil type

Soil	Friction angle °	Tan(ϕ)
Gravel	34	0.67
Sand	32	0.62
Fine sand	30	0.58

B. Influence of other factors

Compaction		Particle form		Granulometry	
LOOSE	-1°...-6°	ROUNDED	-1...-5°	POORLY GRADED	-1...-3°
AVERAGE	0	NORMAL	0	NORMAL	0
DENSE	+1°...+6°	SHARP	+1...+2°	WELL GRADED	+1....+3°

As a conclusion it can be said that the **thrust coefficient** is as follows:
- dense, well-graded, sharp granule gravel soil 0.82
- average sandy soils 0.62
- loose, rounded poorly graded fine sand 0.42

The internal friction angle and thrust coefficient are somewhat dependent on soil moisture, but the main factors are the soil particle size, form and the compaction degree and soil density.

2.2.3.2 Shear strength of cohesion soils

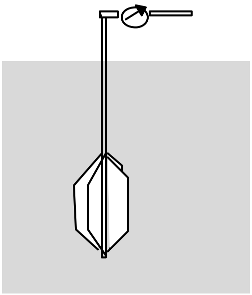


Figure 2.4 Vane tester

For trafficability applications, the shear strength, and soil cohesion of cohesive soils can be measured using a vane tester. It is a simple device containing a certain measuring head with wings and a torque meter. In more comprehensive devices, the turning angle is also recorded, permitting the estimation of the soil deformation modulus.

The soil shear strength generally has a maximum value before the soil collapses; and after remoulding, the soil has lower residual strength. For the first pass, the maximum shear strength can be used, but for multipass evaluation, the use of residual strength is more appropriate, especially for clay soils.

2.2.3.3 Shear strength of peat

Amarjan (1972) gives the following model for estimating the peat shear strength as a function of moisture content and peat decomposition percentage when using a vane tester, Eq.(2.8)

$$\tau = \frac{140}{\mathrm{MC}} \cdot \left(100 - 1.1 \cdot \mathrm{R}\right) \qquad (2.8)$$

of which the following model, Eq(2.9) can be developed for v. Post’s peat humification classes

$$t = \frac{140}{MC} \cdot \left(100 - 2.83 \cdot H^{1.414}\right) \qquad (2.9)$$

where

τ is	shear strength, kN/m² (kPa)
w	water content of peat, %
R	decomposition percent, % (Standard of the USSR)
H	v. Post humification class (Used in Nordic countries)

2.2.4 Soil penetration resistance

2.2.4.1 Soil penetration resistance and Cone Index

Soil penetration resistance depends largely on cone area and angle and somewhat on penetration velocity. There are some studies on theoretical modelling of cone resistance and also empirical studies where different cones are compared. In this report only the penetration resistance (q) measured using the ASAE standard penetrometer protocol and device is considered. In practice, it is equivalent to the old concept of CI (Cone Index), which is expressed in Imperial Units (lb/sq.in). The penetrometer is widely used in terrain evaluation, and the literature references are abundant. As the penetration resistance in most soils is dependent on the penetration depth; penetration resistance curves contain detailed data on variation in soil penetration depth as a function of depth. For practical applications often the ***penetration depth at critical depth*** is used as the sole soil penetration resistance value. The recommended values for determining the critical depth are given in Table 2.5.

Table 2.5. Critical depth for different soil/vehicle combinations (after Farnell penetrometer)

Vehicle mass, kg	Loose dry sand	Reading decrease in depth (abnormal profile)	Reading increase or remain constant in depth	Peat, Muskeg
Wheeled vehicles				
Up to 22 500 kg	**0 ... 0.150**	**0.150 ... 0.450**	**0.150 ... 0.300**	*
Over 22 500 kg	0 ... 0.150	0.225 ... 0.525	0.225 ... 0.380	
Tracked vehicles				
Up to 1 500 kg		*		0 ... 0.150
1 500 to 4 000	0 ... 0.150	0.075 ... 0.380	0.075 ... 0.225	0.075 ... 0.225
4 000 to 7 000	0 ... 0.150	0.150 ... 0.450	0.150 ... 0.300	0.150 ... 0.300
7 000 to 11 000	0 ... 0.150	0.150 ... 0.450	0.150 ... 0.300	0.225 ... 0.380
11 000 to 45 000	**0 ... 0.150**	**0.150 ... 0.450**	**0.150 ... 0.300**	**0.380 ... 0.450**
Over 45 000	0 ... 0.150	0.225 ... 0.525	0.225 ... 0.380	*

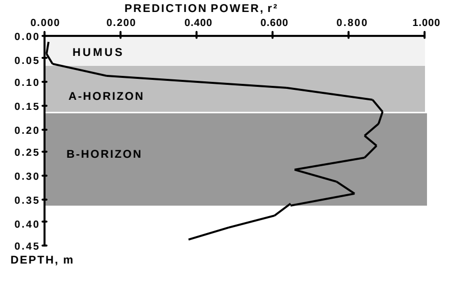


Figure 2.5 Correlation coefficient squared as a function of sample depth. Average soil horizons after Westman (1990).

Anttila (1998) found that, the penetration resistance measured at 0.150 mm depth had the highest predictive power when developing rut depth modelling (see Figure 2.5). It coincides with the transition from A to B horizons in average Finnish moraine soils (Westman, 1990). Therefore, in Finland, the average penetration depth at 0.125 to 0.175 m depth is used as a critical depth.

2.2.4.2 Studies on penetration resistance

There are several studies on soil penetration resistance, most of them having only water content as an input variable, see Appendix Report No. 6. There are several one entry models for different soils using soil moisture as the independent variable. Also, there are some two entry models using soil density or clay content, and moisture content as input variables. Their field of application is already larger. Three entry models using soil moisture, density and clay content or depth are rare.

2.2.4.3 Penetration resistance of cohesion soils

Ayers & Perumpral (1982) developed a universal two entry model for soil penetration resistance, Eq(2.10). The constant C1-C4 for different soils can be developed from field data using the best fitting technique.

$$\mathrm{q} = \frac{\mathrm{C1} \cdot g^{\mathrm{C4}}}{\mathrm{C2} + (\mathrm{MC} - \mathrm{C3})^2} \qquad (2.10)$$

where

q is	penetration resistance, kPa
g	soil dry density, kg/m³
MC	moisture content, % dry weight
C1, C2, C3, C4	constant to be estimated depending upon soil type

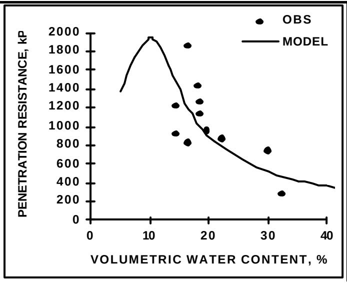


Figure 2.6 Penetration resistance as a function of moisture content in Anttila's data.

Fitting Ayers & Perumpral's (1982) general equation, Eq(2.10) into Anttila's (1998) data, showed that bulk density did not enter into the model; moisture being the only statistically significant variable. The model using volumetric moisture is Eq(2.11)

$$q = \frac{7137}{\left(20 + (MC - 10)^2\right)^{0.431}} \qquad (2.11)$$

The Witney *et al* (1984) three entry model, Eq(2.12) seemed to match the field observations to a certain degree (see Figure 2.7).

$$q = 1000 \cdot \left(15.92 \cdot C_r \cdot \exp^{-0.08 \cdot MC} + 0.0000258 \cdot \gamma \cdot \exp^{\frac{\pi}{1+C_r}} \right) \tag{2.12}$$

where:

q	penetration resistance, kPa
C_r	Clay ratio, (clay/other components)
MC	soil moisture content, % (w/w)
γ	soil density, kg/m^3

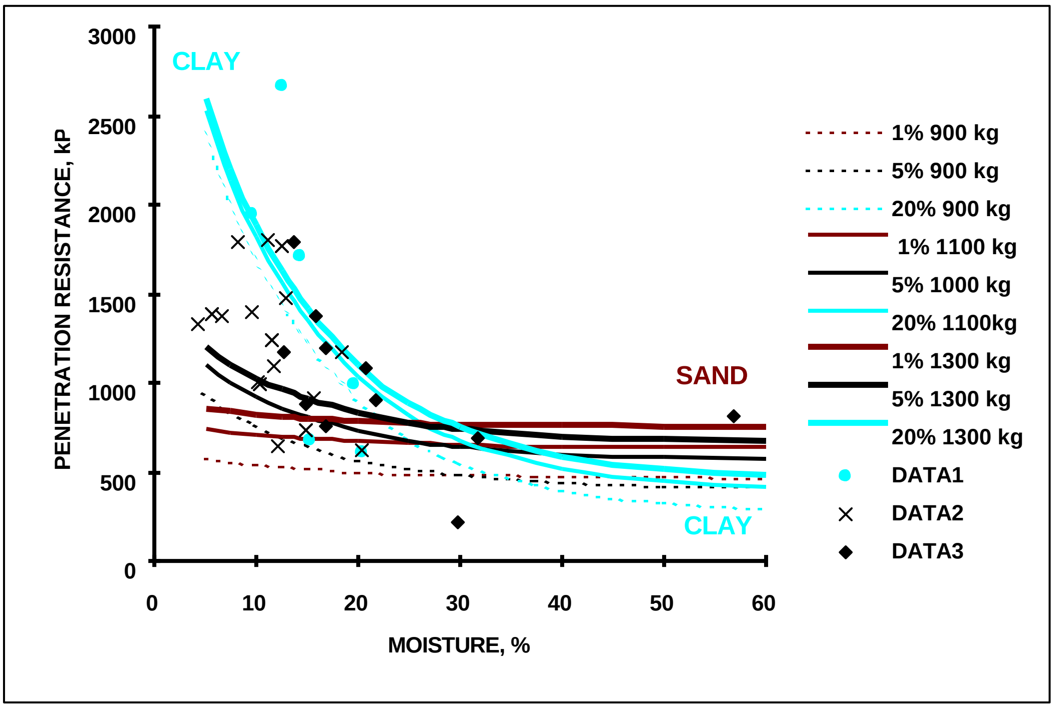


Figure 2.7 Data1 (Rantala 2001, clay), Data2 (Rantala 2001, granular soils) and Data3 (Anttila 1998, silty soils) compared to Witney *et al* model, Eq(2.12).

In conclusion, it can be said that, the estimation of possible sensitive sites can be improved if some data on soil properties, such as fine fraction content or soil bulk density and on soil moisture are available. It allows somewhat more reliable estimates for soil penetration resistance, which, in turn, can be used in mobility models, Figure 2.7. The possible presence of fine fractions in glacial moraines depends also on soil formation processes, and therefore the use of data on local geology may improve the prediction.

2.2.4.4 Penetration resistance of peaty soil

The penetration resistance of peat depends on its decay degree and water content as seen from Amarjan's (1972) model, Eq. (2.13)

The shear strength of the raw peat is high due to the high tensile strength of the fibres, but the penetration resistance and the bearing capacity are low, because of the low bulk density of raw peat. The penetration resistance increases as a function of degree of humification, because as a rule the bulk density is directly correlated with the humification degree; but is inversely correlated with moisture content. The penetration resistance of peat can be estimated using Amarjan's (1972) model, Eq. (2.13 and 2.14).

$$q = \frac{2500}{w} \cdot (100 - 1.4 \cdot R) \qquad (2.13)$$

$$q = \frac{2500}{w} \cdot \left(100 - 3.60 \cdot H^{1.414}\right) \qquad (2.14)$$

where

q on	penetration resistance, kPa
w	water content of peat, %
R	decomposition percent, % (Standard of the USSR)
H	v. Post humification class (Used in Nordic countries)

The following penetration resistance models, Eq(2.15), as a function of peat moisture were developed from the data collected during the field tests; see Figure 2.8.

Gravimetric moisture	Volumetric moisture	
$q = 10504 \cdot \mathrm{MC}_{\mathrm{w/w}}^{-0.561}$	$q = 23062 \cdot \mathrm{MC}_{\mathrm{v/v}}^{-1.287}$	(2.15)

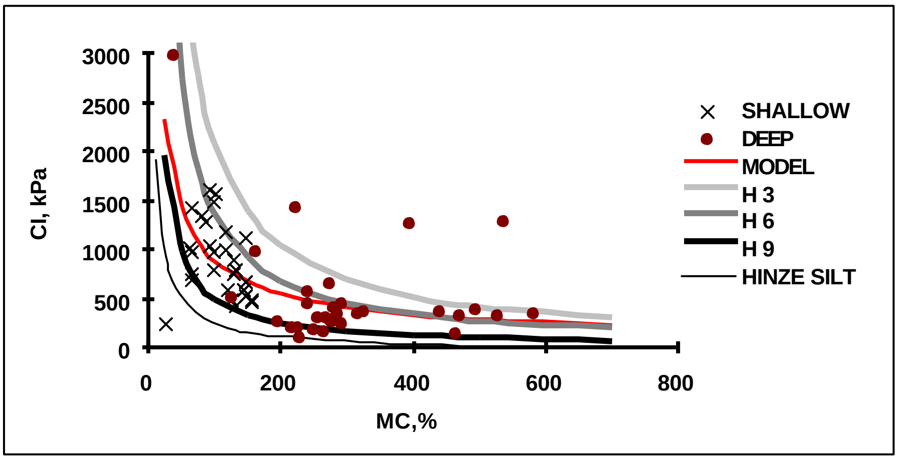


Figure 2.8 The observed penetration resistance as a function of the gravimetric moisture content compared to Amarjan's (1972) penetration resistance model and Hinze's (1990) silt model.

2.3 Wheel modelling

2.3.1 Basic wheel models

A larger literature survey on wheel/soil modelling is presented in Appendix Reports No. 5 and 6. The simplest wheel-soil interaction model uses rigid wheel geometry, while the most comprehensive pneumatic tyre models use different types of spring or rheological models.

Simple models may be reliable in analysing a certain problem in the wheel-soil interaction, such as comparing rather similar tyres in rather similar conditions, but cannot be considered suitable for general modelling, for example comparing new technology tyres in extreme conditions. Being simple and easy to adopt they are used in different submodels.

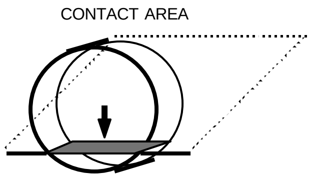


Figure 2.9 Simplified concept of tyre contact area

One of the main criteria in machine site matching is the wheel/soil contact pressure (ground pressure). It is a simplification of the vertical stress the loaded pneumatic tyre (or rigid track) causes on the soil, it can be considered an average contact pressure (Eq 2.16):

$$p = \frac{W}{A} \qquad (2.16)$$

where:

p	tyre contact pressure, ground pressure, kPa
W	wheel load, kN
A	tyre footprint area, contact area, m^2

2.3.2 Tyre footprint area

Tyre footprint area (contact area) is difficult to determine exactly, because it depends upon tyre and soil deformation characteristics. For a pneumatic tyre the footprint area depends on tyre deflection, influenced by tyre inflation pressure and wheel load; but it also depends on the elasticity of the soil. There is a certain critical inflation pressure, above which the tyre behaves like a rigid wheel, but at low pressures the deflection governs the footprint area formation. Under constant inflation pressure the footprint area depends on soil bearing capacity, see Figure 2.10. There are different methods to measure the footprint area, which give somewhat different results. Therefore, tyre footprint area, as well as contact area must be considered as of guideline value only.

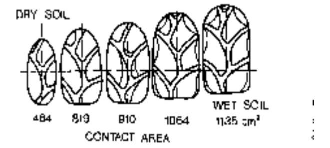


Figure 2.10 Tyre footprint on different soil moisture regimes (Hallonborg 1996)

There are a great number of empirical studies on tyre contact area, as well as numerous models for estimating tyre contact area, of which some are presented in Appendix Report No. 5. Most of the studies are based on agriculture tractors or military vehicles using more flexible tyres than 14-16 ply rating forwarder tyres. The deviation between different studies is large (see Figure 2.11). The models used are given in Table 2.6.

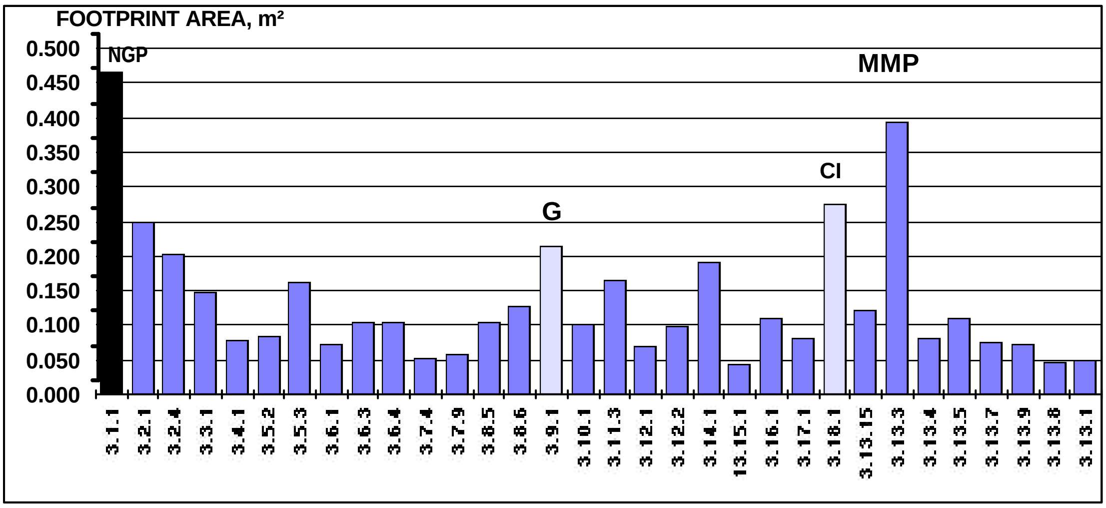


Figure 2.11 Footprint area calculated using different tyre models

Table 2.6. Models used in Figure 2.11

No	Equation	Reference	No	Equation	Reference
Contact pressure and area models					
1	3.1.1	NGP	14	3.8.6	Godbole & al (1993)
2	3.2.1	Schwanghart (1990)	15	3.9.1	Dwyer (1984)
3	3.2.4	-"-	16	3.10.1	Ziani & Biarez (1990)
4	3.3.1	Komandi (1990)	17	3.11.3	Febo & Pessina (1987)
5	3.4.1	Silversides & (1989)	18	3.12.2	Steiner (1979), Radial
6	3.5.2	Grecenko (1995)	19	3.12.2	Steiner (1979), Cross ply
7	3.5.3	-"-	20	3.14.1	Keen & Craddock (1997)
8	3.6.1	Krick (1994)	21	3.15.1	Koolen et al. (1992)
9	3.6.3	-"-	22	3.16.1	Ziesak & Matthies (2001)
10	3.6.4	-"-	23	3.17.1	Boling (1985)
11	3.7.4	Lyasko (1994)	24	3.18.1	Söhne (1969)
12	3.7.9	-"-	25	3.13.15	Limiting CI, Maclaurin
13	3.8.5	Godbole & al (1993)			
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			

2.3.3 Ground pressure, Contact pressure

2.3.3.1 Nominal Ground Pressure

A widely used ground pressure indicator is Nominal Ground Pressure:

$$\mathrm{NGP} = \frac{W}{r \cdot b} \qquad (2.17)$$

where:

NGP is nominal ground pressure, kPa
W wheel load, kN
r wheel radius, m
b tyre width, m

The use of NGP has the following disadvantages:

- it leads to ground pressures far lower than actual ground pressure (see Figure 2.13),
- it assumes nearly 0.3 m sinkage, which is not acceptable for ecological reasons
- tyre deflection, which plays a significant role in the wheel/soil contact does not enter into the formula (model).

NGP gives a rough idea of the minimum ground pressure the wheel can generate, but cannot be used in comparing the ecoefficiency of two different wheels in varying conditions.

None of the other studied tyre ground pressure models seemed perfectly sufficient for assessing the suitability of tyre for sensitive sites. It is recommended however, to adopt models, which include the tyre deflection because it leads to more environmentally acceptable selections. Because the WES-method acts as a frame of reference for the study, the following ground pressure models may be appropriate for assessing the suitability of the forwarders and harvesters to an ecological order.

2.3.3.2 Models for estimating tyre ground pressure

As can be seen from Chapter 2.3.2, there is not a “true” model for estimating the tyre contact area and therefore some indicative models are presented in this context, Eq(2.18)-Eq(2.20)

Dwyer’s (1984) “ground pressure index”

$$p = \frac{W}{b \cdot d} \cdot \sqrt{\frac{h}{\delta}} \cdot \left(1 + \frac{b}{2 \cdot d}\right) \qquad (2.18)$$

A similar ground pressure index can be derived using Maclaurins’s formula:

$$p = \frac{W}{b^{0.8} \cdot d^{0.8} \cdot \delta^{0.4}} \qquad (2.19)$$

The ground pressure index (“G” in Figure 2.11) for an average loaded forwarder tyre is 164 kPa, more than twice the NGP of 75 kPa. Soils having a “bearing capacity” less than 164 kPa can thus be considered as “sensitive”. The ground pressure index “G” is an average pressure derived from different models (“G” in Figure 3.4).

The Limiting Cone Index, “CI” in Figure 2.12, is some kind of mean maximum pressure index. It is closer to the contact pressure a tyre develops on a hard surface, modelled by the new Ziesak & Matthies (2001) model, Z&M in Figure 2.12.

$$p_{CI} = \frac{1.85 \cdot W}{b^{0.8} \cdot d^{0.8} \cdot \delta^{0.4}} \qquad (2.20)$$

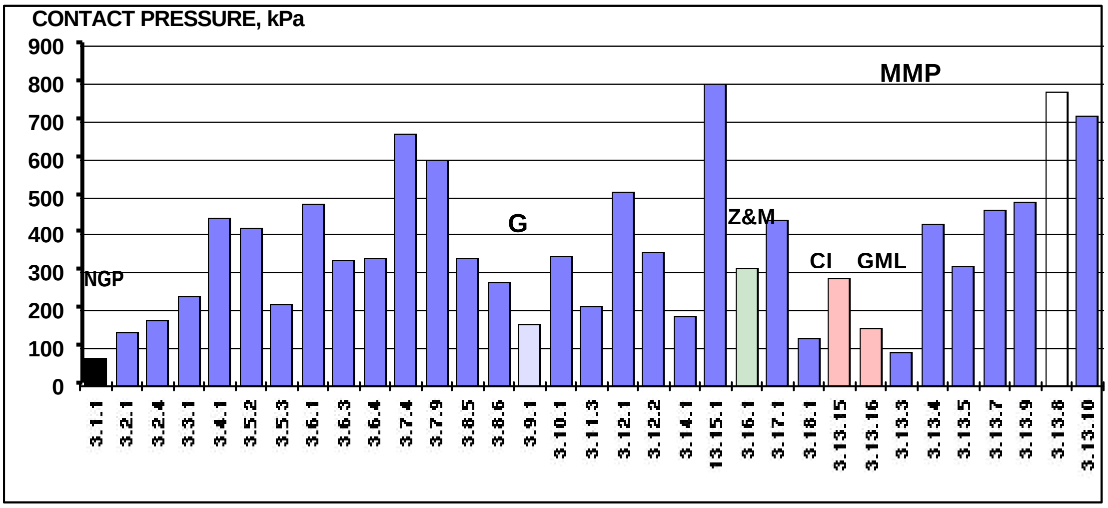


Figure 2.12 Tyre contact pressure calculated using different models

NGP, nominal ground pressure. GML, ground pressure index by Maclaurin (1997), G, ground pressure index by Dwyer (1984). CI limiting Cone Index by Maclaurin (1997). Z&M contact pressure by Ziesak & Matthies (2001)

2.3.4 Mean Maximum Pressure (MMP)

The concept of Mean Maximum Pressure is developed for comparing the performance of different types of military vehicles. There are a large number of formulae for calculating the Mean Maximum Pressure, see Appendix Report No. 5. After Littleton & Hetherington (1987) the observed pressure under a flexible track on sandy soils seems to follow the model developed based on the soil contact pressure under one plate only. Nominal ground pressure (NGP, assuming the pressure distributed evenly over each plate in contact with soil) seems to be a large underestimation (see Figure 2.13).

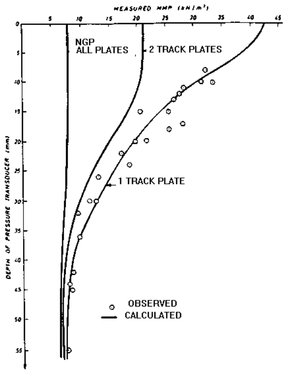


Figure 2.13 Pressure distribution under a track plate

2.3.5 Tyre deflection

2.3.5.1 Modelling of the tyre deflection

Tyre deflection is discussed in more detailed in Appendix Report No. 6.

Loaded tyre deflection is defined as

$$\delta = \frac{d}{2} - r_l \qquad (2.21)$$

where:

δ is tyre deflection, m
d tyre diameter, m
r_l tyre loaded radius, m

As seen in Chapter 2.3.2 the deflection plays a significant role in the modelling of the pneumatic tyre contact area. Because the tyre-loaded radius depends on the wheel load, tyre deflection is not a constant, but depends on wheel load, see Figure 2.14. The wheel load in many agricultural or military applications can be considered as constant, and therefore the deflection can be estimated by an empirical constant for a specific vehicle. In forestry, the load of a forwarder can purposely be varied, and therefore it is important to use deflection models in trafficability models.

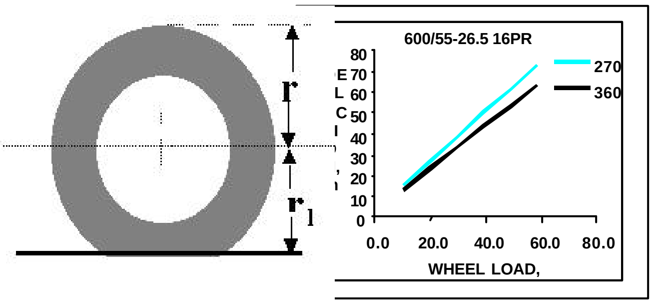


Figure 2.14 Tyre deflection

Tyre deflection depends on:

- tyre carcass stiffness
- structure, cross ply or radial
- ply rating, number of structure layers
- tyre inflation pressure,

of which, the tyre inflation pressure is the dominant determining factor for forestry tyres.

The best estimate for the forwarder tyre deflection becomes, Eq.(2.22)

$$d = 0.008 + 0.001 \cdot \left(0.365 + \frac{170}{p_i} \right) \cdot W \qquad (2.22)$$

where:

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

2.3.5.2 Testing of the tyre deflection model

The tyre deflection model is tested against the field observations of Löfgren (1991). He drove a forwarder with 3 different tyre inflation pressures; 100, 240 and 380 kPa, and three different loads; 1/2, 3/4 and full load, with the total masses of 15.7, 17.3 and 19.9 tonnes on test tracks and recorded the rut depth. The results are depicted in Figure 2.14 together with corresponding sinkage models. As a conclusion a very remarkable diminution in rut depth as a function of tyre inflation pressure can be seen.

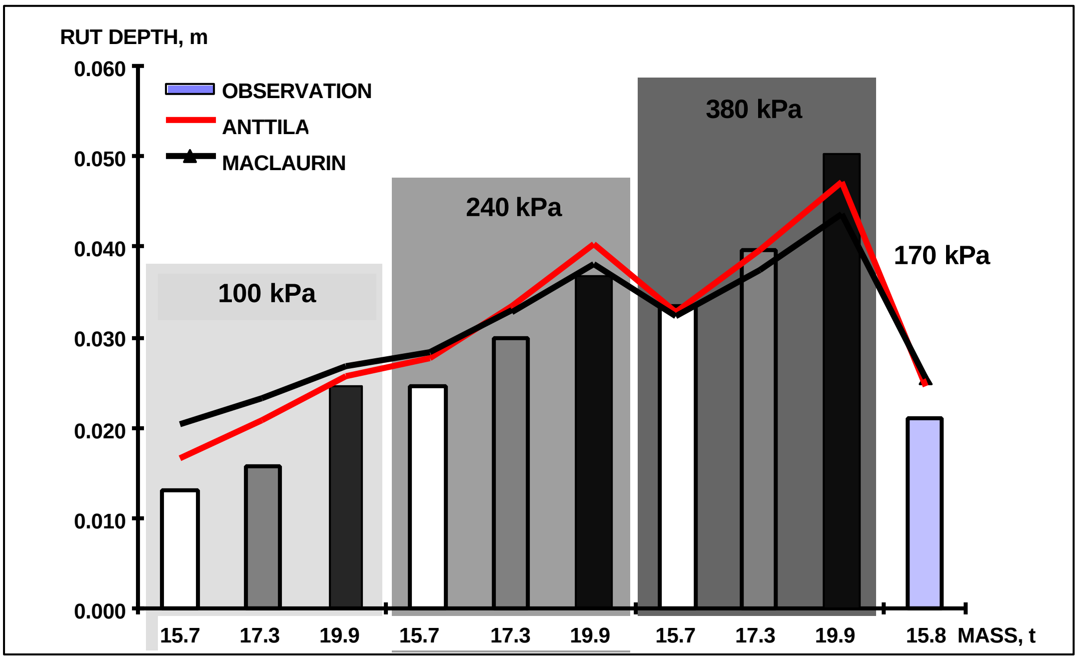


Figure 2.15 Testing of the tyre deflection model in two rut depth models compared to the field observations of Löfgren (1992).

2.3.6 Wheel Numeric

Wheel numeric is a simplified wheel/soil contact model, based on “dimensionless parameters”, in order to simplify the calculus when using Imperial units (lb/sq.in etc.) in field measurements. This approach, developed since the 1960s (Freitag, 1966) led to rather logical, simple semi-empirical wheel models, which are used as soil and wheel parameter inputs in the WES-method for modelling the mobility parameters of:

- Torque, or thrust, gross tractive force
- Towed force, or rolling resistance
- Drawbar pull, or net traction
- Sinkage.

There are several wheel numerics developed by different authors. Most wheel numerics are developed for cohesion soils, because most mobility problems are encountered on wet cohesive soils; but there are also some models for friction soils. The **wheel input** variables for the wheel numerics are:

- Tyre diameter
- Tyre width
- Tyre section height
- Tyre deflection.

The sole **soil input** variable is:

- Soil penetration resistance recorded at a certain depth, Cone Index

Wheel numeric for cohesion soils

The most commonly used Wheel Numeric is that proposed by Turnage (1978), (N_{CI}), Eq(2.23) [1]. It contains the contact pressure/soil bearing factor for rigid wheels (the first term), the influence of the deflection (second term) and the tyre width factor (the third term).

$$N_{CI} = \frac{CI \cdot b \cdot d}{W} \cdot \sqrt{\frac{\delta}{h}} \cdot \frac{1}{1 + \frac{b}{2 \cdot d}} \qquad (2.23)$$

Rather similar, but easier to use is Maclaurin's (1997) wheel numeric (N_M), Eq(2.24):

$$N_M = \frac{CI \cdot b^{0.8} \cdot d^{0.8} \cdot \delta^{0.4}}{W} \qquad (2.24)$$

A different type of wheel numeric is presented by Brixius, (N_B), Eq. (2.25)

$$N_B = \frac{CI \cdot b \cdot d}{W} \cdot \left(\frac{1 + 5 \cdot \frac{\delta}{h}}{1 + 3 \cdot \frac{b}{d}} \right) \qquad (2.25)$$

Wismer & Luth's (1972) mobility models are some of the most cited in literature, but they call for the Wismer & Luth wheel numeric. In fact, it is the same as Turnage's wheel numeric N_{CI}, only Wismer & Luth replaced the term $\frac{\delta}{h}$ by a fixed ratio.

---

[1] Note that in literature the code for different wheel numerics may differ from the codes used in this report

Sand Numerics for friction soils

On friction soils the soil density plays an important role, and therefore ***the penetration resistance gradient*** (GR) is used instead of cone index i.e.

$$GR = \frac{q_2 - q_1}{z_2 - z_1} \qquad (2.26)$$

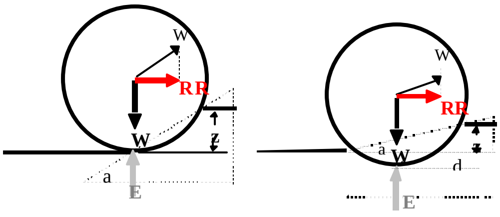
and the Sand Numeric becomes:

$$N_S = \frac{GR \cdot (b \cdot d)^{\frac{3}{2}}}{W} \cdot \frac{d}{h} \qquad (2.27)$$

There are some mobility models for friction soils in the literature, but friction models are not presented in more detail in this report, see Appendix Report No 2.

2.3.7 Rolling resistance

2.3.7.1 Modelling of the rolling resistance



RIGID **PNEUMATIC**

Figure 2.16 Rolling resistance model

Rolling resistance is the horizontal force needed to compact the soil. In the simple model, the wheel settles down to a certain depth resisted by the bearing force (see Chapter 2.2.2). When moving horizontally it must compact the soil, and the wheel can be considered to move on an inclined plane. Rolling resistance depends on wheel sinkage, which is related to the wheel load and tyre deflection, determining the tyre contact pressure, and the soil bearing capacity.

Tyre carcass friction (hysterisis), adds to the rolling resistance.

There are different approaches to model the rolling resistance, a rigid wheel model (**RIGID** in Figure 2.17), pneumatic tyre (**TYRE** in Figure 2.17) or virtual wheel. (**VIRTUAL** in Figure 2.17)

Rigid wheel model for rolling resistance:

$$\mu_R = \sqrt{\frac{z}{d}} \qquad (2.28)$$

Pneumatic tyre model for rolling resistance:

$$\mu_R = \frac{z}{\sqrt{2 \cdot r \cdot z + 2 \cdot r \cdot \delta - 2 \cdot z \cdot \delta - \delta^2}} \qquad (2.29)$$

2.3.7.2 Empirical rolling resistance coefficients

As can be seen from Chapter 2.9.2, the rolling resistance increases as a function of sinkage, being lower on hard surfaces and higher on softer soils. Hard inflated tyres have a smaller rolling resistance on a hard surface, but the decrease in tyre inflation pressure decreases the rolling resistance on softer soils, due to smaller sinkage. For an average forwarder tyre the rolling resistance coefficient is as given in Table 2.7.

Table 2.7 Rolling resistance coefficient on different sites

Terrain	Penetration resistance, kPa	Rut depth, mm	Rolling resistance coefficient
Forest road, hard surface	> 2000	4 – 10	0.05
Compact dry moraine	> 1000	15 – 35	0.10
Sandy moraine	650	30 – 65	0.15
Fresh silty forest soils	450	60 – 95	0.20
Soft, moist depressions	> 350	>95	0.20-0.40

2.3.7.3 Empirical rolling resistance models

There are a large number of WES models for rolling resistance (see Appendix Report No 2). of which, two are presented here.

N.I.A.E[2].-models are based on a large number of drawbar pull tests with farm tractors, mainly in the UK. The published results by various authors are contained in different reports e.g. (Gee-Clough (1978), Gee-Clough *et al* (1978), Dwyer (1984)).

$$\mu_R = 0{,}049 + \frac{0{,}287}{N_{CI}} \qquad (2.30)$$

---

[2] N.I.A.E National Institute of Agricultural Engineering, Silsoe, England

Maclaurin (1990) studied the performance of military vehicle terrain tyres in the U.K. using a single wheel tester.

$$\mu_R = 0.017 + \frac{0.453}{N_{Ci}} \tag{3.31}$$

In Figure 2.17, the results are compared with two WES rolling resistance models, (WES1) Maclaurin (1990) and (WES2) Gee-Clough *et al* (1978).

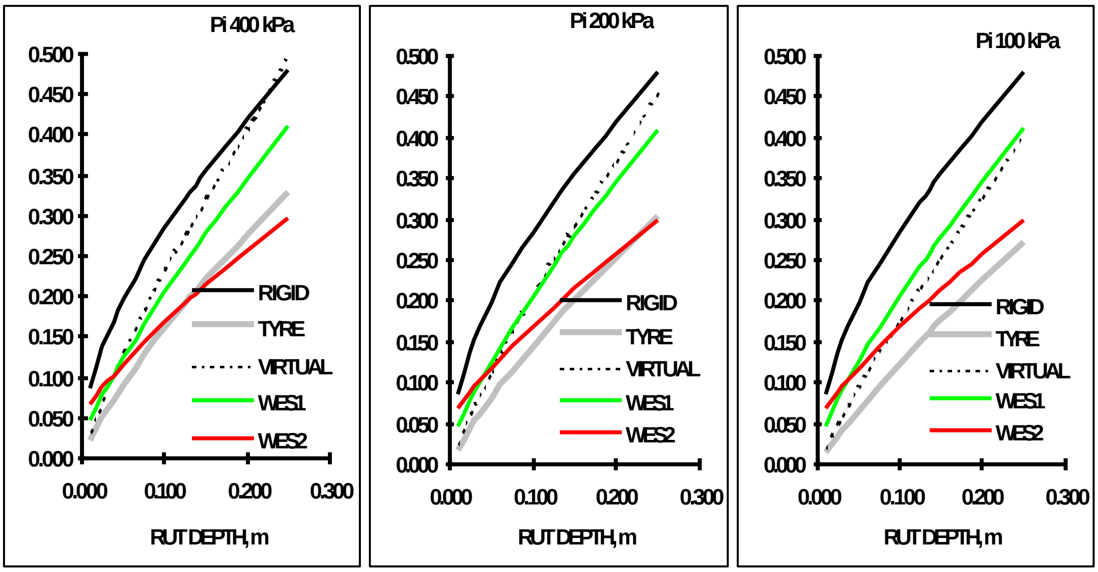


Figure 2.17 Rolling resistance coefficient after different models for a forwarder wheel with different tyre inflation pressure

From Figure 2.17 it can be concluded that, the semi-empirical model WES1 is close to the virtual wheel model, but WES2 follows more the pneumatic tyre model. The rigid wheel model gives maximal values, and the pneumatic tyre minimum values, while the virtual wheel seems to give adequately good estimates.

2.3.8 Thrust

2.3.8.1 The development of thrust

Thrust is a friction force between a tyre and soil, or the grip a tyre can generate from the soil surface to overcome the forces resisting the movement. There are different terms and definitions for thrust, such as gross tractive effort, or gross traction, traction and wheel torque. Generally, the thrust coefficient, or torque ratio is used :

$$\mu_T = \frac{T}{W} = \frac{Q}{r \cdot W} \qquad (2.32)$$

where:

μT is	thrust coefficient
T	thrust, kN
Q	wheel torque, Nm
r	wheel radius, m
W	wheel load, kN

Theoretically the (maximum) thrust can be calculated based on soil cohesion and internal friction, Eq(2.33) (Micklethwait, 1944):

$$T = A \cdot C + W \cdot \tan\phi \qquad (2.33)$$

where:

T is	thrust, kN
A	tyre contact area, m^2
C	soil cohesion, kPa
W	wheel load, kN
ϕ	soil internal friction

The development of thrust depends on the soil deformation modulus. When a wheel begins to turn it creates shear forces into the soil. There are two types of development of shear strength. In loose compacting soils the shear strength develops asymptotically to the maximum. In most soils the shear strength develops to a certain maximum, but after the cohesion forces collapse, the shear strength collapses to a residual strength level, see Figure 2.18.

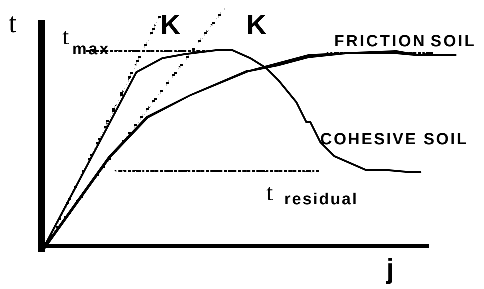


Figure 2.18 Soil shear stress-strain curve of different soils

Thrust can be calculated if the main soil parameters, Cohesion and Friction Angle are known. Those parameters, especially the cohesion, are dependent on soil moisture, and therefore a large number of soil test are needed to collect adequate data on varying conditions. In Table 2.8, the shear strength parameters for some forest soils are given, and the corresponding thrust and thrust coefficient calculated based on a loaded forwarder wheel[3].

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[3] W= 40 kN, d = 1.333 m, b= 0.601 m, pi = 400 kPa, A = 0.201 m^2

Table 2.8 Properties of some forest soils and the corresponding thrust coefficient (partially from Kuonen 1983)

Variable	Cohesion soils → Friction soils				
	Clay	Silty clay	Silt	Fine sand	Sand
Particle size, mm	< 0.002	< 0.06	< 0.02	< 3	< 6
Dry density	1190	1600	1439	1709	1726
Wet density, kg/m^3	1750	2000	1900	2000	1950
Water content, %	47	25	32	17	13
Cohesion, kPa	25	20	0	0	0
Friction angle, °	22	27	33	34	38
T, Cohesion component, kN	5,0	4,0	0,0	0,0	0,0
T, Friction component, kN	16,2	20,4	26,0	27,0	31,3
Thrust, kN	21,2	24,4	26,0	27,0	31,3
Thrust coefficient	0,53	0,61	0,65	0,67	0,78

2.3.8.2 Empirical thrust coefficients

There are some data on average thrust coefficients in different conditions, Table 2.9. Larminie (1984) and Ragot (1976)

Table 2.9 Empirical thrust coefficients on different soils for rubber tyres and steel tracks (Larminie 1984, Ragot 1976)

Surface	Rubber tyres		Steel tracks	
	Larminie	Ragot	Larminie	Ragot
	Thrust Coefficient		Thrust Coefficient	
Dry rough concrete	0.8-1.0	0.88	0.45	0.45
Dry clay loam	0.5-0.7	0.55	0.9	0.58
Wet clay loam	0.4-0.5	0.45	0.7	0.46
Damp gravelly sand	0.3-0.4	0.35	0.35	0.32
Loose dry sand	0.2-0.3	0.20	0.3	0.29
Dry snow	0.2	0.20	0.15-0.35	
Ice	0.1	0.12	0.1-0.25	0.12

2.3.8.3 WES models for the thrust coefficient

There are a great number of semi-empiric thrust coefficient models based on the WES-method, using Wheel Numeric as the input variable (see Appendix Report No 2), of which four are presented here, Eq(2.34)-(2.37). The Wismer & Luth (1972), Dwyer (1978), and Brixius (1978) models are based on farm tractor tests on agricultural soils. The fourth model, Maclaurin (1992) tested different military vehicle tyres on grassland using a single wheel tester. His model is the sum of separate rolling resistance and pull coefficients. The model is for a standard 0.2 slip ratio; in the other models slip ratio is the second input variable.

The models must be considered as a guideline only, because there is no test data on forwarder performance on forestry soils to validate the models.

Wismer & Luth (1972)

$$\mu_T = 0.75 \cdot (1 - \exp^{-0.3 C_N \cdot S}) \qquad (2.34)$$

Dwyer (1978)

$$m_P = \left(0{,}796 - \frac{0{,}92}{N_{CI}}\right) \cdot \left(1 - \exp^{-1 \cdot (4{,}838 + 0{,}061 \cdot N_{CI}) \cdot S}\right) \qquad (2.35)$$

Brixius (1978)

$$m_T = 0.88 \cdot (1 - e^{-0.1 \cdot N_B}) \cdot (1 - e^{-7.5 \cdot S}) + 0.04 \qquad (2.36)$$

Maclaurin (1990)

$$m_P = 0.817 - \frac{3.2}{N_{CI} + 1.91} + \frac{0.453}{N_{CI}} \qquad (2.37)$$

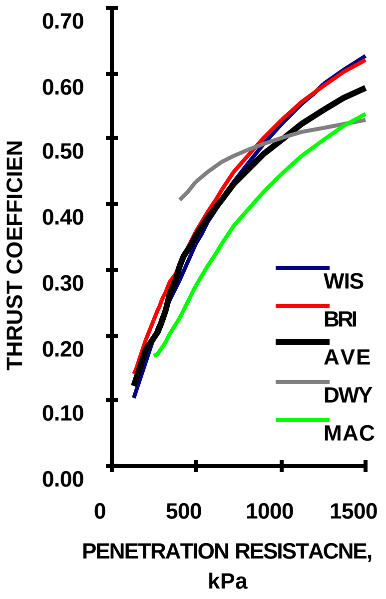


Figure 2.19. Thrust coefficient calculated using different WES-models

The thrust coefficient for an average loaded forwarder wheel calculated using different models is depicted in Figure 2.19. It can be seen that, Maclaurin's model gives somewhat lower thrust coefficients than the models based on farm tractor tests.

The use of chains or wheel tracks increases the thrust coefficient, especially in terrain conditions where extra grip is generated from tearing the surface root mat, or from stones and other micro-relief irregularities.

2.3.9 Net thrust, Drawbar pull

Net thrust, drawbar pull, pull or net pull, is the lateral forward force a wheel can develop when moving. The net thrust coefficient of a driving wheel is:

$$\mu_P = \mu_T - \mu_R \qquad (2.38)$$

When estimating the net thrust of a forwarder or calculating the pull capacity of a skidder, the rolling resistance or rolling resistance coefficient must be replaced by the total of resisting forces, see Chapter 4.2.1.

Net thrust acts as a reserve the tractor can use for acceleration or for pulling an extra load. Therefore it can be used as one of the variables in assessing the sensitivity of a site in site/machine matching, see Chapter 5.2.3.

3. TERRAIN MODELLING

Terrain modelling includes; the terrain/machine and environment/transport modelling demand for different geographical information on micro- and macro-profiles and obstacles. In forestry, the IUFRO-terrain classification has been proposed for adoption (von Segebaden *et al*, 1967) for *"standards for describing the most important factors which may affect forest operations*". However, no generally adopted terrain classification for forestry has been worked out. In Nordic countries a terrain classification scheme was published in 1978 (Eriksson *et al*, 1978), and this is in use in many countries. At that time terrain classification was aimed at serving the intensive research activities needed for the development of the mechanisation process, and some of the terrain variables are rather tedious to measure in the field. Therefore, simplified terrain classifications were adopted for practical wood harvesting in most countries. The same dilemma still exists. The planning of routes, demands detailed terrain data, but this kind of data is insufficiently available. This problem can be solved to some extent using GIS-techniques to assess the probabilities for a certain machine to fulfil the set mission. Therefore, the concept of "terrain classification" must be seen as a clear distinction between primary classification (terrain description) and secondary classification (operational use of the primary data). In terrain classification all forestry activities, not only wood harvesting, must be taken into account.

Two types of terrain variables can be distinguished

- **Macro-topography** can be considered as a group of variables, which influence the movement of the whole vehicle, e.g. all the vehicle wheels encounter the same macro-topography value. For practical applications the minimum grid is 10x10 m
- **Micro-topography** variables consist of the terrain features which influence a single wheel, such as stones and surface unevenness

The third type of variable consists of:

- **Obstacles**, such as rivers, brooks, protected areas and other permanent terrain features, which need special attention
- **Vegetation** can be seen as a collection of obstacles, which vary during a season or in a short time (a plantation is fast growing, or trees can be cut)
- **Snow**, winter traffic needs special planning.

3.1.1 Macro-topography

3.1.1.1 Macro-topography variables

The most important macro-topography variables are:

- **slope angle** (α), usually given as slope percent ($=100 \cdot \tan(\alpha)$)
- **slope direction** is an essential operational variable. The distinction between the favourable (+) and adverse (-) slope depends on the direction of travel.

The two variables are needed to calculate the **slope resistance, (F_S)**.

The other macro-topography variables needed for detailed planning are:

- **slope length**, needed for area planning (mountain/plains) and erosion control
- **slope form**, such as terraced, concave, etc are sometimes needed for special applications, especially for small machinery
- **slope aspect**, important for assessing climatic factors.

The slope angle and practically all the macro-topography variables can be derived from contour maps, and the new GIS-techniques permit the full use of the available information for operations and route planning. The concept of **slope classification** as a primary planning variable becomes obsolete, but can be used for secondary classification for operational planning, giving some rough limits for different machines.

3.1.1.2 Slope resistance

Slope resistance can be calculated using the inclined plane equation, Eq(3.1)

$$F_G = W \cdot \sin a \qquad (3.1)$$

The slope resistance coefficient is:

$$m_{\mathrm{G}} = \sin \mathrm{n}a \qquad (3.2)$$

3.1.2 Micro-topography

Micro-topography or Surface roughness plays an important role in modelling. There are many different ways to describe the micro-topography (surface roughness), the main types being:

- **Surface obstacle classification**, ground condition classification, based on average obstacle height and density.
- **Surface profiles,** using different mathematical models for profiling.

3.1.2.1 Ground condition classification (surface roughness)

The NSR-terrain classification, or its simplified classes, is widely used in forestry. The surface roughness classification is given in Table 3.1.

Table 3.1 Surface roughness classes (After NSR-classification)

Surface class	Obstacle height, m	Allowed Cases	Obstacle height, cm			
			20	40	60	80
			Average distance, m			
1	H(20)	a)	1.6- 5.0			
		b)	5.0-16.0	>16.0	>16.0	>16.0
2	H(20-40)	a)	<1.6	>16.0	>16.0	>16.0
		b)	1.6-5.0	5.0-16.0	>16.0	>16.0
3	H(40-60)	a)	<1.6	1.6-5.0	5.0-16.0	>16.0
		b)	<1.6	1.6-5.0	1.6-5.0	>16.0
4	H(40-80)	a)	<1.6	<1.6	5.0-16	5.0-16.0
		b)	1.6-5.0	1.6-5.0	1.5-5.0	5.0-16.0
5	H(40-80)	a)	<1.6	<1.6	1.6-5.0	5.0-16.0
		:				
		i)	<1.6	<1.6	<1.6	<1.6

3.1.2.2 Surface profiling

There are a large number of different techniques, which can be used in modelling the surface roughness. The principle is to find out certain

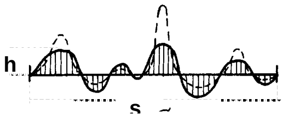


Figure 3.1 Surface profiling

regularities of the surface profile so that, adequate information on obstacle heights and densities are available for trafficability and mobility analysis.

An average equivalent obstacle slope factor k_0 is as follows, Eq(3.2).

$$k_o = \frac{\sum h_s}{s} \qquad (3.2)$$

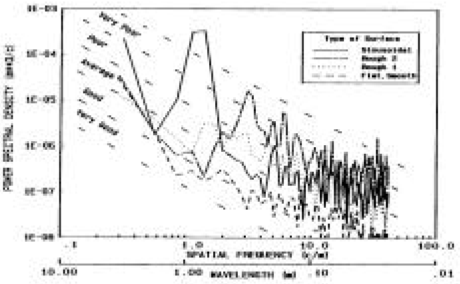


Figure 3.2 Surface roughness frequencies (After Eiyo&Young 1990)

For computer based GIS applications the use of different types of sinusoidal models, combining wave length (=obstacle density) and amplitude (=obstacle height) will be developed, see Figure 3.2.

$$S_n = \frac{2 \cdot \Delta x}{N} \cdot \left(\sum_{k=0}^{N-1} y_k \cdot e^{-\frac{i \cdot 2 \cdot p \cdot n \cdot k}{N}} \right)^2 \qquad (3.3)$$

3.1.2.3 Obstacle resistance

When a wheel travels over a spherical obstacle, the potential energy at the highest point is

$$E_P = m \cdot g \cdot h \qquad (3.4)$$

where

E_P is	potential energy, J
m	wheel mass, kg
g	gravity acceleration, 9.81 m/s^2
h	obstacle height, m

When the wheel descends from the obstacle the stored potential energy is released, and the energy balance =0. But when a wheel of a multiwheeled forwarder passes an obstacle, it must travel a longer distance, and it creates different torques between wheels. The torque difference is noticeable for the tractors with locked differentials, and depends on tractor construction. This causes a loss of energy, and can be considered as obstacle resistance.

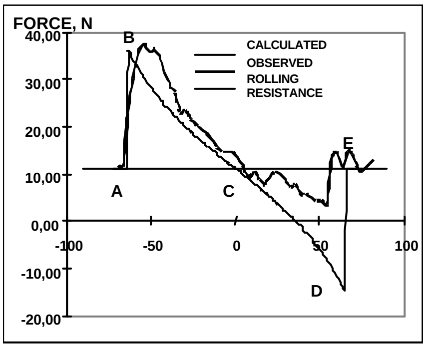


Figure 3.3 Calculated and measured resistance force of a vehicle passing a single obstacle

A simple model for obstacle resistance Eq(3.5) can be derived from Equation (3.4) assuming that a certain percentage of the potential energy is wasted when overcoming a certain obstacle. The loss factor (k) is assumed constant for a certain machine, and depends on the number of wheels and driveline mechanics etc.

$$m_O = k \cdot \frac{\sum_{i=1}^{i} h_i}{d} \qquad (3.5)$$

where:

μ_O	obstacle resistance coefficient
k	energy loss factor depending on tractor’s driveline configuration
h	obstacle height, m
d	travel distance, m

Because the loss coefficient *(k)* is not known, and also the relative obstacle height is only a rough estimate, an average obstacle resistance coefficient can be used for modelling the surface roughness (Table 3.2).

Table 3.2 Probable obstacle resistance coefficient for tractors with locked transmission

Terrain class	Obstacle height, m	Obstacle resistance coefficient
I	**- 0.1**	**0.01**
II	**0.1 – 0.2**	**0.05**
III	**0.2 - 0.4**	**0.10**
IV	**0.4 - 0.6**	**0.15**
V	**0.5 - 0.8**	**0.20**

4. MODELLING OF THE ECOEFFICIENCY OF THE FORWARDER

4.1 Rutting

After logging, wheel traces are left in the soil; sometimes barely visible, sometimes as deep scars in the Earth. Due to its obvious visibility the wheel rut has become one of the yardsticks in deeming the ecoefficiency of a forwarder or of the logging operations.

4.1.1 The concept of rut depth

Rut depth in terramechanics and in ecology has different interpretations, and the measuring technique of rut depth may vary. In terramechanics, rut depth is the observed wheel sinkage at a certain point or section. In ecology it is the observed rut after the operation. For practical purposes there is no difference between the concept of wheel sinkage and the rut depth, and therefore only the rut depth is used in this section. It is however important to distinguish between the concept of:

- **first pass**

  - **first wheel pass**, a single wheel passes the observation point
  - **first vehicle pass**, a single vehicle fitted with several axles passes the observation point, load size stays constant
  - **first (tractor) cycle pass**, an empty tractor passes the observation point and returns over the same point with a load. Load size changes within the cycle under the actual first and second passes.
- **multipass**
  - **wheel multipass**
  - **vehicle multipass**
  - **multi cyclepass**

4.1.2 Modelling of the rut depth

4.1.2.1 First wheel pass rut depth model

Maclaurin (1990) measured the wheel sinkage using the fifth wheel concept and developed the following model for the first pass wheel sinkage, Eq(4.1)

$$z = d \cdot \frac{0.224}{N_{CI}^{\ 1.25}} \tag{4.1}$$

4.1.2.2 First cyclepass rut depth models

Two recent studies on rut depth after the first cycle pass of a forwarder on Finnish moraine and peaty depressions have resulted in the following models:

Anttila's (1998) models

Anttila (1998) studied rut depth on selected straight, even and horizontal sections and gives the following first cycle rut depth models, Eq(4.2-4.3)

$$z = d \cdot \left(0.003 + \frac{0.910}{C_N} \right) \tag{4.2}$$

$$z = d \cdot \frac{0.248}{N_{CI}} \tag{4.3}$$

Rantala's (2001) data

Rantala (2001) studied rut depth on different real worksites, and his data permits the development of the following first cycle pass models for forwarders and harvesters, Eq(4.4-4.7). The model gives somewhat deeper ruts than Anttila's model, mainly due to the fact that it contains rut depth on a curve, on slope and on uneven surfaces.

Peat and clay (soft soils)

$$z = 0.059 + \frac{0.490}{N_{CI}} \qquad (r^2=0.315) \qquad (4.4)$$

$$z = \frac{0.989}{N_{CI}^{1.23}} \qquad (r^2=0.396) \qquad (4.5)$$

Mineral soils

$$z = -0.026 + \frac{0.629}{N_{CI}} \qquad (r^2=0.493) \qquad (4.6)$$

$$z = \frac{0.678}{N_{CI}^{1.46}} \qquad (r^2=0.273) \qquad (4.7)$$

4.1.2.3 Modelling of the multipass rut depth

When a wheel passes over a certain point it compresses the soil and creates the first rut, z_1. The following wheel going on the same line travels over the compressed soil, whose bearing capacity is higher, and the consecutive rutting from the previous rut bottom is smaller. There are quite a large number of papers dealing with first pass sinkage or rut depth as seen from Appendix Report No. 2, but very few authors have published papers on multipass-behaviour of wheels (Holm 1999).

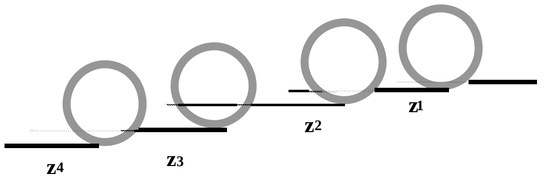


Figure 4.1 Wheel multipass

Scholander (1974) carried out repetitive plate loading tests and developed the following general model for the settlement depth under repeated loading, Eq(4.8)

$$z_n = z_1 \cdot n^{\frac{1}{a}} \qquad (4.8)$$

where:

z_n is rut depth after n^{th} load, m
n number of loadings
z1 rut depth after first loading, m
a soil specific multipass coefficient

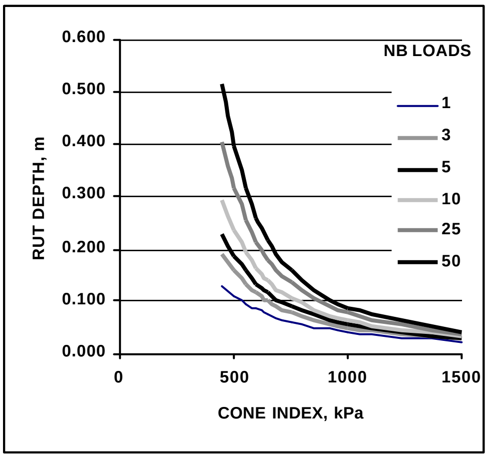


Figure 4.2 Rut depth estimate for a 12 t forwarder with 10 t load

Later Freitag (1965) provided the following model for the second pass with different loads, Eq(4.9)

$$z = \left(z_1^{\ 2} + z_2^{\ 2}\right)^{\frac{1}{2}} \qquad (4.9)$$

where:

z is	rut depth after second pass, m
z_1	rut depth after first pass, m
z_2	estimated rut depth after 2nd pass without no prior soil disturbance, m

In this case the multipass coefficient a=2.

By combining the Equations (4.8) and (4.9), we can introduce a general multipass equation, Eq(4.10).

$$z_n = \left(z_{n-1}^{\ a_n} + z_1^{\ a_n}\right)^{\frac{1}{a_n}} \qquad (4.10)$$

where

z_n is	rut depth after n^{th} pass, m
z_{n-1}	rut depth after $n\text{-}1^{th}$ pass, m
z_1	estimated rut depth n^{th} pass without no prior soil disturbance, first wheel pass rut depth, m
a_n	multipass coefficient for the n^{th} wheel pass

The rut depth estimate for an 8-wheeled, 12 t forwarder fitted with d=1.333 and b=0.700 m tyres carrying 10 t load is presented in Figure 4.2.

4.1.2.4 Multipass coefficient

Different authors have used different values for multipass coefficient a. As mentioned in Chapter 2.2.2.1, Freitag (1965) found out that a multipass coefficient of 2 is valid for soft clay soils. Scholander (1974) measured multipass coefficients on different soils (see Table 4.1). Abebe *et al* (1989) also obtained the same type of results and confirmed that a multipass coefficient for softer soils is 2, see Table 4.2.

Table 4.1. Multipass coefficient (a) for different soil types under different moisture conditions (After Scholander, 1974)

Soil type				Multipass coefficient
Silt	Fine sand	Sand	Gravel	
Particle size, mm				
0.002-0.02	0.02-0.2	0.2-2	2-20	
Soil moisture, %				
20-35				**2**
20-30				**5**
	20-30	10-25		**7**
10-20	10-30	5-20		**10**
		10-20		**13**
		5-20	5-15	**17**
			5-10	**26**

In Appendix Report No 2 the analysis of different data have permitted the development of the following models for the multipass coefficient *a*, Equations(4.11- 4.13)

Table 4.2.Multipass coefficient *a* after Abebe *et al.* (1989)

Soil and load conditions	Multipass coefficient *a*
Loose soil, low load	2 to 3
Medium bearing soil, medium load	3 to 4
Bearing soil, heavy load	4 to 5

The field observations on rut formation in Finnish moraine and peat soils have permitted the development of different multicycle coefficients, which have been presented in Appendix Report No 2. The following models seem to be applicable for different situations, Eq(4.11 - 4.13)

$$a = 0.3 \cdot C_N \tag{4.11}$$

$$a = 1.5 \cdot N_{CI}^{\;0.7} \tag{4.12}$$

$$a = 0.011 \cdot q^{0.9} \tag{4.13}$$

The practical difference between multipass and multicycle coefficients is small, the main difference being the use of number of loadings. In wheel and vehicle models, it is the number of passes, in multicycle models the number of loads passing over the observation points.

4.2 Modelling of productivity

4.2.1 Modelling of the resisting forces

Knowing the resisting forces is important when comparing the ecoefficiency of forwarders and skidders. High resisting forces usually indicate increased probability for ecological damage, because most of the net energy developed by the engine is transferred into the soil. Also, high resisting forces indicate lower velocity, and thus lower productivity.

Total resisting force is the sum of different forces resisting the movement, Eq(4.14)

$$F_T = F_R + F_S + F_O + F_D + F_A + a \cdot m + F_P \tag{4.14}$$

where

F_T	total resistance, N
F_R	rolling resistance, N
F_S	slope resistance, N
F_O	obstacle resistance, N
F_D	steering resistance, winding resistance, N
F_A	air resistance, N
a	acceleration, m/s^2
m	tractor mass, kg
F_P	drawbar pull, N

In winter, the snow resistance must also be added to the calculus, but it has been dropped out in this context.

Also, the slip energy affects productivity, but its influence in normal conditions (slip=0.2) is included in the models. In extreme conditions close to the mobility limit, the role of slip energy becomes decisive.

Rolling resistance is one of the most significant mobility parameters. It depends mainly on soil and slightly on tyre deformation. **Slip** influences rolling resistance, making slip energy an important factor in energy balance calculations and evaluations on soil damage. Therefore, determining wheel **Slip** in connection with rolling resistance and thrust is important. Rolling resistance is related to **soil** properties.

Slope resistance is due to overcoming gravity when moving. Slope resistance is related to the **macro-terrain** profile.

Obstacle resistance is due to the fact that, wheels have different trajectory lengths when passing individual obstacles. Obstacle resistance is more pronounced in tractors with mechanical transmissions and locked differentials, and depends on the type of **tractor.** **Micro-terrain** profile, or **Terrain Class,** is the terrain parameter influencing obstacle resistance, the rougher the surface the larger the obstacle resistance.

Steering resistance is due to the fact that in turning, the wheels must go over different paths with different radii. The difference in travel distance must influence wheel velocity, and part of the lost energy can be accredited to steering resistance due to increased slip and shear forces on the soil. Steering resistance is the horizontal equivalent to obstacle resistance. Large winding forces increase the steering resistance, and thus the risks of soil damage, especially with tractors with locked differentials.

Air resistance. Even the tractor itself has a very large C_W-factor and area, air resistance becomes negligible at low velocities attainable on the forest floor.

Inertia resistance, the difference in the tractor's kinetic energy can be calculated based on differences in **tractor momentary velocity**.

Drawbar pull is essential when analysing the working of skidders, but is zero for forwarders.

4.2.2 Modelling the tractor

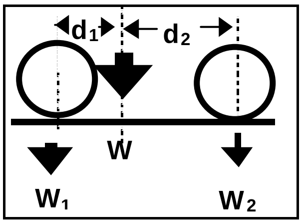
Generally the tractor model consists of summing up the individual wheel forces.

4.2.2.1 Weight distribution on wheels

For simple modelling, two parameters are of prime importance:

- The load distribution between axles and wheels, and
- The net power on wheels.

Those parameters are not directly readable from the manufacturer's catalogue, but need modelling in order to get a more reliable perception of the machine/site matching. The load size can be set, and the centre of gravity of the load depends on the cradle wall position and the length of the logs. Good planning and clear rules can be set for operations on sensitive sites if the load distribution between axles is adequately known.



$$W_1 = W \cdot \frac{d_2}{d_1 + d_2}$$

Figure 4.3 Distribution of load between axles

For this purpose:

- the dimensions of the tractor,
- the mass of the different components, and
- the centre of gravity of different components

must be known with a certain accuracy, and simple geometry used for modelling the tractor weight distribution, especially on slopes. A simple rule for actual forwarders is that 60% of the mass of the empty tractor lies on the front bogie and 40% at the rear, see Figure 4.4. The weight transfer of the load to the front bogie is small, and often the whole load lies on the rear bogie, which leads to the fact, that the load of the rear wheels is much higher than that on the front. Unequal weight distribution increases rutting (Rummukainen & Ala-Ilomäki 1986). Larger forwarders have a hydraulically adjustable headboard to centre the centre of gravity on the rear bogie axle. When using 8-wheeled forwarders on sensitive sites, it seems however, more rational to try to transfer a part of the load to the front axle in order to balance the wheel load between axles, see Figure 4.5. In practice, the influence on rut depth stays rather small.

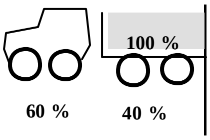


Figure 4.4 Approximate weight distribution

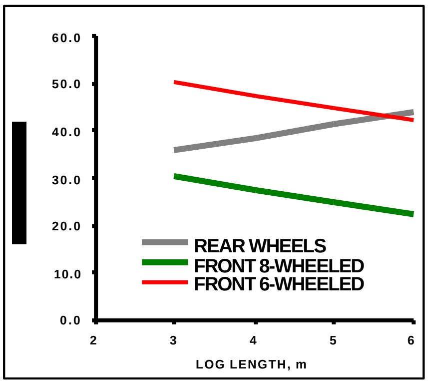


Figure 4.5 Wheel load of a 6- and 8-wheeled tractor as a function of the length of the load

4.2.2.2 Net power on drive wheels

The engine power is usually available in the manual, but all the engine power is not available to move the tractor. Part of the power is used for hydraulic pumps, lost in the drive line and the driver seldom runs the engine at full power. Therefore the net power available for moving the tractor is less than the rated power. A practical empirical model for net power is, Eq(4.15)

$$P_{NET} = 0.5 \cdot P \tag{4.15}$$

where:

P_{NET} is net power on driveline, kW
P rated engine power, kW[4]

4.2.3 Driver

It is impossible to generate a comprehensive simple model to simulate the diver. For the purpose of the study it is adequate to use a coefficient k_{driver} to study the influence of the capacity or motivation of the driver using a coefficient of 0.8- 0.9 for a slow driver, 1 for a normal driver, and 1.1-1.2 for an efficient driver. This allows analysis of the influence of different organisational effects on the economy of timber transport.

4.2.4 Load size

Maximum load size is set by the technical specifications; either the limit may be due to

- size of the cradle, volume constraint, or
- load mass, payload constraint

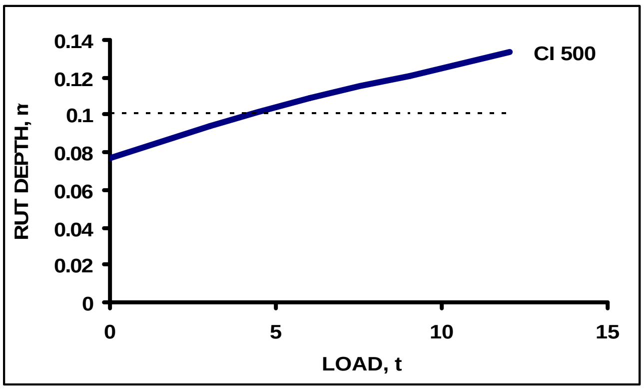


Figure 4.1 Rut depth as a function of load size for the reference forwarder working on low bearing soil

When working on sensitive sites the load size can purposely be reduced in order to lower the ground pressure and thus reduce the soil compaction and rutting, see Figure 4.6. It naturally decreases the productivity, and therefore different ecological and economical analyses are needed in order to find out the most appropriate solution.

---

[4] DIN-norm, SAE power multiply by 0.9

The technical specifications give the constraints for the maximum load, and the planning method should find out the optimal load size for different sensitive sites.

4.2.5 Productivity

For calculating the economic consequences of different alternatives, the production rate and engine costs must be known. The modelling of the engine costs are outside the scope of this paper, but simple production rate models are discussed. Simply, the production rate is, Eq(4.16)

$$P = \frac{1}{t} \cdot L \tag{4.16}$$

where:

P	productivity, m^3/s
t	cycle time, s
L	load size, m^3

So we need to model the cycle time and load size for modelling the productivity. Load size is a terrain dependent variable, whose maximum value is determined by the tractor specifications, rated load and load space.

Cycle time is partially dependent on soil and terrain variables. In this context, the other times i.e. loading, unloading and fixed load times are assumed to be known constants. Of course, a submodel can be developed for each time element. The simplest time model is then:

$$t = t_f + \frac{2}{v_1 + v_2} \cdot d \tag{4.17}$$

where

t is	cycle time, s
t_f	distant independent times (loading, unloading, personal etc.), s
v_1	empty velocity, m/s
v_2	loaded velocity, m/s
d	distance, m

4.2.6 Ground speed

The attainable ground speed depends on:

- available net power and resisting forces
- vibration
- steerability

The attainable ground speed can be estimated using the constraint models for each element.

4.2.6.1 Engine power constraint

The maximum attainable velocity depends on engine power and total resisting forces;

$$v = \frac{k_{driver} \cdot P_{NET}}{F_T} \tag{4.18}$$

where:

v is	ground speed, m/s
k_{driver}	driver constant, Chapter 4.23
P_{NET}	net power on driveline, kW, Chapter 4.2.2.2
F_T	total resisting force, kN

4.2.6.2 Vibration

Vibration can briefly be described by the magnitude of vertical acceleration. The vibration (vertical acceleration) is affected by the engine configuration and ground conditions.

4.2.6.2.1 Vibration limits

The ground velocity of a forwarder is largely dependent on terrain class (see Table 4.3). These kinds of empirical constraints can be entered into the model to limit the velocity to a realistic level. Another way is to use simple vibration models to set the maximal admissible velocities for different wheel and terrain combinations.

Table 4.3 Maximum velocity of a forest tractor on different terrain conditions (Aho& Kättö 1971)

Terrain class	Technical velocity, m/s 1)	Operational velocity, m/s 2)
Forest road	3.55	3.55
Terrain class I 3)	1.55	1.00
Terrain class II 3)	1.30	0.90
Terrain class III 3)	1.10	0.70

1)Technical velocity, allowed driving time < 1 h/d
2)Operational velocity, driving time < 2.5 h/d
3) Old Finnish terrain classification

The maximum vibration limits at the drivers seat are given in ISO norms, see Table 4.4. The maximum acceleration depends on the frequency and plane, and also on the exposure time. For forwarder traffic the low frequency, passing over obstacles, becomes the limiting factor.

Table 4.4 Acceleration limits (ISO 2631)

Frequency	Z-level			X- and Y-level		
	1 min	4 h	24 h	1 min	4 h	24 h
Hz	Acceleration, m/s²					
Tolerance limit						
1	**11.20**	2.12	0.56	4.0	0.71	0.20
4	**5.60**	1.06	0.28	8.0	1.42	0.40
63	44.80	8.50	2.24	126.0	22.40	6.30
Efficiency limit						
1	**5.60**	1.06	0.28	2.0	0.35	0.10
4	2.80	0.53	0.14	4.0	0.71	0.20
63	22.40	4.25	1.12	63.0	11.20	3.15
Comfort limit						
1	1.78	0.34	0.09	0.63	0.11	0.03
4	0.89	0.17	0.04	1.27	0.22	0.06
63	7.11	1.35	0.36	20.00	3.56	1.00

4.2.6.2.2 Modelling the vibration

There is a large number of special programs to analyse the vibration of a machine, but they are too resource demanding for the purpose of the study. For special analysis, dynamic modelling must be adopted; but a simple wheel/obstacle approach seems adequate to develop a constraint model to limit the predicted velocity close to the levels obtainable in the field.

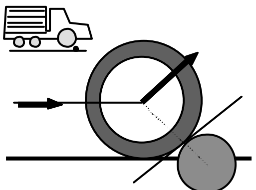


Figure 4.7 A wheel overcoming an obstacle

When a tractor wheel is passing over an obstacle, it changes its trajectory, which causes the vertical acceleration, vibration in plane z, Figure 4.7. From a simple plane geometry, and using static loads, the following model for horizontal velocity v_z, can be derived, Eq(4.19)

$$v_z = \tan \alpha \cdot v_x = \frac{x}{z} \cdot v_x \qquad (4.19)$$

where

v_z	vertical velocity, x-plane, m/s
v_x	horizontal velocity, x-plane, m/s
α	trajectory angle, °

As the acceleration is the derivate of the velocity, and by using simple plane geometry, the following simple vertical acceleration model can be developed.

$$a_z = \frac{(r_W + h)^2}{(r_W)^3} \cdot v^2 \qquad (4.20)$$

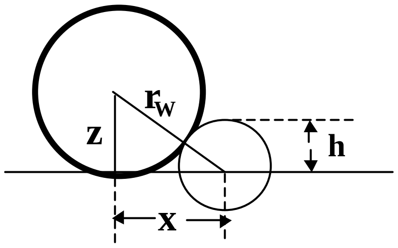


Figure 4.2 Wheel geometry for modelling the vertical acceleration

4.2.6.2.3 Vibration constraint velocity

By letting a certain maximum allowable vibration acceleration, technical, efficiency or comfort, the maximum horizontal velocity for a wheel can be calculated, Eq(4.21)

$$v_{max} = \frac{\sqrt{a_{max} \cdot (r_W + h)^3}}{r_W} \tag{4.21}$$

Because the acceleration of the central axle of a bogie is lower, an arbitrary correction coefficient can be used, and the model for a bogie wheel becomes, Eq(4.22)

$$v_{max} = \frac{\sqrt{a_{max} \cdot (r_W + h)^3}}{r_W} \cdot \sqrt{2} \tag{4.22}$$

where

v_{max}	maximal attainable horizontal velocity, m/s
a_{max}	limiting vertical acceleration, m/s
r_1	radius of the wheel, m
r_2	radius of the obstacle, m
h	height of the obstacle, m

In Figure 4.9 the different velocity limits as a function of obstacle height are depicted for a bogie with 1.330 m tyres. The used maximum vertical limits are
Momentary, a=5.60 m/s², duration 1 min
Tolerance, a=2.12 m/s², duration 4 h
Efficiency, a=1.06 m/s², duration 4 h
Comfort, a=0.36 m/s², duration 24 h

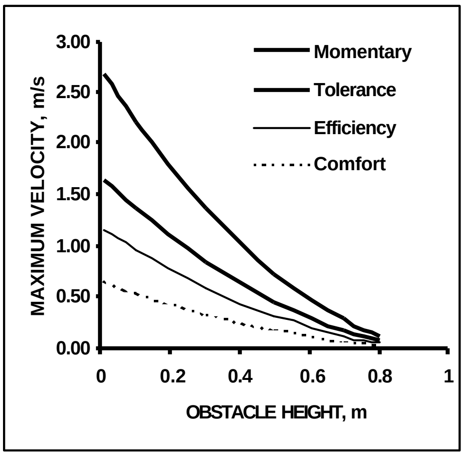


Figure 4.9 Constraint velocity as a function of obstacle height for a bogie with d=1.330 m wheels

4.2.6.3 Constraint limit set by winding

For more detailed routing, the maximum attainable velocity must be in harmony with the spatial limits of the corridor. It is evident, that a higher velocity can be obtained on a clearcutting area. On very narrow winding corridors the steering becomes the limiting factor, and therefore some kind of empirical constraints can be set for very winding trails.

5. INTERPRETATION OF THE RESULTS

The assessment of a certain site as sensitive or less sensitive should be based on a comprehensive decision making process. In the simplest case one variable may be sufficient, but in most cases there is not any single criterion on which the decision can be based. The decision is rather a process to compare different alternatives and to find out the most appropriate machine/site matching cases.

The results obtained by the models using different terrain, soil and machine data input can be directly used in comparing two machines. Deeper rut depth or higher rolling resistance means that probably this tractor type is less suitable than the other tractor type having shallower ruts and lower rolling resistance. In other cases, high drawbar pull, net traction and gross traction indicate good mobility and better performance. In some cases orderly yardsticks are needed to help the decision making process.

There is not any one standardized classification for ecoefficiency, but the final decision stays with the user. Therefore, some tentative classifications for practical applications are given. They cannot be considered as targets or norms, but to help a less experienced user to compare the results of different calculations and to help him in weighing the different factors, such as mobility or soil damage in his decision making.

5.1 SOIL DAMAGE

The direct environmental effects of a vehicle pass can be classified as:

- Soil damage
    - Soil compaction
    - Rut formation
- Damage to the vegetation
    - Root damage to remaining trees, other tree damage
    - Other vegetation damage
- Pollution and other effects.

The problem is two-fold, the extent of the damage, and the ecological and economical consequences of the damage.

In the Northern hemisphere, especially when using wheeled forwarders, rutting is a more severe problem than soil compaction. Because this report is concentrated more on problems related to forwarders, rutting is the main criteria when selecting machinery, and the effects of soil compaction are only for some kind of general notice. One reason is that even though there are a large number of individual studies on different types of soil damage and their consequences, no comprehensive modelling has yet been generally accepted.

Soil damage is either permanent or recoverable. Most of the studies are carried out just after the traffic has passed, and therefore long-term effects are poorly known. Most of the soil damage is expected to be more or less permanent in the Northern hemisphere, but more permanent in tropical conditions due to climatic and edaphic factors.

5.1.1 Rut depth

In the recommendations for the Quality Survey of Logging Operations given ***by The Forestry Development Center Tapio*** (Finland), the definitions for a rut are formulated as[5]:

> *Rut depth*
>
> *As a rut is accounted a rut deeper than 100 mm measured from the soil surface. The soil surface level is the moss layer bottom.*
> The rut means over 100 mm deep and 0.5 m long depressions, which are not elastic (recovering by itself) but the surface layer is punch sheared.
>
> *The 0-point for the rut depth measurement is the nearest centreline point of the trail to the sample plot. From this 0-point a 15 m section is measured in both directions, and the rut depth is measured from these sections.*

Figure 5.1.Measuring of the rut depth

For rut depth, only two classes are used: acceptable/non acceptable. The limit is set at 0.1 m rut depth, which is based on the work quality assessment recommendations of Forestry Development Centre Tapio. For practical evaluation, the work quality is acceptable if the average rut depth does not exceed 0.1 m for more than 10% of the total length of the trails on a site. It is therefore possible to operate on sites with deeper than 0.1 m rut depth sites, but their occurrence must be low.

---

[5] Äijälä (2002)

Table 5.1 Rut depth classes

Rut depth class	Acceptable	Avoidable
Rut depth, m	<=0.10 m	>0.10 m

5.1.2 Soil compaction

The problems related to soil compaction have been largely studied both in agriculture and in forestry, and the references in literature are abundant. The problem can be divided into two approaches:

- Changes in soil density due to the machine passes
- Effect of soil density
    - Environmental consequences
    - Effects on productivity of the soil.

The soil compaction mechanism i.e. the movement of soil particles under a wheel load moving closer to each other causing the reduction in soil pore volume and increase in soil density, can be modelled using soil mechanics. Soil mechanical solutions on pressure distribution in soil under loading give a reliable picture on the extent and severity of the phenomenon, even though the forest soil is rather inhomogeneous, and wheel loads are dynamic.

5.1.3 Root damage

Root damage can be classified as damage to the existing root system of a living tree due to mechanical forces, and the reduction of root growth due to less favourable soil conditions after soil compaction.

5.1.3.1 Root damage in rutting

Figure 5.2. Root damage

Root damage in rutting consists mainly of the shear forces causing the root to break, or a significant part of the root bark to peel off exposing the root to fungal attack. Cutting off a part of the root system may reduce the growth rate of the tree, but generally the effects of decay due to the attack of fungi is considered as the main economically important consequence of root damage. Nilsson and Hyppel (1968) concluded that damage further than 0.7 to 0.9 m from the tree centre did not cause economically significant decaying. Isomäki & Kallio (1974) found that deformation of the roots less than 20 mm in diameter caused only discolouration of the trunk wood.

In the recommendations for the Quality Survey of Logging Operations given ***by The Forestry Development Center Tapio*** (Finland), the definition for root damage is formulated as:

> *Root damage*
>
> *A damage situated below the root collar. Only the damages situated within a 1 m circle from the centreline of the tree are accounted. However, the damages on the roots less than 20 mm in diameter are not counted.*

5.1.3.2 Soil compaction and root growth

Soil compaction

There is a certain dependence between tyre contact pressure and soil density after the wheel pass. Soil compaction depends on the flexibility, form and area of the loading surface, the loading force and on the soil properties. There are a large number of soil mechanical/soil compaction models, but the difficulty in their application is that the mechanical properties of forest soil are seldom known and the soil contact area is usually only an approximation. Therefore, no soil compaction model can be recommended as a normative tool for solving soil compaction problems at this stage. As an example of the tyre/soil density, Figure 5.3 is calculated based on Schwanghart's (1990) approach (see Appendix Report No. 8). A simple model for estimating the tyre inflation pressure and the resulting soil density is, Eq(5.1)

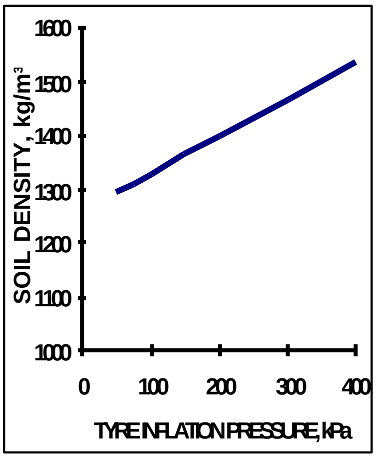


Figure 5.3 Soil density as a function of tyre inflation pressure.

$$g = 1165 + 2.1 \cdot p_c \qquad (5.1)$$

where:

γ soil density, kg/m^3
p_c tyre contact pressure, kPa

Root growth

It has been demonstrated in several studies, that the root growth or the crop yield decreases as a function of the increase in soil density. Because the growth also depends on soil properties other than density, separate models must be developed for different soil and climatic conditions, and no general model can be given. As an example, the dependence between the relative root growth and the soil density is depicted in Figure 5.4. Gooderham studied root growth in different soils and Russel (1997) studied different species on the same soil. They used soil penetration resistance

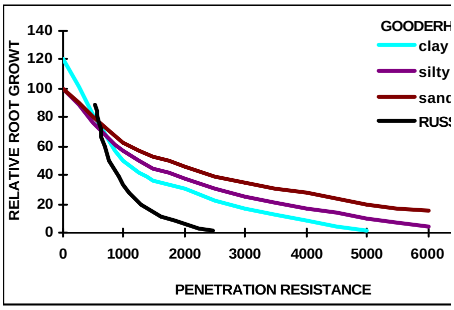


Figure 5.4 Relative root growth as a function of soil penetration resistance

as the indicator of soil density. It can be seen that the root growth is already low on soil densities bearing the forwarder wheel (CI > 600 kPa). This means that, more fertile sites where soil porosity is high, are more susceptible to soil compaction than higher bearing sites with higher soil density.

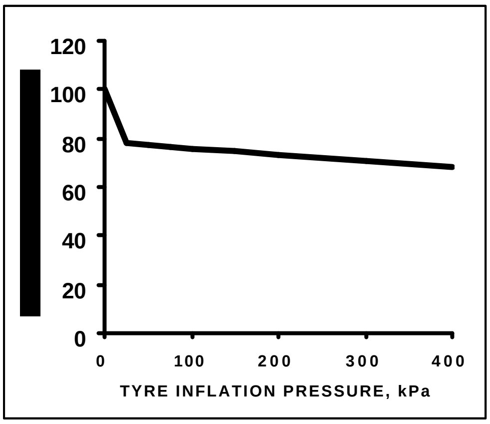


Figure 5.5 The influence of tyre inflation pressure on relative root growth

Tyre contact pressure is the governing factor in soil compaction of the upper layers. As the vertical stress in soil is generally halved at the depth equal to the width of the loading surface, the pressure bulb under wider tyres extends into deeper layers than narrower ones. Therefore the tyre width is the governing factor for the compaction of the deeper layers.

Calculations with varying tyre inflation pressures show that, the changes in tyre inflation pressure have only a minor effect on relative root growth, see Figure 5.5.

5.1.4 Erosion risks

It is generally known that erosion risks in level Nordic moraine soils are of less importance than on alluvial tropical soils, or in mountainous conditions. But a certain erosion risk evaluation must be included into the harvesting planning process. This means that, the planning officer must know the risk evaluation principles, and perform a risk evaluation on sites, where erosion risks are to be expected.

There is quite a large volume of literature available to support the development of erosion risk evaluation, generally developed for comparing different land use alternatives. In principle, the soil erosion risks increase:

- to about the second power of slope percent
- as a function of slope length
- as a function of soil erodibility factor, which generally depends on the fine particle content of the soil.
- share of bare soil surface
- rain energy, precipitation and time

This means that, erosion risk is high in mountainous conditions, under heavy rainfall, on fine grained soils if large patches of vegetation has been destroyed. Environmental risk analysis and recommendations for soil recovery operations after logging must be added into the work plan.

Even the adoption of the MUSLE[6]-method needs calibration and adaptive research studies (Tornero & Molano 2002) the use of the principles of the method eases decision-making. For example, it has been applied in evaluating the erosion in Italian Eucalyptus plantations (Callagari et al 2000).

5.2 Classification of the trafficability and mobility

5.2.1 Number of passes

One of the trafficability classifications is based on the number of passes possible in certain conditions. The **technical limit** go/no-go situation is 1 pass. In this case noticeable environmental damages are to be expected, as well as high operative costs due to excessive wear of machine components and high fuel consumption. Also generally the driving velocity is low and the permitted load is minimal, hence the productivity becomes low. Also, there is a high risk of total failure with expensive rescue costs. The operational efficiency improves as a function of the number of expected passes, and thus a 2 to 5-pass limit can be set as the lowest **economic trafficability limit** for timber transport. The conditions from an ecological point of view can be classified as good if 25 passes are possible, see Table 5.2.

Table 5.2 Environmental classification based on number of passes

Number of passes	Technical limit	Environmental acceptance
1-3	No-go	Not acceptable
3-5		Not acceptable
6-10	Economical	tolerable
11-25		good
25-	Environmental	excellent

---

[6] Modified Universal Soil Loss Equation

5.2.2 Rolling resistance

Rolling resistance increases as an inverse function of soil bearing capacity, and high rolling resistance indicates poor terrain trafficability and tractor mobility. The limit for good and fair conditions can be set at 0.2.

Table 5.3 Mobility classes based on rolling resistance coefficient

Mobility and trafficability class	Rolling resistance coefficient
Good	<0.20
Fair	0.20 to 0.30
Poor	>0.30

5.2.3 Pull coefficient

Net pull force (drawbar pull) indicates the force the wheel or the tractor can generate over the main forces resisting to movement, consisting of rolling resistance, obstacle and steering resistance and slope resistance. In skidding it is essential for dragging the logs, in forwarding it is a reserve, which can be used for acceleration and overcoming some minor local changes in resistance to movement, either due to lowering in bearing capacity or changes in surface profile.

For decision-making, recommendations can be given concerning the net pull and net pull coefficient. Too low a pull coefficient indicates that, the tyre is working close to its limits, and obviously it must increase the slip in order to generate more pull for overcoming some extra resistance. The following table (Table 5.4), is presented as a first attempt to use the pull coefficient as a variable for mobility and trafficability classification in order to screen out sensitive site and tractor combinations.

Table 5.4. Mobility classes based on net pull coefficient

Mobility and trafficability class	Pull coefficient
Good	>0.25
Fair	0.15 to 0.25
Poor	<0.15

The indicative class limits for rut depth (<0.1 m), rolling resistance coefficient (<0.2) and pull coefficient (>0.25) are compared with each other in Figure 5.6, where the wheel performance is calculated for different Cone Index values for a loaded forwarder wheel. All the three limits are situated around 500 kPa, which becomes the limiting value for sensitive sites.

It seems, that generally, the rut depth (0.1 m) becomes the first limit, especially for multipass operations.

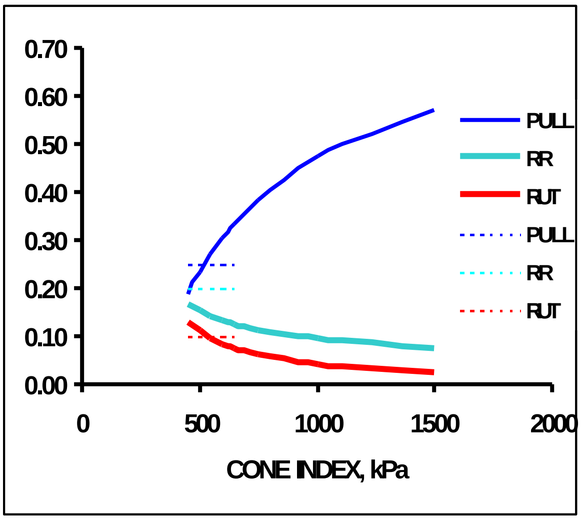


Figure 5.6 Rut depth, rolling resistance and pull coefficients plotted against Cone Index. Class limits given with plotted lines

5.2.4 Traction

The available traction must exceed the total resisting force, e.g. the net traction must be positive. But the traction needed to overcome the resisting forces must also be in harmony with the:

- available torque, and
- tyre or track characteristics

Part of the tyre characteristics e.g. deflection are included in the thrust model. It is important to also compare the required forces (resisting forces) with the tyre characteristics such as maximum load.

5.2.5 Slip

Wheel slippage is not avoidable, because the traction is generated from the shear stress of the soil. Generally, the highest traction efficiency is attained at 0.15 to 0.2 slippage; and this level can be considered as good (see Figure 5.6). When the slip ratio passes over 0.4 the share of effective energy begins to

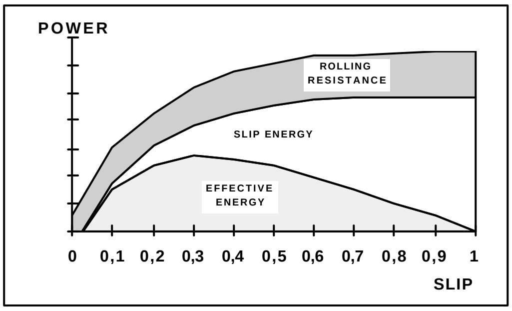


Figure 5.7 Power distribution as a function of slip

decline fast, and this level can be considered as a limiting value from an environmental point of view.

The total energy transferred into the soil increases as a function of increasing slippage, causing greater soil damage without significantly increasing the traction. Therefore, the use of chains or tracks is recommended in soil conditions where, the soil surface layer is weak or slippery, and the tyre lugs are insufficient to generate adequate grip.

For estimating the mobility and trafficability the following values (see Table 5.5) can be given as a guideline. It should be noted that, many programs are based on a fixed 0.2 slip ratio.

Table 5.5. Mobility classes based on slip

Mobility and trafficability class	Slip
Good	<0.20
Fair	0.2 to 0.4
Poor	>0.4

5.3 Ground pressure

As seen from Appendix Report[7] No. 5 there is no universally adopted method for estimating the ground pressure at the tyre/soil interface. In fact, the contact pressure in different parts of the contact area varies. For lower loads it is higher at the centre than close to sides, and higher under the lugs than under the tread, but for certain conditions under high loads the peak stress may develop under the side walls (Burt *et al* 1987). An average ground pressure is, however, an operational variable for assessing the machine/soil matching.

5.3.1 Nominal ground pressure

Nominal ground pressure (NGP) is widely used as a mobility variable, although it has the disadvantage of neglecting the influence of tyre deformation. It has the advantage of being a simple numeric, which is easy to assess. In Figure 5.8 the NGP for an 8-wheeled, 12 t forwarder, fitted with 0.700 or 0.600 m wide tyres is depicted.

---

[7] Modelling of the wheel and soil. 1. Tyre and soil contact

The nominal ground pressure is a minimum tyre ground pressure that the tyre might develop in very soft conditions. It can be used to compare different tractors using roughly the same tyre configuration and inflation pressure. It leads to erroneous decisions when comparing special, low pressure tyres with normal, high pressure tyres. It also overestimates the positive influence of adding to the tyre width. Another deficiency is that it is independent of soil properties.

NOTE: ***The NGP formula for tracked vehicles does not apply for tandem axles fitted with flexible tracks, and therefore it is not recommended for use.***

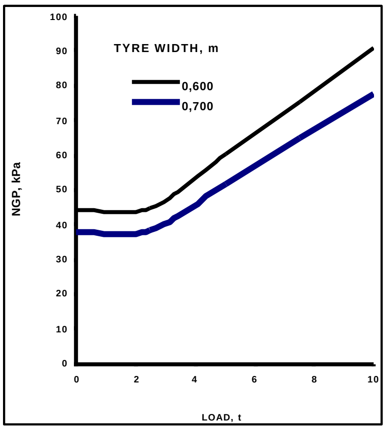


Figure 5.8 Nominal ground pressure of a 12t forwarder as a function of load size

The environmental damage is related to the wheel/soil interaction, and high NGP is less destructive on good bearing soils than on sensitive sites. The correct application of NGP presumes certain information of the soil conditions, e.g. the recommended NGP value for normal moraine soils or for organic soils etc. Therefore, the use of the ratio NGP/some soil bearing capacity variable is more rational.

Olsen & Wästerlund (1989) recommend 35 to 50 kPa NGP as the highest allowable value for (Swedish) forestry. When taking into account the limits of using NGP, the following table (Table 5.6) for interpreting the NGP values can be given.

Table 5.6. Ecologically acceptable NGP values

NGP, kPa	Class	Reference value	Recommendations
17		Man with boots, static loading, Two feet	
35		Man with boots, dynamic loading, One foot	
35 to 50	Good	12 t forwarder with 5 t load	Olsen & Wästerlund's recommendation
50	Fair		
80		12 fully loaded (10 t) forwarder with 0.7 m tyres	
90		12 fully loaded (10 t) forwarder with 0.6 m tyres	

Wronsky & Humphreys (1994) give the following values for estimating the environmental risks:

- Immobilisation at first pass occurs when the soil strength (CI) is about 3 times the NGP
- Immobilisation at 50th pass occurs when the soil strength (CI) is about 5 times the NGP
- Single pass causing a rut depth less than 0.15 m, CI= 4.5 times NGP
- Single pass causing a rut depth less than 0.1 m, CI= 7.2 times NGP

Assuming a wheel load of 40 kN, wheel diameter of 1.333 m and tyre width 0.700 m, corresponding to 86 kN NGP, the following indicative values can be calculated, (Table 5.7). The limit for sensitive site is thus around 620 kPa penetration resistance.

Table 5.7. Minimum soil penetration resistance for forwarder transport calculated after Wronsky & Humphreys' recommendations (1994)

Limit	Ratio CI/NGP	Minimum penetration resistance, kPa
Technical mobility	3	260
0.15 m rut depth, tolerable	4.5	400
Economic mobility	5	450
0.1 m rut depth, acceptable	7.2	620

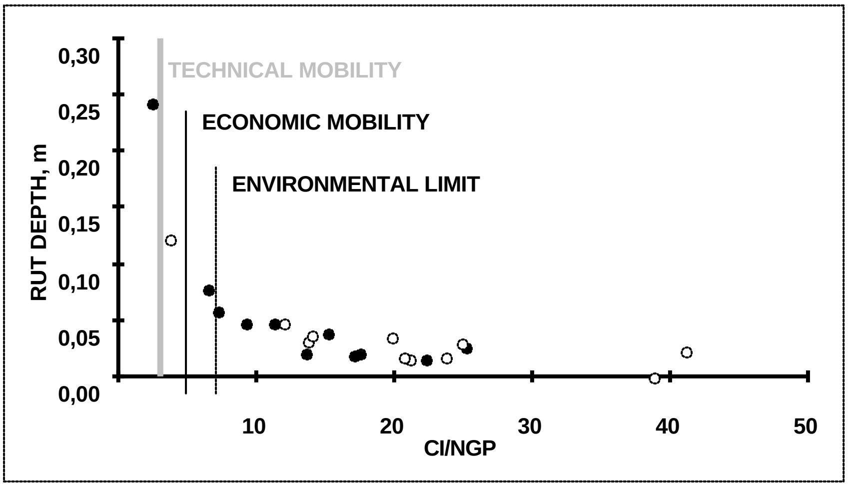


Figure 5.9. CI/NGP-ratio and Wronsky & Humphreys' (1994) limits fitted with Anttila's (1998) data

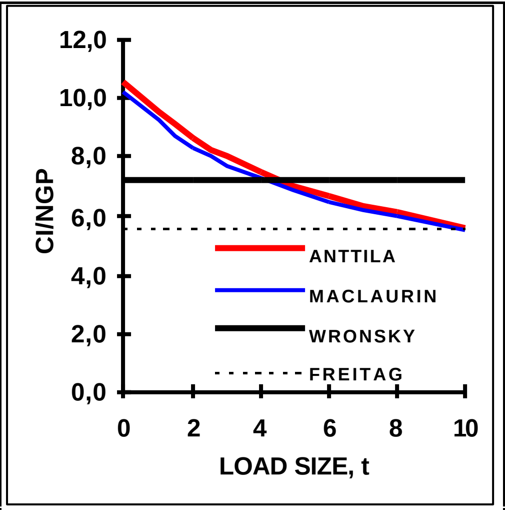


Figure 5.10. CI/NGP ratio using different rut depth models. Limiting rut depth is put to 0.1 m.

The Wronsky & Humphreys' limits seem applicable for fully loaded forwarders with rather high NPG-values, see Figure 5.9. If tested for lower NPG values, such as partially loaded forwarders, the recommended limits seem to be underestimated. In Figure 5.10, different rut depth models are compared. The reference vehicle is a 10 tonne forwarder with 0 to 10 tonne loads. Tyre dimensions are b=0.700 m and d=1.330 m. The rut depth for each load is set at 0.1 m, and the corresponding CI is calculated. The calculated CI/NGP ratio is presented in Figure 5.10. It can be seen that, Maclaurin's and Anttila's models are load dependent, due to the inclusion of the deflection into the model. Evidently a partially loaded forwarder has somewhat worse relative mobility, e.g. the low NPG does not indicate correctly the sensitiviness of the site for a partially loaded tractor. It has to be kept in mind, that true tyre deflection may differ from the value calculated based on deflection models, especially under lower loads.

Makkonen (1988) gives the following site matching NPG based on the experience of skidders in Canadian forestry, Table 5.8.

Table 5.8 Ground strength classification (Makkonen 1988)

Class	1. Very good	2. Good	3. Moderate	4. Poor	5. Very poor
Description	Very freely drained	Freely drained	Fresh	Most wet	Very wet
Nominal footprint pressure, kPa	>200	70 – 200	40 – 70	20 – 40	0-20

5.3.2 Tyre ground pressure models

None of the studied tyre ground pressure models seemed perfectly suitable for assessing the goodness of tyre for sensitive sites. It is recommended however, to adopt models, which include the tyre deflection because it leads to more environmentally acceptable selections. Because the WES-method forms the frame of reference for the study, the following ground pressure models may be appropriate for assessing the suitability of forwarders and processors for an ecological order:

Dwyer's (1984) "ground pressure index"

$$p \;=\; \frac{W}{b\cdot d}\cdot\sqrt{\frac{h}{\delta}}\cdot\left(1+\frac{b}{2\cdot d}\right) \tag{5.2}$$

A modification of Maclaurin's (1997) formula for Limiting Cone Index (Eq. 5.5) can be used as an estimate for the contact pressure for a forest tyre (Eq. 5.3) on hard surface, because it matches well with the empirical model developed by Ziesak & Matthies (2001) Eq. (5.4.). When neglecting the constant 1.85 the model can be considered as a type of "ground pressure index" comparable to Dwyer's model, Eq(5.3).

$$\mathrm{p} = \frac{\mathrm{W}}{\mathrm{b}^{0.8}\cdot \mathrm{d}^{0.8}\cdot d^{\,0.4}} \tag{5.3}$$

$$\begin{aligned} p_c = &-3947 + 0.000452\cdot\frac{W\cdot PR\cdot p_i}{b\cdot d} + 29.4\cdot\ln\left(\frac{W}{9.81}\right) - \frac{4239}{p_i} - 253.3\cdot d^2 - \frac{1149.5}{b} \\ &- 2911.8\cdot\ln(1000\cdot b) + 1807\cdot b\cdot d + \frac{1.295\cdot W}{b\cdot d} - 0.009\cdot W^2 - \frac{7117.3}{PR} - 440.6\cdot\ln(PR) \\ &+ \frac{1144.4}{h} + 3845\cdot\ln(h\cdot 1000) - \frac{2.26\cdot b}{1000}\cdot\left[\left(\frac{1000\cdot d}{2}\right)^2 - (500\cdot d - 1000\cdot h)^2\right] \end{aligned} \tag{5.4}$$

The ground pressure index for the average loaded forwarder tyre is 164 kPa, twice the NGP of 75 kPa. Soils having a "bearing capacity" less than 164 kPa, can thus be considered as "sensitive".

They represent some kind of an average pressure, "G" in Figure 5.11. The Limiting Cone Index, $\mathrm{p_{CI}}$, Eq(5.5), (see Chapter 3.10) and Ziesak & Matthies model can be considered as a mean maximum pressure index, "CI" in Figure 5.11.

$$\mathrm{p_{CI}} = \frac{1.85\cdot \mathrm{W}}{\mathrm{b}^{0.8}\cdot \mathrm{d}^{0.8}\cdot \delta^{0.4}} \tag{5.5}$$

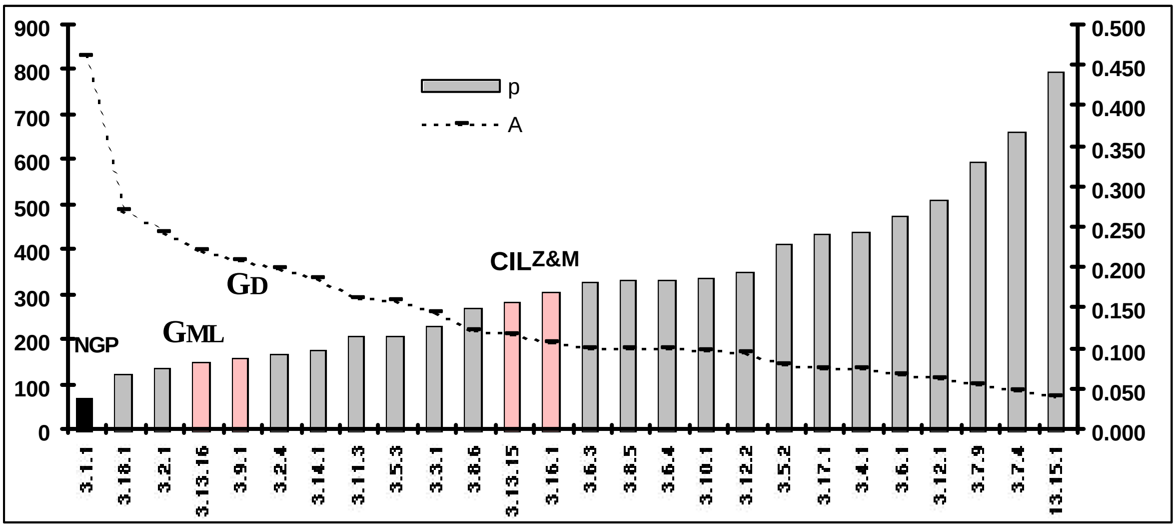


Figure 5.11 Tyre contact pressure (p) and contact area (A) calculated using different models. **NGP: nominal ground pressure, G_D: ground pressure index by Dwyer, GML, equivalent Maclaurins's ground pressure index CIL: limiting Cone Index by Maclaurin, Z&M: contact pressure by Ziesak & Matthies**

5.3.3 Mean maximum pressure, MMP

Larminie (1988) gives the following recommendations for MMP-site matching, Table 5.9.

Table 5.9. MMP required for satisfactory performance (Larminie 1988)

Condition	MMP levels for performance priority		
	Ideal	Satisfactory	Maximum acceptable
Temperate climate, fine-grain soils			
Articulated steering	150	200	300
Skid steering	120	160	240
Tropical, wet soils			
Articulated steering	90	140	240
Skid steering	72	112	192
European bogs	5	10	15
Muskeg	30	50	60
Over snow	10	25-30	40

As a rule, the penetration resistance must be about 85% of the MMP. (q=0.827·MMP). This limit is compared with the Anttila's (198) data in Figure 5.12.

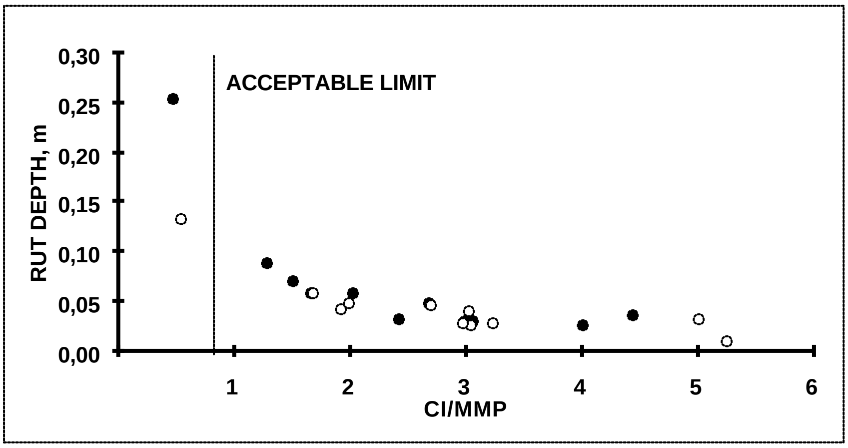


Figure 5.12. Larminie's (1988) recommended CI/MMP limit compared with Anttila's (1998) data

5.4 Soil properties

5.4.1 Cone index, penetration resistance

The following cone index recommendations for different types of vehicle pass, have been given by different authors, Table 5.10.

Table 5.10 Trafficability of silty soils after Murfitt *et al* (1975)

Penetration resistance [1], kPa	Bearing description
0 to 21	Approximately at the liquid limit. No practical bearing value
40 to 62	A man has difficulty walking on the soil without sinking
103 to 165	A special tracked vehicle (*Weasel*) can travel about 50 passes
186 to 228	D4 tractor can travel for about 50 passes
276 to 352	D7 tractor can travel for about 50 passes
372 to 497	Jeep can travel about 50 passes
517 to 662	Track mounted heavy bulldozers
683 to 935	Passenger cars
1034 plus	No trafficability problems

1) Remoulded soil conditions, for virgin soils about 20% higher

5.4.2 Limiting Cone Index

Based on the analysis of recent studies, Hetherington (2001) questions the use of MMP as a simple specification of trafficability. Particularly he notes, that quoting a limiting value for operations on sandy soils is not appropriate because of the fact that heavier vehicles often generate more drawbar pull on friction soils than light vehicles. Also, the physical meaning of MMP for a wheel is less clear than for tracked vehicles. It is evident, that MMP cannot be used as a norm, but still it can be used as a yardstick to help in decision making for screening out sensitive sites.

Instead of using MMP directly, Maclaurin (1997) introduces a new concept - limiting cone index CI_L. The Limiting Cone Index is the cone index of the weakest soil across which, a vehicle can make a single pass thus it is also the limit of technical mobility (go/no-go situation). He gives the following models (Eq. 5.5 and 5.6) for determining the limiting cone index:

$$CI_{Lwheel} = \frac{1.85 \cdot W_w}{2 \cdot n \cdot b^{0.8} \cdot d^{0.8} \cdot \delta^{0.4}} \qquad (5.5)$$

$$CI_{Ltrack} = \frac{1.63 \cdot W_w}{2 \cdot n \cdot b \cdot e \cdot p^{0.5} \cdot d^{0.5}} \qquad (5.6)$$

where

CI_{Lwheel}	limiting cone index for wheels
CI_{Ltrack}	limiting cone index for tracks
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

The CI_L-values are more suitable for cohesive soils than for friction soils, because of the different reactions of (dry) friction and (wet) cohesive soils under loading. Because sandy soils usually have better trafficability and are less problematic than cohesive soils, models can be used only generally to screen out sensitive sites.

5.4.3 Wheel numeric

Wheel numeric is a WES-method variable calculated using a special formula, which includes tyre and soil parameters. Different authors have proposed different empirical wheel numeric models for determining the best fitting combinations of tyre dimensions and deflection with observed tyre performance. The most common wheel numeric, N_{CI}, is selected as a reference (see Figure 5.10). Note, that Maclaurins's (1997) wheel numeric is of the same magnitude, but is simpler to calculate. Limiting values are as given in Table 5.11.

Table 5.11. Indicative N_{CI}-values for estimating tractor tyre performance.

Mobility class	N_{CI}
Good	> 3.0
Fair	1.5 – 3.0
Poor	< 1.5

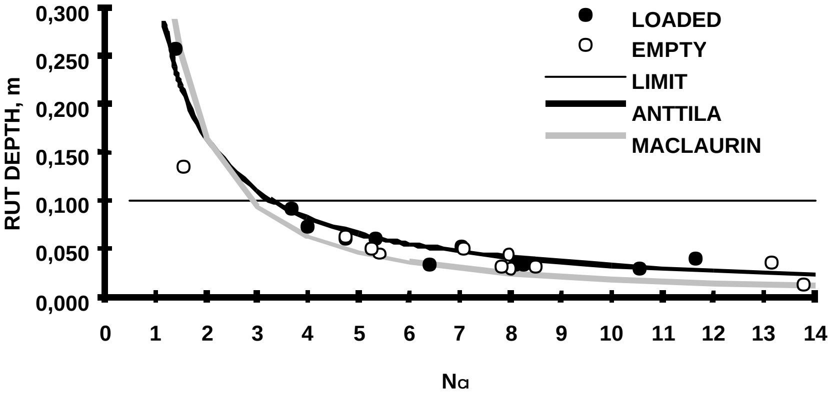


Figure 5.13. Rut depth as a function of N_{CI}

In Figure 5.14 the rolling resistance and pull classes are depicted as a function of NCI. There seems to exist a certain acceptable matching between the two classifications.

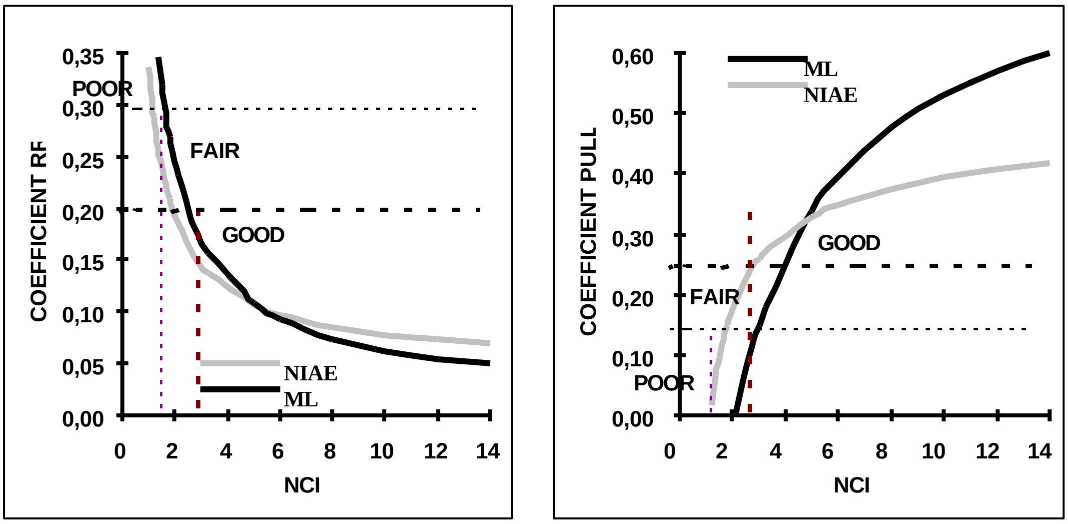


Figure 5.14. Rolling resistance and pull coefficient and the corresponding mobility classes as a function of wheel numeric N_{CI}, calculated using NIAE and Maclaurin models.

6. AVAILABLE PROGRAMS

6.1 PRO-FOR

A computer program 'PRO-FOR' developed by the Technical University of Munich (Ziesak & Matthies 2001) calculates the ground pressure using the model based on a series of tyre contact tests. The program also calculates the highest allowable soil moisture for the given soil type. The results seems to match quite well with the models, where Freitag's (1987) soil moisture equations are used for estimating the soil moisture at 500 kPa penetration, corresponding to 0.1 m rut depth as shown in Figure 6.1. It shows, that if the soil identification is correct and moisture is known, the models give accurate enough estimates, encouraging the continued development of modelling.

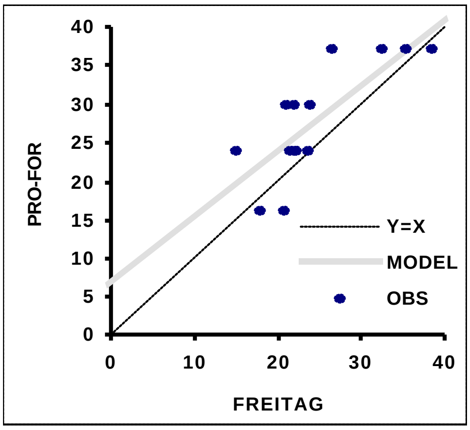


Figure 6.1 Comparison of the maximal soil moisture given by PRO-FOR program with Freitag's (1987) soil strength model

6.2 ECOMODEL

ECOMODEL is a Visual-Basic program which calculates the rut depth using tractor data and soil penetration resistance as input variables.

6.3 SELTRA

SELTRA is one of the development stage models, permitting the comparison of different WES-models in forwarding.

6.4 SIMPLETRACTOR

SIMPLETRACTOR is an EXEL-sheet for rapid evaluation of the productivity and costs of different machines. Also some appropriate technology, machinery and methods are included.

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Appendix 1. Bearing capacity of Finnish peatlands

Table 0.1 Permitted ground pressure on different peatland site types after Huikari *et al* (1963) and Saarilahti (1982)

Author	Huikari *et al* (1963)			Saarilahti (1982)		
Site subtype	Main site type			Main site type		
	Fen	Spruce swamp	Pine swamp	Fen	Spruce swamp	Pine swamp
	Permitted ground pressure, kN/m²					
Rich fen	15	15	20			
Herb rich	30	30	30			
Sedge	30	40	40			
Myrtillus		30			40	
Vaccinium		30				
Carex globules		40	40	24-26		26
Small sedge	25	30	30	22		
Eriophorum	25	30	30			30
Sphagnum	15		15	31		24
Rimpi bog	5		5	18		

Appendix 2. The Forest Act

THE FOREST ACT

Issued in Helsinki 12th December 1996

Chapter 2, Section 5

> *Felling and the measures to be performed in connection with it shall be implemented in such a way that the tree stand left to grow in the felling area is not damaged. Damage to the tree stand growing outside the felling area is also to be avoided when carrying out the felling operation and the measures associated with it. In addition, such* ***damage to the terrain that results in deterioration of the growing conditions*** *for the tree stand shall be avoided.*