TERRAIN MOBILITY MODEL AND DETERMINATION OF OPTIMAL OFF-ROAD ROUTE

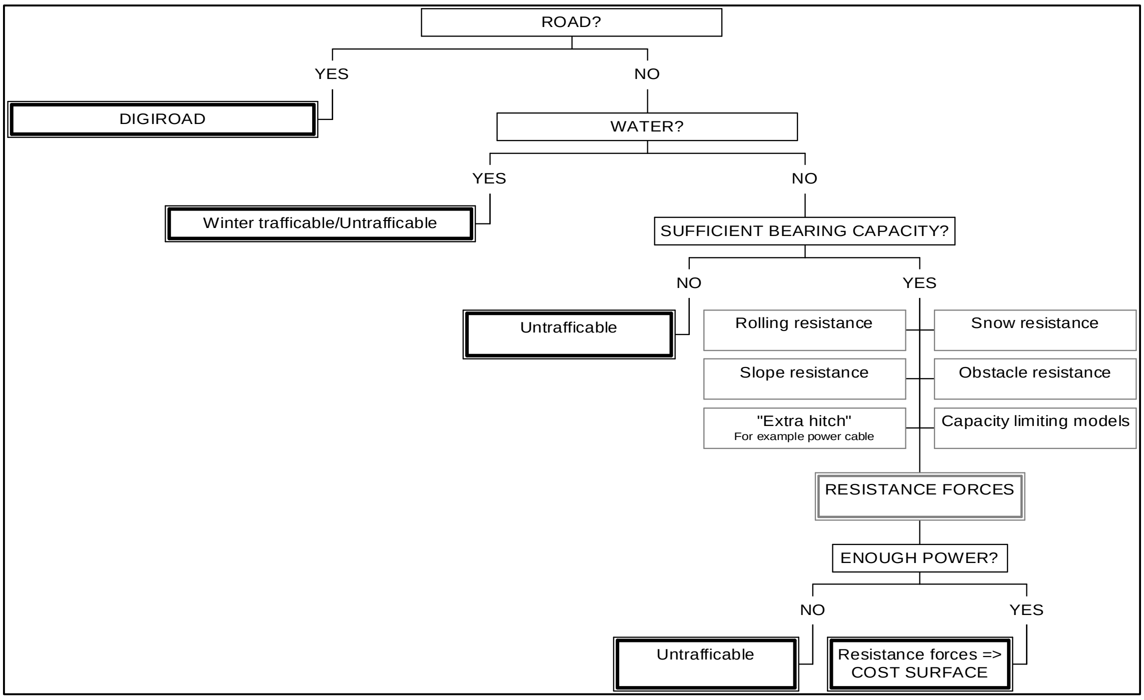
Antti Suvinen

Table of contents:

1 Introduction

Terrain mobility depends on the soil's capacity to resist forces put onto it by a rolling wheel or a moving track (Saarilahti, 2002b). In this paper, the study focus is on the interaction between wheeled forest tractors and soil. This interaction takes place through the wheel. Also, macro- and micro-topography, obstacles, vegetation, soil moisture, snow and frost have an effect on terrain mobility, routing and forest operations. These components can be managed using GIS-techniques. Especially when solving routing problems with GIS-techniques, the cost surface based approach is effective. Figure 1.1. presents the simplified structure of terrain's cost surface determination.

Figure 1.1. *A structure of terrain's cost surface determination.*



In this paper all components are described as objects. This is based on object-oriented programming. Also, chapters of this paper, which describe the main components of terrain mobility, are named as objects. Even if chapters of other components, like an engine or a tyre, are not separated into their own objects, they are managed like objects.

2 Machine object

Terrain mobility also depends in addition to properties of the terrain, on the machine's measures and weight, number of wheels and the wheel's properties. Understanding Machine object needs the following information:

- Type of machine (harvester, forwarder, skidder, etc.)
- Weight of the machine
- Volume/weight of the load
- Measures of the machine
- Power transmission
- Power of the engine
- Number of wheels
- Measures of the wheels
- Tyre's inflation pressure.

2.1 Properties of the machine and it's derivatives

2.1.1 Type of machine

In this paper, forest tractors are divided into two groups:

1) Load bearing tractors (for example forwarders)
2) Unloaded tractors (for example harvesters and excavators).

The mass of the load-bearing tractor depends on the size of the load, whereas, the mass of the second group of tractors is constant.

2.1.2 Weight distribution on wheels and wheel load

Anttila (1998) has given the following models to estimate the wheel load of the forest tractor's front and rear bogie:

$$W_f = \frac{0{,}6 * M_T * g}{n_W} \tag{2.1}$$

$$W_r = \frac{(0,4 * M_T + M_L + M_B) * g}{n_W} \qquad (2.2)$$

, in which:
W_f = wheel load of the front axle's wheels, kN
W_r = wheel load of the rear axle's wheels, kN
M_T = tractor's own mass, kg
M_L = mass of the load, kg
M_B = mass of the bogie
n_W = number of wheels of the axle.

Formulas 2.1 and 2.2 give the wheel load of each wheel. Depending on the calculated quantity we need results of formulas 2.3 and 2.4, maximum wheel load (W_{max}) or total load of the machine (W), which can be calculated using the following formulas:

$$W = (M_T + M_L + M_B) * g \qquad (2.3)$$

$$W_{max} = \textit{bigger value of } W_f \textit{ or } W_r. \qquad (2.4)$$

2.1.3 Measures of the tractor

In some rare cases (e.g. narrow underpasses) measures of the tractor can be the limiting factor for mobility. The Tractor's exterior measures, which are inputs for machine object are:

h = height, cm
l = length, cm
w = width, cm.

2.1.4 Properties of the wheel

The terrain mobility of the vehicle can be described with two elements, terrain and vehicle (Saarilahti, 1991). Interaction between these two elements takes place through the wheel or track. In this paper we focus especially on wheeled vehicles. Users of the system give the following three dimensions of each wheel:

b = breadth, m
d = diameter, m (r = radius = d/2), m
p_i = inflation pressure, kPa.

The tyre's deflection is the difference between an unloaded and loaded wheel (Saarilahti, 2002a). Deflection can be calculated using the following model:

$$\delta = \left(0{,}365 + \frac{170}{p_i}\right) * \frac{W_i}{1000} \tag{2.5}$$

, in which: δ = deflection, m
p_i = inflation pressure, kPa
W_i = wheel load, kN (Saarilahti 2002a).

Tyre contact pressure can be derived using Maclaurin's (1997) formula:

$$q = \frac{W_i}{B^{0,8} * d^{0,8} * \delta^{0,4}} \tag{2.6}$$

,in which: q = tyre contact pressure, kPa
W_i = wheel load, kN
d = diameter of the unloaded tyre, m
δ = deflection of the loaded wheel, m.

Rolling resistance of the pneumatic tyre is difficult to model. A common solution is based on the rigid wheel model using a larger hypothetical wheel radius:

$$R = \frac{z^2 + \left(\sqrt{r^2 - (r - z - \delta)^2} + \sqrt{r^2 - (r - \delta)^2}\right)^2}{2 * z} \tag{2.7}$$

, in which: R = radius of the hypothetical wheel, m
z = sinkage, m

r = radius of the real wheel, m

δ = deflection of the loaded wheel, m. (Saarilahti 2002a)

A simple model to estimate tyre contact area is, wheel load divided by tyre contact pressure or:

$$AREA = \frac{W}{q} = d^{0,8} * b^{0,8} * \delta^{0,4}. \qquad (2.8)$$

Tyre contact area divided by breadth of the tyre is tyre contact length or:

$$L = \frac{AREA}{b} = \frac{d^{0,8} * \delta^{0,4}}{b^{0,2}}. \qquad (2.9)$$

The previous tyre contact length formula is for square contact areas, but typically the tyre contact area is an ellipse or a circle. If we substitute tyre contact area (formula 2.8) into the formula of circle area, we find the radius of theoretical circle tyre contact area.

$$r_{theor} = \sqrt{\frac{AREA}{\pi}} = \sqrt{\frac{d^{0,8} * b^{0,8} * \delta^{0,4}}{\pi}}. \qquad (2.10)$$

2.1.5 Engine power and transmission

The power of the engine is often given with DIN-norm or SAE-norm. But this given engine power is not totally available for the mobility of the tractor, because of numerous accessories, (e.g. the alternator and hydraulic pumps mechanics transmission and hydraulics transmission). Normally a driver of the forest tractor can’t use the whole engine power capacity. Therefore, we can use the following coefficients to modify given engine powers to a usable form:

- DIN-norm: 0.55
- SAE-norm: 0.50. (Saarilahti 1991)

Dividing available net power of the engine by resistance forces of the tractor's mobility, we find the velocity of the tractor. If the calculated velocity is too low we find there is not enough available net power. Saarilahti (1991) has proposed the minimum theoretical velocity is about 0.1 - 0.05 m/s. In this paper we use 0.1 m/s as a minimum velocity. We can monitor the sufficiency of available net power by studying if the inequality 2.11 is true:

$$\frac{P_{net}}{F_T} \geq 0{,}1 \, {}^{m}\!/_{s} \tag{2.11}$$

, in which: P_{net} = available net power of the engine, kW
F_T = sum of resistance forces of tractor's mobility, kN.

If the inequality 2.11 is false, mobility of the tractor is impossible and the value of the cost surface is set as an infinite number.

3 Terrain object

Resistance forces of the forest tractor are often divided into five groups:

- slope resistance
- drawbar pull
- rolling resistance
- air resistance
- inertia resistance.

Drawbar pull is zero for forwarders and harvesters. When the velocity is constant, inertia resistance is zero. Air resistance becomes negligible at the low velocities attainable on the forest floor. In practice, only slope resistance and rolling resistance are significant. On the forest floor we have to also cater for obstacle resistance induced by the micro-topography of the terrain (Saarilahti, 1991).

There could also be reasons other than the tractor's net power capacity, why the mobility of the tractor is difficult or disadvantageous. For example sensitive environments, gardens or dangerous elements like power cables can hinder or make logging difficult.

In this chapter we go through the factors of terrain trafficability and theories of how to model these factors, based on free data of geographic information. In this paper factors, which have an effect on terrain trafficability are split into two categories:

- constant factors
- dynamic factors.

Constant factors are seasonally independent; whilst dynamic factors vary depending on seasonal elements like snow, ice or frost.

3.1 Constant factors of the terrain object

3.1.1 Slope resistance

Slope resistance is calculated using the inclined plane equation:

$$F_G = \mu_G * W \qquad (3.1)$$

, in which: F_G = slope resistance, kN
μ_G = slope resistance coefficient
W = wheel load, kN.

The slope resistance coefficient is calculated:

$$\mu_G = \mathrm{SIN}\alpha \qquad (3.2)$$

, in which: α = slope angle, °.

When driving downhill on a slope, slope resistance effects are in the same direction as the tractor's engine power. In other words slope resistance works like expulsive force. This applies only on gentle slopes. When the downward slope becomes steeper, the slope becomes a limiting factor to the tractor's mobility. Among other factors, this is a result of the increasing vibration. In this paper, expulsive force resulting from a downward slope is at its maximum when the slope angle is 5 degrees. The downward slope again becomes a resistance force when the slope is 10 degrees. In this paper, the slope resistance results of a downward slope steeper than 15 degrees is equivalent to an uphill slope, whose absolute value is 5 degrees less than the downward slope in question. In this paper the slope resistance coefficient at various slope angles is calculated as in table 3.1.

Table 3.1. The slope resistance coefficient at various slope angles. RF = Resistance force. EF = Expulsive force.

Slope angle, α	**Slope resistance coefficient, μ_G**	**Explanation**
$\alpha>0°$ (= uphill)	$\mu_G = \sin\alpha$	RF
$\alpha=0°$ (= flat)	$\mu_G = 0$	-
$0°>\alpha\geq-5°$ (= downhill)	$\mu_G = \sin\alpha$	EF
$-5°>\alpha>-15°$ (= downhill)	$\mu_G = -0{,}0174311\alpha - 0{,}174311$	EF ($\alpha > -10°$) RF ($\alpha < -10°$)
$\alpha\leq-15°$ (= downhill)	$\mu_G = \sin(\lvert\alpha\rvert -10°)$	RF

In this paper, a lateral inclination steeper than 8.5 degrees becomes a limiting factor. If this limiting value is passed, the cost surface is set as an infinite number. If lateral inclination is less than the limiting value, it has no influence on the cost surface.

3.1.2 Obstacle resistance

When a single wheel travels over an obstacle, the potential energy at the highest point is:

$$E_p = m * g * h \qquad (3.3)$$

, in which: E_p = 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 becomes zero. This is valid when monitoring a single wheel, but when a wheel of a multi-wheeled forest tractor passes over an obstacle, there is a loss of energy, which can be considered as obstacle resistance (Marklund, 1987).

Saarilahti (1997) has presented a model for the obstacle resistance coefficient:

$$\mu_O = \frac{k * \sum_{i=1}^{i} h_i}{d} \qquad (3.4)$$

, in which: μ_O = obstacle resistance coefficient

k = specific coefficient depending on the tractor's driveline configuration, energy loss factor

h = obstacle height, m

d = travel distance, m.

According Saarilahti's (1997) research, the coefficient (*k)* is between 10 and 30 percent. In this paper, the energy loss factor (*k)* is 30 percent or 0.3. If an obstacle is too high to drive over, or obstacle resistance becomes a limiting factor, the cost surface is set as an infinite number.

3.1.3 Forbidden elements or elements requiring special caution

There can also be elements other than large rocks or steep slopes, which inhibit the mobility of forest tractors e.g. water systems in summertime. Sensitive environments and cultivated fields are examples of elements, where mobility is technically possible, but should be forbidden. Mobility near power cables or similar objects, requires special caution from the driver of the forest tractor.

Elements similar to those in the previous paragraph are taken into account by multiplying the cost surface by a so-called ‘coefficient of disadvantage’. The coefficient of disadvantage value depends on how inconvenient the element is. So the value may vary between zero and an infinite number. Values can also vary depending on the time of day.

3.2 Dynamic factors of the terrain object

3.2.1 Snow resistance

Typically, forest tractors crowd out or compact snow and create thrust on soil (Saarilahti, 1991). Snow resistance depends on the thickness of the snow cover, and on the density of snow. The effects of snow cover on the mobility of forest tractors has been studied, e.g. by Silvennoinen and Haarlaa (1971), Ala-Ilomäki *et al* (1985) and Sirén (1988). Nuttal and McGowan (1962) have stated that the capacity of pneumatic wheeled tractors ends when the snow cover is 30 percent of the wheel’s diameter. According to Saarilahti (1991) a forest tractor with tyre chains can move when the snow cover is over 50 percent of the wheel’s diameter. In this paper, snow resistance is calculated depending on the user’s estimation of snow density:

Low snow density: $F_S = 35 * h$ (3.5)

High snow density: $F_S = 60 * h$ (3.6)

, in which: F_S = snow resistance, kN

h = thickness of the snow cover, m.

If the snow cover is over 30 percent of the wheel’s diameter, the program proposes the use of tyre chains. The value of the cost surface is set as an infinite number, if the thickness of the snow cover is over 50 percent of the wheel’s diameter.

3.2.2 Soil bearing capacity

3.2.2.1 Classification of soil types and shear strength

In terramechanics, different mineral soil types can be divided into two groups:

- frictional soils
- cohesive soils.

In terramechanics, peat lands are often equated with cohesive soils. The shear strength of soils follows the classical Coloumb's formula:

$$\tau = c + \sigma * \tan\varphi \qquad (3.7)$$

,in which: τ = shear strength, kN/m^2 (kPa)
c = soil cohesion, kN/m^2 (kPa)
σ = load, kN/m^2 (kPa)
φ = soil internal friction angle, °.

It can be seen, that in pure cohesive soils internal friction is zero and shear strength consists only of cohesion. That is:

$$\tau = c. \qquad (3.8)$$

In pure frictional soils, cohesion is zero and shear strength depends on soil internal friction angle and load. (Saarilahti 1991)

In table 3.2, soil cohesion or internal friction angle of different soil types is presented. The values of soil cohesion and internal friction angles are not constant but vary depending on soil moisture (Ahokas, 2002). In table 3.3 soil strength is estimated based on internal friction angle and soil cohesion.

Table 3.2. Soil internal friction angle and cohesion, according to different sources.

Source	Gardemeister et.al. 1968	Rantamäki et.al 1979	Helenelund 1974	Kuonen 1983
Soil type	**Internal friction angle (°)**			
Boulder bed	42	-	-	-
Gravel	34	32-35	-	-
Sand	32°	30-33	29-45	34-38
Fine Sand	30	-	-	-
Silt	-	27-30	-	33
	Cohesion (kPa)			
Clay	-	-	-	25
Clayey silt	-	-	-	20

Table 3.3. Soil strength estimation according to soil cohesion or internal friction angle.

Internal friction angle, ° (Chen 1999).	**Estimation**	**Shear strength (=cohesion), kN/m^2 (Korhonen et.al. 1974)**
< 30	Very loose	≤ 10
30 – 35	Loose	10 – 25
35 – 40	Compact	25 – 50
40 – 45	Dense	50 – 100
> 45	Very dense	> 100

3.2.2.2 Plasticity theory

Soil bearing capacity can be defined based on the plasticity theory (Saarilahti, 1991). The plasticity theory has been initially developed to estimate bearing capacity of footings. Geo-technically, bearing capacity means that contact pressure, which gives sufficient safety against crushing load and keeps the sinkage within acceptable limits (Rantamäki *et al,* 1979). In terramechanics, the plasticity theory has been especially developed by Karafiath and Nowatzki (1978) and Silversides and Sundberg (1989).

In this paper, the plasticity theory is chosen to estimate bearing capacity (not for example the WES-method), because the influence of frost on the bearing capacity in that case is quite easy to model. Even if the plasticity theory formula seems to be complicated, it is rather simple to use. Maybe the most important reason for using plasticity theory is that it needs only simple derivatives of the type of soil and strength parameters (Rantamäki *et al*, 1979).

In plasticity theory, the ultimate bearing capacity is calculated using three different bearing capacity factors, which depend on the soil internal friction angle:

$$p_m = c * N_C + \gamma_1 * z * N_q + 0{,}5 * B * \gamma_2 * N_\gamma \tag{3.9}$$

,in which: p_m = ultimate bearing capacity, kN/m^2
c = cohesion, kN/m^2
N_C, N_C, N_C = bearing capacity factors
γ_1 = unit weight of soil (above foundation), kN/m^3
γ_2 = unit weight of soil (below foundation), kN/m^3
z = depth of the foundation below ground, m (is equivalent to the sinkage of the tyre, but in this paper is set to be zero)
B = width of the footing (width of the wheel), m

Silversides and Sundberg (1989) have developed the previous formula to solve crushing load under the forest tractor's tyre:

$$W_{imax} = \pi * r^2 * (1{,}3 * c * N_C + 0{,}6 * \gamma * r * N_\gamma) \tag{3.10}$$

, in which: W_{imax} = safe wheel load, kg
r = radius of the circle equivalent to tyre contact area, m (See equation 2.10)
c = cohesion
N_C,N_γ = bearing capacity factors
γ = unit weight of soil, kN/m^3.

Compared to equation 3.9, the model of Silverside and Sundberg (1989) assumes the depth of the foundation or tyre's sinkage to be zero, so the second term of the equation 3.9 is eliminated. In this paper the plasticity theory is used as Silversides and Sundberg (1989) have presented.

For frictional soils, where cohesion is (almost) zero, the cohesive component of the formula 3.10 is eliminated. So the safe wheel load on frictional soils is calculated:

$$W_{imax} = \pi * r^2 * (0,6 * \gamma * r * N_{\gamma}). \qquad (3.11)$$

Bearing capacity factor (N_{γ}) depends on the soil internal friction angle. Based on nomograms of Balla (1962) N_y can be estimated with a third degree equation:

$$N_y = 0,0488\varphi^3 – 3,6055\varphi^2 + 90,9482\varphi - 760,7648. \qquad (3.12)$$

The equation is valid between 20 and 40 degrees, and the foundation is assumed to be on the ground. Unit weights of different soil types (γ) are presented in table 3.4.

Table 3.4. Unit weight of different soil types. Tons/m^3-values according to Gardemeister *et al,* (1968) and kN/m^3-values are found by multiplying previous values by gravity acceleration.

Soil type	**Unit weight of soil**	
	Tons/m^3	**kN/m^3**
Peat	1,0 - 1,1	9,8 – 10,8
Humus	1,1 - 1,5	10,8 – 14,7
Mud	1,1 - 1,4	10,8 – 14,7
Muddy clay	1,4 - 1,6	13,7 – 15,7
Muddy silt	1,4 - 1,7	13,7 – 16,7
Rich clay	1,4 - 1,7	13,7 – 16,7
Lean clay	1,6 - 1,9	15,7 – 18,6
Fine silt	1,7 - 2,0	16,7 – 19,6
Fine sandy silt	1,8 - 2,0	17,7 – 19,6
Fine sand	1,7 - 2,0	16,7 – 19,6
Sand	1,5 - 1,9	14,7 – 18,6
Gravel	1,6 - 2,0	15,7 – 19,6
Silty till	1,8 - 2,1	17,7 – 20,6
Find sandy till	1,9 - 2,2	18,6 – 21,6
Sandy till	1,8 - 2,2	17,7 – 21,6

When the soil internal friction angle is zero, as in cohesive soils, the bearing capacity factor N_γ, is also zero. That means the frictional component of the formula 3.10 is eliminated and the safe wheel load on cohesive soil is:

$$W_{imax} = \pi * r^2 * (1,3 * c * N_C) \qquad (3.13)$$

The bearing capacity factor for a rectangular plate (N_C) can be estimated with Skempton’s (1951) formula:

$$N_C = 5 * (1 + 0,2 * \frac{B^*}{L^*}) * (1 + 0,2 * \frac{d}{B^*}) \qquad (3.14)$$

, in which: B^* = shorter side of the foundation (tyre contact area), m

L^* = longer side of the foundation (tyre contact area), m
d = depth of the foundation below ground (is equivalent to the sinkage of tyre, but in this paper is set at zero), m.

Because the sinkage of the tyre is set at zero in this paper, the safe wheel load on cohesive soils is:

$$N_C = \pi * r^2 * \left(1{,}3 * c * \left(5 * \left(1 + 0{,}2 * \frac{B^*}{L^*}\right)\right)\right) \tag{3.15}$$

or

$$N_C = \pi * r^2 * \left(1{,}3 * \tau * \left(5 * \left(1 + 0{,}2 * \frac{B^*}{L^*}\right)\right)\right). \tag{3.16}$$

3.2.3 Rolling resistance

Rolling resistance is the horizontal force needed to compact soil. Rolling resistance is caused by transformation of soil and a wheel, and it can be calculated with the simple model:

$F_{Ri} = \mu_R * W_i$ (3.17)

, in which: F_{Ri} = rolling resistance of the single wheel, kN
μ_R = rolling resistance coefficient
W_i = wheel load of the single wheel, kN.

Rolling resistance of a pneumatic tyre is difficult to model. A common solution is based on a rigid wheel model using a larger hypothetical wheel radius or a virtual wheel (See equation 2.7). A pneumatic tyre's rolling resistance using the virtual wheel is:

$$\mu_R = 0.04 + \frac{z}{\sqrt{2 * R * z}} \tag{3.18}$$

, in which: μ_R = rolling resistance coefficient
z = sinkage, m
R = radius of the virtual wheel (See equation 2.7).

The constant 0.04 in equation 3.18 is the tyre internal rolling resistance.

In soil engineering, settlements of the structure found on soil are divided into four groups:

- initial settlement
- primary consolidation settlement
- settlements caused by plastic-elastic lateral transition of soil
- secondary settlement (Rantamäki *et al*, 1979).

The sinkage below the tyre of a forest tractor is the result of dynamic load. This load is temporary, so the sinkage below the forest tractor is near to the initial settlement. An average initial settlement of the rectangular plate is:

$$z = \frac{q * B}{E} \tag{3.19}$$

, in which: z = initial settlement (sinkage of the tyre), m
q = foundation pressure (tyre contact pressure), kPa (kN/m^2)
B = width of the footing (or tyre), m
E = Young's modulus of the soil, kN/m^2 (Janbu et.al. 1956).

In the previous formula we assumed that the load influences on the ground and the longer side of the plate, or the longer side of the tyre contact area is twice as long as a shorter one. Young's moduli of the different soil types are presented in table 3.5. We can solve the sinkage of the tyre and substitute the sinkage value into formula 3.18 and solve the rolling resistance coefficient and also the rolling resistance of single wheels. Total rolling resistance of the forest tractor is the sum of rolling resistances of single wheels:

$$F_R = \sum F_{Ri}. \qquad (3.20)$$

Table 3.5. Young's moduli of different soil types (Jumikis, 1973).

Soil type	**Young's modulus, kN/m^2**
Gravel	100 000 – 200 000
Sand	10 000 – 80 000
Compact clay	3 000 – 15 000
Loose clay	500 – 3 000
Peat	100 – 500

3.2.4 Soil moisture and bearing capacity

Soil moisture varies depending on the seasons and weather. Soil moisture, along with the soil type, significantly affects the soil bearing capacity and terrain mobility. In this paper, soil moisture is taken into account; modifying the shear strength of cohesive soils. Bearing capacity on frictional soils is rather constant regardless of soil moisture (Helenelund, 1966). The soil moisture's affects on rolling resistance can be taken into account modifying Young's modulus.

Bearing capacity of cohesive soil can be increased with the frictional component, if water content is below the liquid limit:

$$\tau = c + \sigma * \tan\theta \qquad (3.21)$$

, in which: c = cohesion, kN/m^2 (kPa)

σ = q = tyre contact pressure, kN/m^2 (kPa) (equation 2.6)

θ = angle depending on water content, ° (Helenelund 1966).

In this paper, angle (θ) is zero, when water content is the same as the liquid limit. When soil moisture is zero, angle θ is 30°. This quantity is assumed to be linear between the liquid limit and totally dry ground. Natural soil moisture and the liquid limit of different soil types are presented in table 3.6.

Table 3.6. Natural soil moisture (W) and the liquid limit (L_L) of different soil types (Korhonen and Helenelund 1964).

Soil type	**w, %**	**L_L, %**
Peat	500 – 1100	
Humus	40 – 95	
Mud	120 – 400	80 – 170
Muddy clay	55 – 130	70 – 135
Muddy silt	50 – 100	45 – 70
Rich clay	60 – 110	45 – 75
Lean clay	35 – 70	30 – 50
Silt	25 – 45	25 – 45
Fine sandy silt	20 – 40	25 - 45
Fine sand	15 – 30	
Sand	5 – 25	
Gravel	5 – 15	
Silty till	15 – 30	
Fine sandy till	10 – 15	
Sandy till	10 – 15	

3.2.5 Frost

3.2.5.1 Bearing capacity of frozen ground

The depth of frost varies largely with weather, depth of the snow cover, soil moisture and vegetation. The deepest frost penetration exists in rough-grained soils. (Hartikainen, 1978)

For example a frozen gravel road could bear a 5-10 times bigger load than an unfrozen one (Sotilasgeologia I). In this paper, bearing capacity of frozen ground is calculated with the formula, which Onninen (1992) has developed to estimate bearing capacity and mobility of frozen peat lands. This formula is based on the plasticity theory, and in this paper it is also applied to mineral soils.

Onninen (1992) states that frost works like a pressure spreading plate, which spreads pressure onto the surface of unfrozen soil. So the pressure affects a wider area than the tyre contact area on the ground. Therefore, in this paper we add a constant (K) into equation 3.10:

$$K = \frac{B^{*\prime} * L^{*\prime}}{B^{*} * L^{*}}. \tag{3.22}$$

Also, the constant (N_C) (See Skempton's formula equation 3.14), is different from an unfrozen ground situation:

$$N_C = 5 * (1 + 0{,}2 * \frac{B^{*\prime}}{L^{*\prime}}) * (1 + 0{,}2 * \frac{d}{B^{*\prime}}). \tag{3.23}$$

The variables in equation 3.22 and 3.23 are:

B^* = shorter side of the tyre contact area
L^* = longer side of the tyre contact area
$B^{*\prime}$ = shorter side of the pressure contact area on the surface of unfrozen soil (=B^* + 2 * d * tanβ)
$L^{*\prime}$ = longer side of the pressure contact area on the surface of unfrozen soil (=L^* + 2 * d * tanβ)
d = frost penetration depth, m
β = pressure spreading angle in soil, °.

Onninen (1992) has empirically found that a tangent of β in frozen peat is about 0.9. In this paper we use the same value on peat lands, but in mineral soils we use a tangent of β is 1.

3.2.5.2 Rolling resistance on frozen ground

On frozen ground, rolling resistance is usually noticeably less than on unfrozen ground. That is especially true on soft ground. In this paper, on every frozen soil type, rolling resistance is set to be 0.02. Because tyre internal rolling resistance is 0.04, total rolling resistance on frozen ground is 0.06.

3.2.6 Bearing capacity of ice and rolling resistance on ice

The bearing capacity of ice depends on depth and strength of the ice, and the spreading of the load on the surface of the ice. Ice can be categorised as blue ice and snow ice. The effective depth of ice is the depth of blue ice and half of the depth of snow ice. In table 3.7 the maximum weight of the vehicle on different depths of effective ice is shown. (Puutavaran veteen- ja jäälleajo, 1991)

Table 3.7. Maximum weight of a vehicle on different depths of effective ice (Puutavaran veteen- ja jäälleajo 1991).

Effective ice depth, cm	**Maximum weight of a vehicle, tons**
20	2,0
25	3,0
30	4,5
40	7,0
50	12,0
60	17,0
70	23,0
80	31,0
90	39,0
100	48,0
105	60,0

With rising temperature above 0 °C, the bearing capacity of ice decreases rapidly. Decreasing of bearing capacity depends on temperature before the thaw period, thickness of ice and thickness of the snow cover above the ice. The maximum weight of the vehicle is decreased 5 tons per every day that the average temperature is more than 0 °C. If the thickness of ice is more than 105 centimetres then, there is one day allowed per every 10 centimetres over 105 centimetres when the temperature can be 0°C – +4°C and maximum weight of the vehicle is not decreased. When the temperature is over +4°C haulage on ice must stop immediately. (Puutavaran veteen- ja jäälleajo 1991)

Rolling resistance on ice is about the same as rolling resistance on a paved road. In this paper, the rolling resistance coefficient on ice is set to at 0.015, and this coefficient is constant regardless of wheel parameters.

4 Tree stand object

Tree stand information is obtained from SLICES-data, which contains for example, information about tree diameter classes, species and sites. This information is used by the system’s routing engine, which could take into account for example, in which areas the haulage is centred.

5 Road object

Road information is obtained from DIGIROAD-data, which is produced by the Finish National Road Administration. This data contains information about the road network and it’s topology and conditions.

6. Weather object

6.1 Frost

Variation of soil temperature depends on the variation of air temperature and the energy balance of soil (Saarelainen, 1986). In Finland, the freezing and thawing of soil are annual phenomenon (Saarelainen, 1986). Frost always means a better bearing capacity (Helenelund, 1966). Thawing takes place both on the surface of the ground and the interface of frozen and unfrozen soil. But thawing in the latter so sluggish, that it has no practical implication (Soveri and Kauranne, 1969). Frost below the thawing soil layer prevents thawed water flowing into deeper soil layers (Soveri and Kauranne, 1969). This leads to over-saturation of the surface soil layer (Soveri and Kauranne, 1969). Also snow-melt often increases the soil water content. Disturbance of over-saturated ground causes a loss of soil bearing capacity, and at worst the surface layer might sludge (Kauranne ym, 1972).

The stronger the adhesion between pore water and soil particles, the worse the pore water freezes (Aittomäki, 1986). Even in frozen ground, a part of the water is in the liquid form, and there are also dissolved ions and organic compounds

(Kujala, 1986). Loading causes thawing of the frozen ground, but this depends significantly on load time (Tsytovich, 1973). If load time is very short, the frost has no time to thaw at all (Kujala, 1986).

There are several formulas to calculate and estimate the frost penetration depth. Maybe the simplest one is Stefani's formula, which was originally developed to estimate the depth of ice:

$$z = k\sqrt{F} \tag{6.1}$$

, in which:
z = the frost penetration depth, cm
k = coefficient, which depends on soil type
F = cold content, °Ch. (Saarelainen 1986)

The cold content is the sum of the average day temperatures of the sub-zero period, multiplied by the length of the sub-zero period. The unit of the sub-zero period's length is hours, and the cold content is always a positive value. The coefficient (*k)* depends on soil type. (Onninen, 1995)

In table 6.1 values of the coefficient *k*, are presented depending on soil type. These values in the table are from Soveri and Johansson (1966). They have also stated, that freezing of rough-grained soil types depends only a little on soil moisture. But the finer the soil type, the more significant the moisture of the ground's surface layer is for freezing.

Table 6.1. Values of the coefficient, *k* (Stefani's formula) depending on soil type. (Soveri and Johansson 1966).

Soil type	**Coefficient, *k***
Gravel and sand	1,159
Gravelly and sandy till	1,146
Fine sandy and silty till	0,986
Fine sand	0,921
Clay	0,906-0,828

Equation 6.1 is valid on uncovered ground. Porous snow is a good insulator and reduces the formation of frost (Knutsson, 1984). Effects of snow can be taken into account by reducing cold content with a coefficient, which is a function of the snow depth (Knutsson, 1984). In table 6.2 these coefficients depending on the depth of snow are shown. Multiplying normal cold content by this coefficient provides the modified cold content:

$$F_{mod} = a * F. \tag{6.2}$$

Table 6.2. Coefficient (*a)* presented as a function of the depth of snow (Frost i Jord, 1976).

Depth of snow, cm	**Coefficient, *a.***
10	0,90
20	0,60
30	0,40
40	0,20
50	0,15
60	0,10
> 70	0,05

During the winter, frost penetrates deeper into the ground, and the depth of frost is at it’s deepest when the cold content has reached it’s maximum. This happens when average day temperature goes up to over 0 °C. Then thawing also begins, which takes about 48 days in Finland, depending on annual and geographical variation. The time of bad roads continues a bit longer than that, because the absorption of thawed water takes longer the worse water penetrates ground, and the rainier the spring is. In the years 1958-1964 traffic restrictions existed for an average of six days after the whole frost had been thawed. (Soveri and Varjo, 1977)

Stefani's modulus can also be used to estimate thawing. Then we estimate only the thawing on the surface ground layer, and thawing from below the frost layer is ignored. The depth of thawing is calculated with the formula:

$$d = 1{,}1\sqrt{F} \tag{6.3}$$

, in which: d = depth of thawing, cm
F = hours, when degrees are above zero, °Ch. (Luoma, 1986)

7 Cost surface of terrain

7.1 Cost distance

Cost distance in the GIS-package is calculated with the following formula:

Cost distance = Surface distance * Vertical factor * ((Friction(a) * Horizontal factor(a) + Friction(b) * Horizontal factor(b))/2).

In which:

Vertical factor = slope resistance, kN
Horizontal factor(a) = lateral inclination, go/no-go -situation
Horizontal factor(b) = sum of resistance forces, which affect on horizontal direction and are not depending on moving direction, kN.

The vertical factor and Horizontal factor (a) depend on moving direction. So they vary even inside one grid. Horizontal factor (b) is constant inside a grid and in this paper it consist of the following resistance forces:

- obstacle resistance, kN
- snow resistance, kN
- rolling resistance, kN
- "coefficient of disadvantage" (See chapter 3.13).

Horizontal factor (b) is the sum of previous forces, divided by the theoretical minimum horizontal resistance (in this paper it is equals to rolling resistance on a paved road). If soil or ice bearing capacity is exceeded, Horizontal factor (b) is set to as an infinite number. Horizontal factor (b) varies depending on the seasons and weather objects.

7.2 Example grids cost distance calculation

The terrain cost surface model has been implemented as a complete calculation procedure for validation of parameters. The sensitivity of parameters of the submodels will be presented in table form. Final cost grid examples will be calculated in sample areas.

REFERENCES:

Ahokas, J. 2002. Maamekaniikka. Maa- ja kotitalousteknologian julkaisuja 8.

Aittomäki, A. 1986. Maan jäätymisen ja sulamisen termofysiikka. Teoksessa: Routa maa- ja pohjarakentamisessa. Suomen rakennusinsinöörien liitto. RIL K66-1986.

Ala-Ilomäki, J., Högnäs, T. & Sirén, M. 1985. Lumen vaikutus metsätraktorin liikkuvuuteen. Metsähallitus koeselostus. 4.12.1985.

Anttila, T. 1998. Metsämaan raiteistumisen ennustaminen WES-menetelmää käyttäen. University of Helsinki, Department of forest resource management. Publications 17.

Balla, A. 1962. Bearing capacity of foundations. Journal of the Soil Mechanics and Foundations Division. Vol. 88, No. 5.

Chen, F. H. 1999. Soil engineering: testing, design and remediation.

Frost I Jord. 1976. Norges Teknisk-Naturvitenskaplige Forskningsråd. Nr. 17. Oslo.

Gardemeister, R., Korhonen, K-H. & Arhippainen, E. 1968. Geotekniikka. Teoksessa: Maa- ja vesirakennus. p. 81-144. RIL 67. Suomen Rakennusinsinöörien Liitto.

Hartikainen, O-P. 1978. Maanrakennustekniikka. 6. edition 1995. Otatieto Oy.

Helenelund, K. V. 1966. Kitkamaalajien kantavuusominaisuuksista. Valtion teknillinen tutkimuslaitos. Tiedotus 3:97.

Helenelund, K. V. 1974. Maanrakennusmekaniikka. Teknillisen korkeakoulun ylioppilaskunta, TKY 137.

Janbu, N., Bjerrum, L. & Kjärnsli, B. 1956. Veiledning ved lösning av fundamenteringsoppgaver. Norges geotekniska Institut, publikasjon 16.

Jumikis, A.R. 1973. Settlement tables for centrically loaded, rigid circular footings on multilayered soil systems. New Brunswick. New Jersey. College of Engineering. Engineering Research Bulletin 54.

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

Kauranne, L.K., Gardemeister, R., Korpela, K. & Mälkki, E. 1972. Rakennusgeologia II. Otakustantamo.

Knutsson, S. 1984. Tjäle och frost. Teoksessa: Handboken Bygg. Geoteknik. Stockholm. p 526-537.

Korhonen, K-H. & Helenelund, K.V. 1964. Geotekniikka ja pohjarakennus. Valtion teknillinen tutkimuslaitos. Tiedotus 3:78.

Korhonen, K.-H., Gardemeister, R. & Tammirinne, M. 1974. Geotekninen maaluokitus. Valtion teknillinen tutkimuskeskus. Geotekniikan laboratorio, tiedonanto 14.

Kujala, K. 1986. Jäätyneen maan mekaaniset ominaisuudet ja jäätyneen maan käsittely rakentamisessa. In: Routa ja pakkanen rakentamisessa. INSKO. Julkaisu 21-86.

Kuonen, V. 1983. Wald und Guterstrassen. Pfaffhausen, Switzerland.

Luoma, R. 1986. Roudan sulatus ja rikkomismenetelmät. In: Routa ja pakkanen rakentamisessa. INSKO. Julkaisu 21-86.

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

Marklund, B. 1987. Torque distribution on wheeled vehicles affects damage on the forest ground. Proceedings of 9th ISTVS Conference, Barcelona, Spain 31st Aug. - 4th Sept. 1987, I. p. 347-354.

Nuttall, Jr. C. J. & McGowan, R.P. 1962. Scale models of vehicles in soils and snows. Proceedings of the 1st ISTVS Conference, Torino-Saint Vincent, 12-16 Giugno 1961: 656-677.

Onninen, H. 1992. Jäätyneen suon kulkukelpoisuus. Kulkukelpoisuuden arviointi. Helsinki, Maanpuolustuksen tieteellinen neuvottelukunta (MATINE), raporttisarja B 1992/3.

Onninen, H. 1995. Jäätyneen suon kulkukelpoisuus.Helsinki, Maanpuolustuksen tieteellinen neuvottelukunta (MATINE), raporttisarja A 1995/1.

Puutavaran veteen- ja jäälleajo. 1991. Metsäteho. Työsuojeluhallitus. Helsinki.

Rantamäki, M., Jääskeläinen, R. & Tammirinne, M. 1979. Geotekniikka. 11. edition, 1992. Otatieto Oy.

Saarelainen, S. 1986. Routivuusluokitus ja roudan syvyyden arviointi. In: Routa ja pakkanen rakentamisessa. INSKO. Julkaisu 21-86.

Saarilahti, M. 1991. Maastoliikkuvuuden perusteet. Metsäntutkimuslaitoksen tiedonantoja 390.

Saarilahti, M. 1997. Estevastus ja estetyö maastossa liikkuvien koneiden kulkumalleissa. In: Metsätieteen aikakausikirja - Folia Forestalia 1/1997. p. 73-84.

Saarilahti, M. 2002a. Modelling of the wheel and tyre. Helsinki. Not published.

Saarilahti, M. 2002b. Soil interaction model. Helsinki. Not published.

Silvennoinen, U. & Haarlaa, R. 1971. Metsätraktoreiden liikkuvuus lumessa. Silva Fennica 5(2): 145-167.

Silversides, C.R. & Sundberg, U. 1989. Operational efficiency in forestry. Vol 2. Practice. Kluver Academic Publishers, Dordrecht/Boston/London.

Sirén, M. 1988. Olika skogstransportfordons framkomlighet i snö. In: Vinterkunskap och vinterdata. Samarbetsorganisationen för fordon-markforskning, nummer 35:229-239.

Skempton, A. W. 1951. The bearing capacity of clays. Proceedings, Building Research Congress. Vol 1. London.

Sotilasgeologia I. 1997. Puolustusvoimien Koulutuksen Kehittämiskeskus.

Soveri, J. & Varjo, M. 1977. Roudan muodostumisesta ja esiintymisestä Suomessa vuosina 1955-1975. Vesientutkimuslaitoksen julkaisuja 20.

Soveri, U. & Johansson, J. 1966. Havaintoja lumesta raivatun maan routaantumisesta ja sulamisesta Suomessa vuosina 1958-1964. Valtion teknillisen tutkimuslaitoksen julkaisuja 107.

Soveri, U. & Kauranne, L.K. 1969. Suomen rakennusgeologia. Teknillisen Korkeakoulun Ylioppilaskunta. Moniste n:o 272.

Tsytovich, N.A. 1975. The mechanics of frozen ground. Washington, McGraw-Hill.