Preliminary Planning of Road Systems Using Digital Terrain Models

Kevin Liu[1]
John Sessions
Oregon State University,
Corvallis, U.S.A.

ABSTRACT

Unlike the traditional way of forest road planning in which the forest engineer manually tries to find alternative routes to access areas scheduled for harvest, a computerized method using data from a digital terrain model is presented. The method identifies feasible road segments, evaluates their variable and fixed cost components and then determines the optimal set of road segments to be used and the year in which the roads are to be constructed.

Keywords: *optimal road alignment, digital terrain model, harvest planning.*

INTRODUCTION

Traditional methods used in transportation planning have relied largely upon the individual skill of the engineer to develop one or more transportation alternatives on a contour map. The engineer then calculates the sum of construction, transport, and road maintenance costs for each alternative. This can be an expensive and time-consuming task. The forest management plan may cover thousands of hectares and tens or hundreds of timber entry points over a planning period of many years.

Digital terrain models (DTM's) were introduced into forest harvest planning in North America in the 1970's following early uses of digital terrain data by civil engineering for applications such as representing the elevation surface of highway construction zones [6].

A digital terrain model is a grid-like representation of the topography with each point of the grid representing (x,y,z) ground coordinates. Burke [2] constructed DTMs for harvest and transportation planning. Young and Lemkow [11] developed several planning routines that rely on DTMs for terrain data. Both of these early attempts demonstrated that terrain data could be efficiently converted into digital form, stored and manipulated. Reutebuch [7] developed the ROUTES computer program to assist planners in finding and evaluating route locations based on digital terrain data. As the planner manually moves a digitizing cursor over a topographic map, the sound level and frequency of a beeper alerts the planner as to if the grade line is too flat, too steep or within limits.

Xu Shenglin [10] superimposed a grid over a topographic map and used a method developed by Kobayashi [4] to develop locations of forest roads using a microcomputer. The intersections of grid lines represented timber entry points (landings) and the grid lines between intersections represented possible road sections. He first calculated a cost-benefit ratio for each road section and then used a dynamic programming algorithm to find the optimal combination of roads.

The objective of this paper is to suggest the use of digital terrain models to automatically (1) identify a network of possible road segments, (2) estimate the construction, transport, and maintenance cost of each road segment, and (3) use a network-based algorithm to choose among the possible road segments to form a preliminary transportation plan.

SOLUTION PROCEDURE

The solution method has three steps:

(1) Identification of possible road segments on the digital terrain model and calculation of the costs for each road segment.

(2) Analysis to find the combination of road segments which minimizes the sum of the construction, maintenance and transport costs.

(3) Display of the results of the analysis on the digital terrain model or contour map so the transportation planner can review and verify the results in the field.

IDENTIFYING ROAD SEGMENTS

The set of possible road segments is constrained by the maximum gradients that transport vehicles can negotiate and environmental factors such as unstable slopes which must be avoided.

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[1] *The authors are respectively: Graduate Student and Professor, Department of Forest Engineering.*

It is assumed for this presentation that environmental factors are not limiting. Later, it is shown how environmental factors can be taken into account. It is assumed that at each grid point on the digital terrain model that eight potential links exist corresponding to moves to adjacent grid points (Figure 1). Each grid point on the digital terrain model is assigned a unique row and column number.

Each potential link represents one possible direction the loaded truck could go. Although this seems like a large number of links, it is a small subset of all possible road links. Other options will be discussed later.

For each of the eight possible links, the gradient is calculated between the relevant grid points using the elevation differences between grid points and the straightline distance between the grid points. No additional factor was used for weave, but one could be added. For each road segment, the gradient is checked against the maximum grade a loaded truck could negotiate in one direction and the unloaded truck could negotiate on the return trip. Any road segment (link) which has a gradient which exceeds the allowable gradient for either the loaded truck or the unloaded truck is not added to the road network.

EVALUATING COSTS

The construction, transport and maintenance costs are calculated for each segment. The construction cost is based upon the sideslope estimated from the digital terrain model.

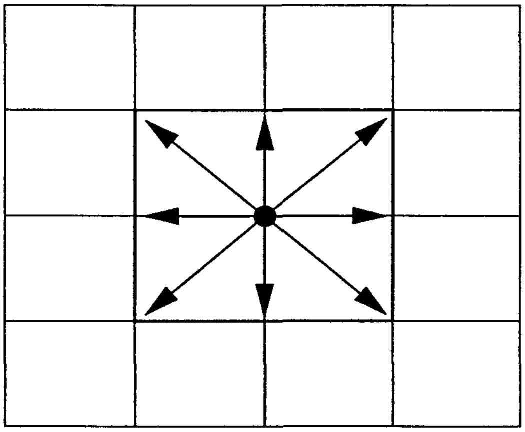

Figure 1. Possible road segments from a grid point.

The sideslope is calculated from the grid points perpendicular to the travel direction. This sideslope is then used to determine the earthwork for balanced section construction (cross section of the cut volume is balanced by the cross section of the fill volume). For road segments on steep sideslopes, full bench construction (no road on fill) is used to estimate earthwork. The road construction cost can then be estimated using standard engineering estimating procedures.

Transport times are estimated using the gradient of the road segment and an assumed alignment class following procedures from Byrne et al. [1]. The transport times are summed for the loaded truck to travel in one direction on the road segment and the unloaded truck to return empty in the other direction. The truck travel times are multiplied by their respective truck cost per minute and divided by the expected log load to derive a US $/100-ton/segment for the round trip travel of the truck over the road segment.

Road maintenance costs of two types are considered, variable maintenance costs and fixed maintenance costs. The variable maintenance costs are proportional to the volume transported. These costs can be expressed as a US $/100-ton/segment and are found from a table as a function of road gradient. The fixed maintenance costs are those which are not a function of volume transported and are generally periodic (annual). These maintenance costs are estimated by road grade on a US $/km [US $/mile] basis and the discounted sum of a series of annual costs are calculated and added to the construction cost.

ASSEMBLING THE NETWORK

The road links generated from the digital terrain data provide a link list for the network with the beginning and ending nodes for each link having a unique node name. The code used in the following example is Cxxx-Ryyy for each node where xxx is the column number on the digital terrain model and yyy is the row number.

The network node for each timber origin is identified along with the year in which timber will enter the transportation system. Similarly, the node corresponding to each timber destination is identified.

NETWORK SOLUTION

A network has now been constructed for which the objective will be to identify the set of road segments which minimize the sum of construction, transport and road maintenance costs. For smaller problems, mixed integer linear programming (Kirby, [3]), could be used to obtain an exact solution. This is impractical for the size of problem resulting from generating road segments from a digital terrain model. The mixed integer linear programming approach is appropriate if the number of integer variables is less than about 500. One integer variable is usually needed for each combination of time period and road segment requiring construction. A network of 5000 road segments, 650 nodes and 10 time periods results in about 50,000 integer variables, 50,000 non-integer variables and 6,500 equations. As an alternative, a heuristic algorithm developed by Sessions [8] and implemented in the microcomputer program NETWORK II was chosen. This algorithm solves an iterative sequence of shortest path problems, at each iteration converting the fixed costs into equivalent variable costs.

The solution to the network problem is then plotted on the DTM or on a contour map for review of the transportation planner.

EXAMPLE

To demonstrate how the program works, a preliminary transportation plan for a small area (480 hectares, 1190 acres) is developed from a digital terrain model with 25 rows and 25 columns or a total of 576 cells. Each cell is 91.4 m [300 ft] by 91.4 m [300 ft].

The road cross section used here is shown in Figure 2. The road data are in Table 1.

Excavation quantities are estimated using a shrinkage factor of 1.15. The cut slope is 1/2:1 and the fill slope is 1-1/2 to 1. For slopes steeper than 60 percent, full bench construction is assumed, otherwise a balanced section is used. The maximum road gradient is 16 percent for loaded and unloaded trucks travelling either uphill or downhill.

Log Hauling Data:

The load per truck is about 25 tons. Travel times are estimated for a single-lane gravel-surfaced forest

Table 1. Road parameters and costs for example.

Running surface = 3.66 m [12 ft]
Gravel depth = 20.3 cm [8 in]
Ditch width = 0.91 m [3 ft]
Turnouts per km = 3
Turnout length = 30.5 m [100 ft]
Common excavation = 85%
Rock excavation = 15%
Excavation cost (common) = US \$.65/m^3 [US \$0.50/yd^3]
Excavation cost (rock) = US \$2.61/m^3 [US \$2.00/yd^3]
Culverts per km = 4
Culvert cost = US \$300/culvert
Clearing and grubbing cost = US \$3705/hectare [US \$1500/acre]
Seeding cost = US \$494/hectare [US \$200/acre]
Miscellaneous = US \$6212/km [US \$10,000/mile]

Table 2. Travel time table showing time to travel 1.62 km [1 mile] with the truck loaded and to return 1.62 km [1 mile] in the opposite direction.

Grade*	Min.	Grade*	Min.
-16	8.0	0	5.1
-15	7.6	1	5.1
-14	7.2	2	5.1
-13	6.8	3	5.8
-12	6.4	4	6.4
-11	6.0	5	7.1
-10	5.6	6	7.8
-9	5.3	7	8.5
-8	5.1	8	9.1
-7	5.1	9	9.8
-6	5.1	10	10.7
-5	5.1	11	11.6
-4	5.1	12	12.5
-3	5.1	13	13.4
-2	5.1	14	14.3
-1	5.1	15	15.2
		16	16.1

* Direction of loaded truck.

road of fair alignment using the travel time table (Table 2) from Sessions [9]. To simplify the description, log truck cost is assumed independent of grade at US $51.3/hr and road maintenance costs are not considered.

Timber Entry Points and Destinations:

The destination in this example is at column zero, row zero on the digital terrain model (identified as the label "C000-R000") and there are four timber entry points (Table 3).

The number of road segments meeting the gradeability requirements were 3278 out of approximately 5000 possible road segments on the digital terrain model. Using a real discount rate of 4 percent, the discounted cost of road construction and transport for the best solution from NETWORK II was US $151,400. About 6.3 km [3.9 miles] of road were constructed (Figure 3).

The solution time for road segment generation using an INTEL 386 33-Mhz processor was 35 seconds and solution for the network required an additional 55 seconds.

DISCUSSION

This paper outlined a methodology for planning preliminary road systems. A small example of approximately 480 hectares [1190 acres] on a 25 x 25 digital terrain model requiring 3278 links was demonstrated. Using 16 megabytes of extended memory approximately 200,000 links could be accommodated using the heuristic algorithm in NETWORK II. At 8 possible links per cell, this would permit at least 25,000 cells to be analyzed simultaneously. At a column and row spacing of 30.5 m [100 feet] this would permit about 2430 hectares [6000 acres] to be analyzed. At a column and row spacing of 91 m [300 feet] an area of about 20,240 hectares [50,000 acres] could be analyzed.

The choice of using adjacent grid point intersections as road segment intersections has been arbitrary. Additional road segment options could have been generated by permitting road segments to terminate at non-adjacent grid points. The grade at intermediate points where the road segment crossed a grid line could be determined by interpolation. Although the number of links would increase, there is a potential for improved solutions. Alternatively, the cell size could be reduced.

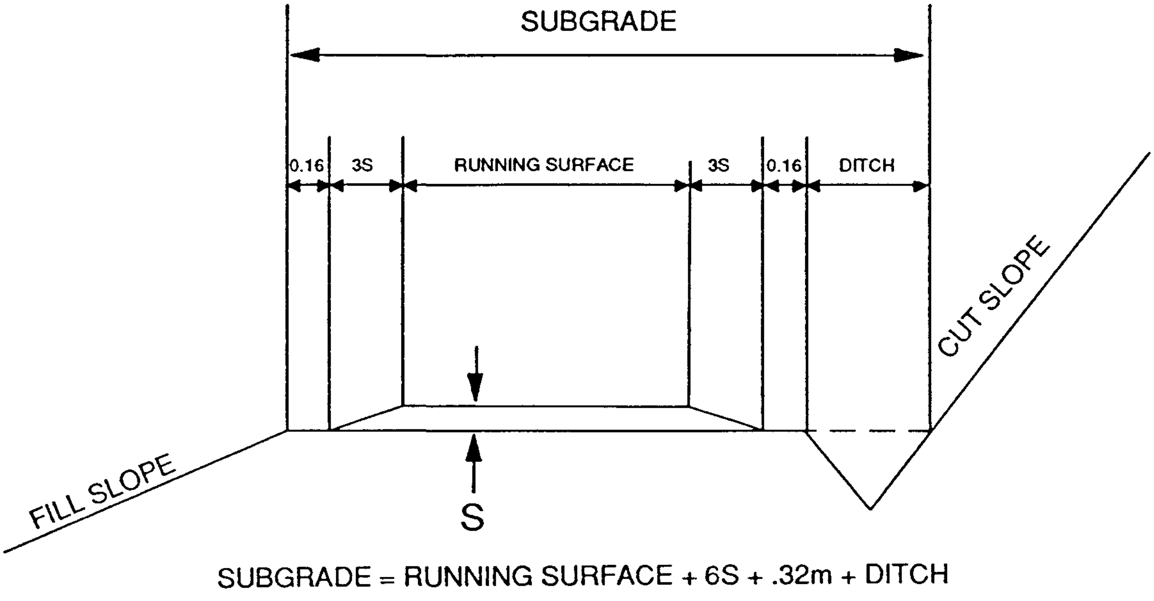

Figure 2. Road cross section.

Table 3. Timber entries and destinations

Entry Point	Destination	Timber Volume Tons	Harvest Year
C005-R006	C000-R000	10600	1993
C017-R005	C000-R000	11300	1998
C008-R019	C000-R000	10890	2003
C022-R017	C000-R000	12500	2008

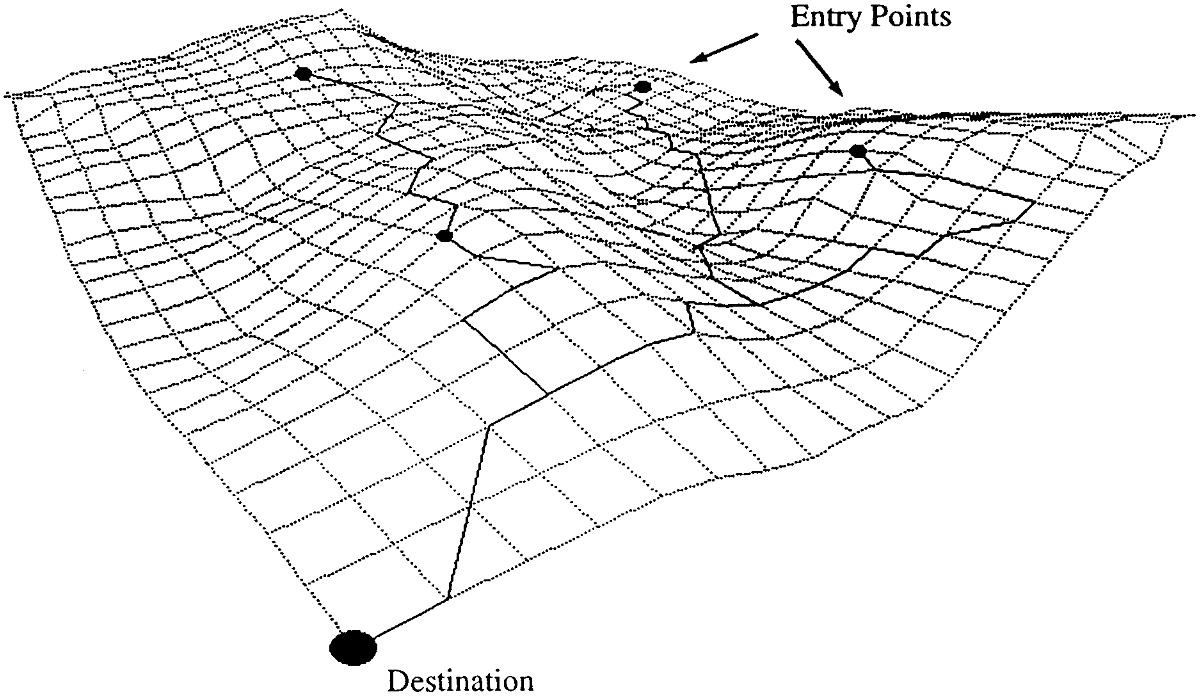

Figure 3. Road segments in solution for example network.

In this example soil information or slope stability information was not used in the creation of feasible road segments. With geographic information systems (GIS) this information is becoming more accessible and could be used as a cell attribute to determine (1) if a road segment is permissible, (2) how soil and ground slope would affect cut and fill slopes and (3) how existing vegetation would affect road construction costs.

It was assumed that there are no existing roads. Existing roads can be incorporated by identifying them by their closest grid point and adding them to the list of feasible road segments with zero construction cost.

It has also been assumed that the transport cost for a link is independent of the characteristics of adjacent links. That is, that the truck speed is not significantly affected by characteristics of the road sections behind the link or in front of it. This may not be the case. The assumption that transport costs for each link are independent was made for two reasons: (1) it requires a substantially simpler algorithm, and (2) the information available at the stage of preliminary road planning is often not detailed enough for truck simulation to determine travel time and cost. Truck simulation programs using detailed road geometry and vehicle interaction such as those developed and used by the Cummins Engine Company, the USDA Forest Service, World Bank, CSIRO, various universities or others could be used to adjust the routes once the preliminary transport corridors have been identified and more detailed information becomes available. At the same time, more sophisticated estimates of earthwork could also be made rather than the simpler road cross sections assumed during the preliminary analysis.

And finally, this analysis has assumed the timber entry points are known. The rules for extending the network technique to simultaneously determine timber entry points and road locations have been described by Sessions [8]. The extended network would include "harvesting" links as well as road links.

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