

# TERRAIN MOBILITY MODEL AND DETERMINATION OF OPTIMAL OFF-ROAD ROUTE

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## Abstract

The paper describes a concept for GIS based terrain mobility modelling and optimization of off-road route. The concept of generation of cost surface is based on machine, terrain, tree coverage, road and weather objects. Different cost surface alternatives can be generated according to changing information in objects. A regular costpath analysis is used to determine alternative routes in different conditions. It has been shown that adequate number of useful parameters can be found from national level digital maps for supporting off-road analysis.

## 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 is focused on the interaction between wheeled forest tractors and soil. This interaction takes place through the contact surface. 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 approach based on the cost surface is effective. Figure 1. presents the simplified structure of terrain's cost surface determination.

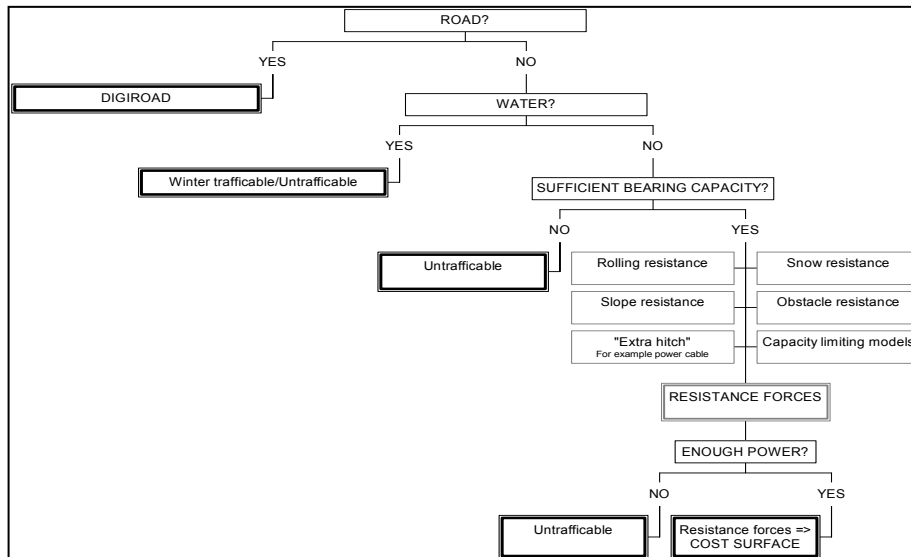


Figure 1. A structure of terrain's cost surface determination.

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 called 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 dimensions and mass, number of wheels and the driveline's properties. Understanding Machine object needs the information about 1) Type of machine (harvester, forwarder, skidder, etc.), 2) Mass of the machine, 3) Volume/mass of the load, 4) Dimensions of the machine, 5) Power transmission, 6) Engine power, 7) Number of wheels, 8) Dimensions of the wheels and 9) Tyre's inflation pressure. The forest tractors are divided into two groups: Load carriers (for example forwarders) and prime movers (for example harvesters and excavators). The total mass of the load carrier depends on the size of the load, whereas, the mass of the second group of tractors is constant. Weight distribution on wheels and wheel load can be estimated by models developed by Anttila (1998). The tractor's dimensions are used as inputs for machine object are height, length and width. 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. The tyre's deflection is the

difference between an unloaded and loaded wheel (Saarilahti, 2002a) and deflection can be calculated using the model presented by Saarilahti (2002a).

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 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.

### **3. Terrain object**

Resistance forces of the forest tractor are often divided into five groups: 1) slope resistance, 2) drawbar pull, 3) rolling resistance, 4) air resistance and 5) 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**

Slope resistance is calculated using the inclined plane equation. 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.

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). According to 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.

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**

Typically, forest tractors displace 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.

Soil bearing capacity can be estimated using classification of soil types and shear strength. In terramechanics, different mineral soil types can be divided into two groups:

- frictional soils
- cohesive soils.

The values of soil cohesion and internal friction angles are not constant but vary depending on soil moisture (Ahokas, 2002). 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.

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 (Rantamäki et al, 1979).

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.

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.

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. (Puutavaran veteen- ja jäälleajo, 1991)

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)

#### **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

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 (Tsytoich, 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 (Saarelainen 1986), which 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).

During the winter, frost penetrates deeper into the ground, and the depth of frost is at its deepest when the cold content has reached its 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)

## 7. Cost surface of terrain

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

$$\text{Cost distance} = \text{Surface distance} \cdot \text{Vertical factor} \cdot ((\text{Friction(a)} \cdot \text{Horizontal factor(a)} + \text{Friction(b)} \cdot \text{Horizontal factor(b)})/2).$$

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”.

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.

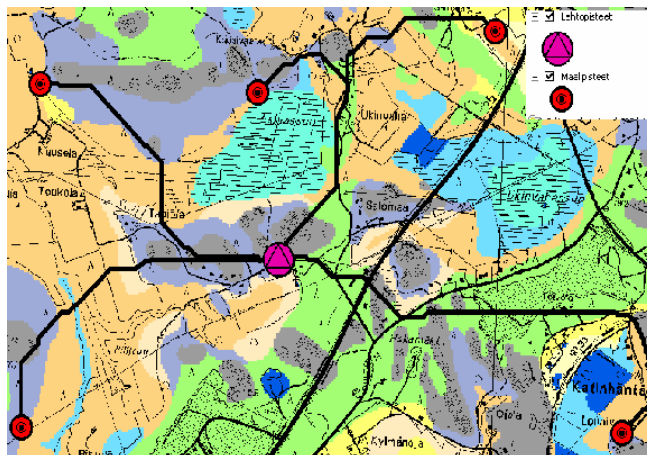


Figure 2. Optimal route to sample forest stands according to soil type map of Finland.

The terrain cost surface model has been implemented as a complete calculation procedure for validation of parameters. Final cost grid example was calculated in sample area (Figure 2). Thus, different cost surface alternatives can be generated according to changing information in objects. A regular costpath analysis can be used to determine alternative routes in different conditions. This has shown that useful parameters can be found for national level digital maps for supporting off-road analysis.

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