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AN OFF-ROAD ROUTING USING GIS-ANALYSIS

The paper describe concept for the GIS based terrain trafficability modelling and the optimization of an off-road route. The concept of the generation of the cost surface is based on machine, tyre, terrain and weather objects. Different cost surface alternatives can be generated according to changing information in objects. The analysis of soil bearing capacity is based on plasticity theory. A regular cost surface analysis was used to determine the optimal off-road route between two points. In addition, the five per cent corridor around the least-cost route was generated. It has been shown that useful parameters can be found for national level digital maps for supporting the off-road analysis.

Keywords: Off-road routing, vehicle mobility, terrain trafficability, GIS, cost surface analysis

Наук. співроб. Анті СУВІНЕН – Гельсінський ун-т, Фінляндія

Планування маршрутів руху лісових машин на базі ГІС-аналізу

Описано концепцію моделювання опорної прохідності лісових машин та оптимізацію маршрутів їх руху на базі ГІС-технологій. Оцінювання несучої здатності ґрунту базується на теорії пластичності. Для визначення оптимального маршруту лісової машини виконувався вартісний аналіз з використанням даних про лісову машину, її шини, місцевість та погодні умови. Крім того, навколо напрямку оптимального маршруту генерувався 5 %-ий коридор найменшої вартості використання лісо-

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вої машини. Дослідження доказало можливість планування оптимальних маршрутів руху лісових машин на національних цифрових картах.

Ключові слова: планування маршрутів руху в умовах бездоріжжя, мобільність транспортного засобу, опорна прохідність, ГІС, вартісний аналіз.

1. Introduction

Terrain trafficability means the ability of terrain to support the passage of vehicles (ISTVS Standards). Vehicle mobility in turn means the overall capability of a vehicle to move from place to place while retaining its ability to perform its primary mission (ISTVS Standards). Rounsevell (1993) uses the term tractability to cover trafficability, mobility and their interaction (and workability). Tractability is an important part of logging, as haulage in the forest is an aggregate form of off-road transportation (Saarilahti 1991). Harvesters also operate on the forest floor.

There are a lot of studies and articles in existence that deal with components related to tractability, but very few of them handle it as a comprehensive system which can be managed by computer techniques. Also, off-road routing for forestry purposes is in most cases not computerised, although existing digital maps and GPS systems could support such routing methods. Traditionally information on terrain tractability and elements affecting it can be gathered by field measurements, and information on all the components which have an effect on terrain tractability can be handled using GIS techniques. This can reduce the need for field measurements, but the technique also has its limitations. Not all terrain tractability models are usable for this purpose, as they have to be compatible with the available GIS data. On the other hand, there is little in the way of GIS data as such that can be used directly in these models, but relevant data sets can be modified by means of mathematical models.

In this paper I will first introduce used materials. In addition, uncertainty related on these data and some methods to management the uncertainty are introduced. Second I will demonstrate the terrain tractability model and sub models related to it. Also used GIS techniques are described. Finally, I will simulate the described model and GIS methods with routing example.

2. Methods and materials

2.1. Object model

The general structure of the model is based on an object model which uses the cost surface technique to describe actual conditions in the terrain. The cost surface technique is a form of raster GIS modelling, which is used to combine multiple criteria in space (Tomlin 1990). In accordance with the object-oriented programming approach, all the components of the terrain tractability model are described and named as objects. As seen in Figure 1, there are a few objects connected with the terrain and the vehicle which form the main components of the whole system. These objects all together create the intangible object called terrain tractability, which is concretized through the contact surface of the wheel. The bearing capacity of soil is determined using plasticity theory, based on research of Karafiath and Nowatzki (1978).

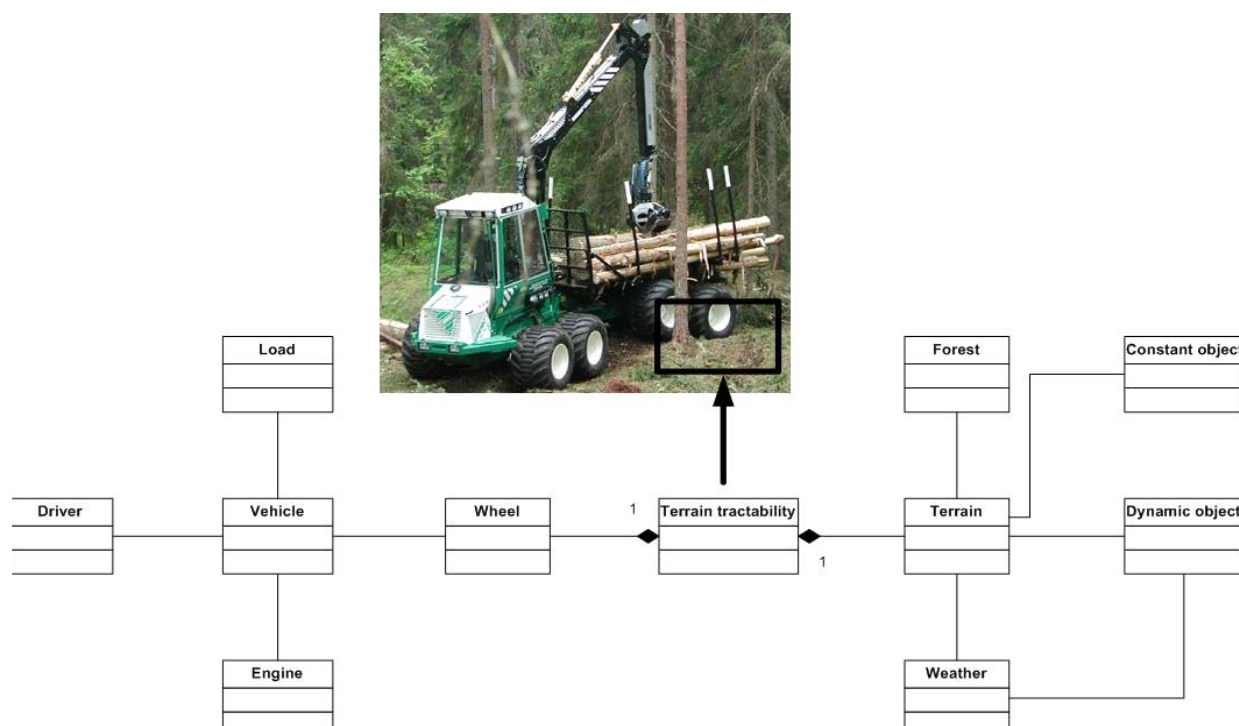


Figure 1. Simplified class diagram of terrain tractability

2.2. Vehicle, engine load and wheel objects

The machine object requires the information on 1) the type of machine (prime mover or load carrier – skidders are ignored here, as they are not relevant in Finland), 2) its weight, and 3) its dimensions. The load object applies only to vehicles which are categorized as load carriers. Wheel loads of different types of forest tractors' front and rear bogies can be estimated with models developed by Anttila (1998).

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) and mechanical and hydraulic transmission. Thus the driver of a forest tractor is not normally able to use the whole engine power capacity. We therefore use a coefficient 0.5 to the SAE norm and 0.55 for the DIN norm in order to obtain a realistic estimate for the usable engine power (Saarilahti 1991). Dividing the available net engine power by the resistance forces affecting the mobility of the tractor, we obtain its velocity. If the calculated velocity is too low, we find that there is not enough available net power. Saarilahti (1991) has proposed a theoretical minimum velocity of about 0.1-0.05 m/s. We use 0.1 m/s as a minimum velocity in this paper.

Interaction between the terrain and the vehicle takes place through the wheel or track. Attention is focused here especially on wheeled vehicles. The user of the terrain tractability modelling system must supply the following three dimensions for each wheel: width (b), unloaded diameter (d) (or radius, $r = d/2$) and inflation pressure (p_i). Based on these dimensions and values obtained from the machine and load objects, the system calculates several parameters:

- Tyre deflection (Saarilahti 2002a).
- Tyre contact pressure (Maclaurin 1997).
- Tyre contact area by dividing the wheel load by tyre contact pressure.
- Tyre contact length by dividing tyre contact area by the width of the tyre.

When calculating tyre contact length the contact area is applied to be rectangular, but the tyre contact area is typically an ellipse or a circle. If the estimated tyre contact area is substituted into the formula for a circular are, we obtain the radius of the theoretical, circular tyre contact area.

The vehicle, which is used in this simulation study, is assumed to be a forwarder with two axes on both the front and rear bogies. Its mass is 15 000 kg and the maximum load 14 000 kg. The peak engine power is 155 kW (with a DIN norm). All eight wheels have same dimensions:

- wheel width: 0.65 metre
- wheel diameter: 1.35 metre
- inflation pressure: 400 kPa.

2.3. Terrain object

The resistance forces applying to the 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, and when the velocity is constant, inertia resistance is zero. Air resistance becomes negligible at the low velocities attainable on the forest floor. Thus only slope resistance and rolling resistance are significant in practise, although we also have to cater for obstacle resistance induced by the micro-topography of the terrain and steering resistance. (Saarilahti 2002 b)

There may also be other constraints on the mobility of tractor. E.g. sensitive environments, gardens and dangerous elements like power cables can hinder or make logging difficult.

This section deals with terrain trafficability factors and theories regarding their modelling based on geographical information. We divide the factors affecting terrain trafficability into two categories:

- constant factors
- dynamic factors.

The constant factors are seasonally independent; whereas the dynamic factors vary on a seasonal basis, e.g. the weather, water, moisture, snow, ice and frost.

2.3.1. Constant factors used in this simulation study

Constant terrain variables of two types are often distinguished: macrotopography and microtopography. The macrotopography consists of a group of variables which influence the movement of the whole vehicle. In practical applications the minimum grid size is around 10×10 metres. The main macrotopography variable is the slope angle. The microtopography refers to terrain features which influence a single wheel (Saarilahti 2002 b).

Slope resistance is calculated using the inclined plane equation. When driving downhill, the slope resistance acts in the same direction as a pull force. This applies only on gentle slopes, however, for as a downward slope becomes steeper, it turns into a limiting factor for the mobility of the tractor, partly as a result of increasing vibration and its negative effects on braking and turning operations. The lateral inclination can also be a limiting factor for the mobility of a vehicle.

2.3.2. Constant factors, which are ignored in this simulation study

When the wheel descends from an obstacle, the stored potential energy is released, and becomes zero. This is valid when monitoring a single wheel, but when one 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 Saarilahti's (1997) research, the energy loss factor is between 10 and 30 percent.

Steering or winding resistance is due to the fact that when turning, the wheels must go over different paths with different radii, so that the difference in travel distance must influence the wheel velocity, and part of the lost energy can be attributed to steering resistance caused by increased slip and shear forces at the contact with the soil. Steering resistance is in a sense a horizontal equivalent to obstacle resistance. Large-scale winding increases both steering resistance and the risk of soil damage (Saarilahti 2002 b).

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 objects in connection with which movement is technically possible but should be forbidden. E.g. power cables can also requires special caution on the part of the driver. The above objects are taken into account by multiplying the cost surface by a 'coefficient of disadvantage', the magnitude of which depends on how inconvenient the object is, and may vary between zero and infinity. It can also vary depending on the time of day.

2.3.3. Dynamic factors used in this simulation study

The dynamic factors are ones that vary depending on seasonal elements. They are often linked with water and its winter forms snow, ice and frost. In this paper, snow, ice and frost are ignored.

Soil bearing capacity can be estimated using a classification of soil types based on plasticity theory 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). My simulation study does not take into account this variation, but is more like case study.

In this paper, the soil bearing capacity is determined using the plasticity theory, which was initially developed to determine the bearing capacity of footings. Geotechnically, bearing capacity means a contact pressure that gives sufficient safety from crushing loads and keeps the sinkage within acceptable limits (Rantamäki et al. 1979). The applications of plasticity theory to terramechanics has been developed especially by Karafiath and Nowatzki (1978) and Silversides and Sundberg (1989). In this paper, the plasticity theory is chosen for estimating bearing capacity (in preference to the WES method, for example), because it needs only simple derivatives of the soil type and strength parameters (Rantamäki et al. 1979), which can be obtained from soil type data.

Rolling resistance is the horizontal force needed to compact the soil, and is caused by transformation of the soil under the influence of a wheel. The bigger the sinkage below the tyre is the bigger is the rolling resistance. It is difficult to model the rolling resistance of a pneumatic tyre, but one common solution is based on the rigid wheel model, using a larger, hypothetical wheel (a virtual wheel or surrogate wheel) (Saarilahti, 2002a).

2.3.4. Dynamic factors, which are ignored in this simulation study

Soil moisture, along with the soil type and density, significantly affects soil strength and terrain trafficability (Hintze, 1991). Soil moisture varies depending on the seasons and the weather, and is taken into account by modifying the cohesion of cohesive soils. The bearing capacity of frictional soils is fairly constant regardless of soil moisture (Helenelund, 1966). The effects of soil moisture on rolling resistance can be taken into account by modifying Young's modulus.

2.4. GIS-data and their uncertainty

In this study, is used two GIS-data, which are Digital Elevation Model (DEM) and soil type data. DEM is derived from basic map's contours, whose interval is 5 meters and also form lines with 2.5 meters interval have been utilized. Every 25 x 25 meter pixel has its elevation value. From DEM is calculated slope, using ArcInfo GRID program and Horn's method, in every pixel. Horn method has proven to be the most effective slope algorithm, if the difference of altitude is significant (Ahlajärvi, 2002). Slope has two main components, which are gradient and aspect. In Finland the average accuracy of DEM is 1.76 meters and the standard deviation is 1.39 meters.

Soil type data is a set of vector data, scale 1:20 000, describing soil type areas larger than 2 hectares. In addition, some smaller scale areas are described, but the absolute minimum is 0.1 hectares. The data have been collected by field observations and digitization (Geokartta, 2002).

**Table 1. Example of misclassification matrix of soil data
(adapted from Ahlajärvi 2002)**

The class in soil type data	The soil type class in reality, %						
	Rock	Moraine	Sand	Fine silt	Clay	Marsh	Water
Rock	88-90	10					
Moraine	8	86-88					
Sand			86-93				
Fine silt				81-88	5-10		
Clay				10-15	86-93		
Marsh	2-5	2-5	2-5	2-5	2-5	100	
Water							100

GIS data entail (nearly) always sources of error, of course, and thus there is always some inaccuracy and uncertainty in GIS applications of this kind. The uncertainty can be evaluate and manage with several methods. Davis and Keller (1997) have used fuzzy modelling to examine the transition of the pairs of the soil type areas. In this kind of application the misclassification matrix (Table 1.) can be used as fuzzy model's membership function. Davis and Keller (1997) have assu-

med that the soil type is correctly defined in the pivot of the soil type area and the uncertainty is growing on the edge of the area.

In the field-based Monte Carlo – simulation the examined area is compartmentalized in fields, in which the two most probable soil type classes are the same. Only one random number is generated for one field and single pixels inside the field are divided in different soil type classes based on pixel's probability distribution. Especially Canters (1997) has studied the use of this field-based Monte Carlo simulation technique. In addition, some other techniques, e.g. indicator kriging method and rough classification, can be used in evaluating and managing the uncertainty of GIS data.

2.5. Cost surface analysis and determination of the least-cost route

The GIS program used here was ArcGISTM, in which the PATHDISTANCE-formula is used to calculate the least-accumulative-cost distance over a cost surface from a source cell while accounting for surface distance and horizontal and vertical cost factors. The surface distance and the vertical factor depend on the direction of movement, so that they can vary even inside one pixel, whereas horizontal factors are constant inside one grid square at a certain moment, but varies depending on the season and weather. Vertical factor is the same as slope resistance. In this paper, only rolling resistance has taken into account when determining the horizontal factors. In this application cost surface is the sum of rolling resistance and slope resistance. If the wheel load exceeds the soil bearing capacity or vehicle's net engine power is not sufficient for the sum of resistance forces, the cost surface is set as an infinite number. So, the cost surface formula in this paper is:

$$R_{TOTAL} = R_R + R_S + k,$$

in which: R_{TOTAL} – sum of resistance forces, kN (cost surface value); R_R – rolling resistance, kN (Horizontal factor); R_S – slope resistance, kN (Vertical factor); k – ∞ if bearing capacity or net engine power are not sufficient, otherwise 0.

Rolling resistance is constant inside one pixel, but slope resistance depends on the moving direction of the vehicle.

The PATHDISTANCE-formula creates an output raster in which each cell shows the least accumulative cost back to the source cell. The formula creates also a direction raster, which provides a road map, identifying the route from any cell back to the source cell. Created cost surface (or cost-weighted distance) and direction raster are utilized in determination of least-cost route between two points. In this paper, the value of the cost surface is a kind of mobility index.

2.6. A corridor around the least-cost route

The least-cost route defines the optimal route between two points, but it does not tell anything about the sensitivity of the route. The route may be very narrow in some cases but on certain areas the path can divert from the least-cost route without significantly increasing costs. This sensitivity can be demonstrated by creating a corridor around the least-cost route. First we should fix the biggest allowed increment compared to least-cost route. Then the neighbours of the starting cell are selected into the processing list. Next, the cell from processing list with the least

accumulative cost-weighted distance is selected as a processing cell. The transit cost, from starting cell throughout the processing cell to the destination cell, are compared to the least-cost routes accumulative cost. If the increment of cost is less than the biggest allowed increment, the neighbours of processing cell are appended into the processing list and processing cell is appended into the corridor around the least-cost route. In any case, the processing cell is removed from the processing list and marked with "processed" symbol, so that it will not process again. This loop is repeated until the processing list is empty.

3. Simulation of the off-road routing and discussion

The terrain cost surface model was implemented as a complete calculation procedure for validation of its parameters, final cost grid examples being calculated for the sample area in southern Finland. The optimal off-road route for an empty forwarder (parameters of forwarder and its tyres has been introduced in chapter 2.2) is shown in Figure 2 with solid line. This optimization is for summer conditions, when the soil moisture is relatively high. The bearing capacity of the mire in the middle of the map is not sufficient, so that the route goes along a strip of sandy soil to the east of this. The route to the west of the mire would be shorter one but clay areas' bearing capacity is lower and the rolling resistance is higher comparing to the route in Figure 2.

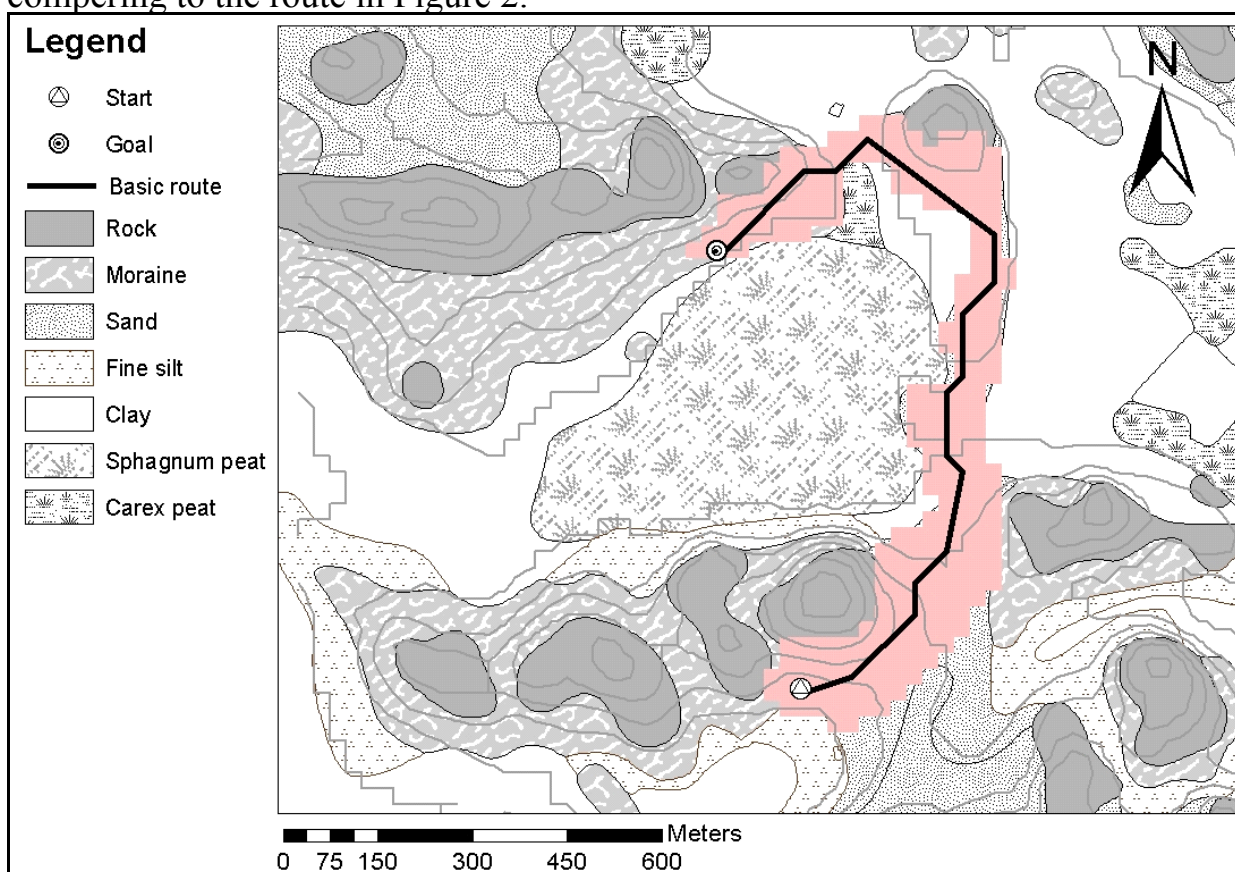


Figure 2. Simulation of the least-cost off-road route (the solid line) and the 5 per cent corridor around it (the red area) in sample area

In Figure 2 is also shown a corridor around the least-cost route with red area. This corridor allows the resistance forces of tractors movement to increase with five per cent from its optimum. As it can be seen in Figure 2 relative flat areas

with high bearing capacity allow the corridor to extend quite broadly, but steep and soft terrain narrow the corridor effectively.

Different cost surface alternatives can be generated according to changing information in objects. This makes easy to do sensitivity analyses. A regular cost surface analysis can be used to determine alternative routes in different conditions. It has shown that useful parameters can be found for national level digital maps for supporting off-road analysis. Timber purchase organizations could also use this kind of an application to find the best logging order for forest stands that it is handling or the types of stands that it needs more of in order to meet its purchase goals.

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