Turk J Agric For
28 (2004) 273-279

A New Method of Designing Forest Roads

Abdullah E. AKAY*
Kahramanmaraş Sütçü İmam University, Faculty of Forestry, Department of Forest Engineering,
46100 Kahramanmaraş - TURKEY

Received: 13.11.2003

Abstract: An unlimited number of alternative paths can be generated to connect 2 end points. Modern optimization techniques, which perform a systematic search for an optimum solution, can be used to solve such complex problems. In the field of highway design, various optimization techniques have been applied to locate a path between 2 known locations. However, there has been little optimization application in current forest road design systems. These systems are used as a tool to perform the mathematical calculations required to make basic manual road design. This study introduces a new method that integrates 2 optimization techniques for designing forest roads: linear programming for cut and fill balance and a “heuristic” approach (simulated annealing) for the selection of vertical alignment. This method provides the designer with a rapid evaluation of alternatives to design a path with minimum total costs, while conforming to design specifications, environmental requirements, and driver safety.

Key Words: Forest road design, Optimizing road alignment, Minimizing road cost

Orman Yollarının Planlanmasında Yeni Bir Metot

Özet: İki noktayı bağlamak için sınırsız sayıda alternatif yol üretilebilir. Optimal çözüm için sistematik bir araştırma yapan modern optimizasyon teknikleri böyle kompleks bir problemin çözümünde kullanılabilir. Karayolu planlanmasında, bilinen iki nokta arasından bir yol geçirmek için değişik optimizasyon teknikleri uygulanmaktadır. Bununla birlikte, günümüz orman yolu planlama sistemlerinde optimizasyon uygulamaları azdır. Bu sistemler elle yapılan temel yol dizaynında gerekli matematiksel hesaplamaları yapmak için kullanılır. Bu çalışma orman yollarının planlanmasında iki optimizasyon sistemini bütünleştiren yeni bir metodu tanıtmaktadır: kazı-dolgu dengelenmesi için lineer programlama ve düşey doğrultma için "heuristic" yaklaşım (simulated annealing). Bu metot, toplam maliyeti en az olan ve aynı zamanda dizayn şartlarını, çevresel şartları, ve sürücü güvenliğini sağlayan bir yol planlaması için, tasarımcının alternatifleri hızlı değerlendirmesini sağlar.

Anahtar Sözcükler: Orman yolu planlaması, Yol güzergahının optimizasyonu, Yol maliyetinin en aza indirilmesi

Introduction

For low volume forest roads, construction and maintenance costs are the largest components in the total cost of producing timber (Pearce, 1974). The roadway grade should be carefully selected, not only to minimize the total road cost but also to reduce the environmental impact and to improve driver safety. Such problems with many solutions can be solved using optimization techniques that systematically search for a solution with minimum cost among the acceptable solutions.

Various optimization techniques have been developed for highway design, but there has been little application in forest road design. Mixed integer programming was developed to determine the vertical highway alignment with minimum earthwork cost (Trypia, 1979). Dynamic programming has been used in several studies for optimizing vertical alignment (Trietsch, 1987; Goh et al., 1988). Linear programming has also been used to select roadway grades that minimize the cost of earthworks (Easa, 1987; Easa, 1988a, 1988b). Chew et al. (1989) proposed solving a 3-dimensional (3D) highway route selection problem where the optimal horizontal and vertical alignments are determined simultaneously. A 2-stage model was proposed by Ichihara et al. (1996) to optimize vertical alignment for a forest road, considering only the construction cost. In this model, a genetic algorithm (GA) was used to identify the optimum

* Correspondence to: akay@ksu.edu.tr

combinations of points where the gradient changes, and dynamic programming (DP) was used to design the optimum longitudinal grade in the second stage.

The fundamental route location problem normally involves similar stages for both forest roads and highways. The systems currently available for forest road design are not capable of generating alternative grade lines, determining the best fitting vertical alignment for optimizing earthwork, or minimizing the total cost of construction and maintenance. In addition, they employ the mass diagram approach to balance the cut and fill quantities. However, the accuracy of the mass diagram is limited where soil characteristics along the roadway vary.

In recent years, advances in the processing speed and real-time rendering of high-resolution 3D graphics on microcomputers have permitted locating a route interactively on a 3D display of a ground surface generated by a digital elevation model (DEM). Improved remote sensing makes DEMs more useful. LIDAR (light detection and ranging), one of the fastest growing systems, is accurate to approximately 15 cm in the vertical, and to 1.0 m in the horizontal (Ahmed et al., 2000).

In this study, a new method has been developed as a decision support system for forest road design. It automates many of the current, time consuming tasks while implementing a decision support framework. The method has 3 main steps: (1) selecting a feasible trial route by establishing a series of intersection points on a 3D image of the terrain, subject to geometric specifications and environmental requirements; (2) locating the horizontal and preliminary vertical alignments, minimizing earthwork costs, and calculating total road cost; and (3) selecting the vertical alignment with minimum total cost using a combinatorial optimization technique. This paper presents the theory behind the optimization capabilities of this method. No description of this method is presented in detail here, but it can be found in Akay (2003).

Materials and Methods

High-resolution DEMs are used to provide terrain data to support the analysis of road design features such as ground slope and other landform characteristics. The DEM data file is a set of scattered metric data points (X, Y, and Z) that represent the ground surface. Other input data include soil types, stream distance, road design standards, economic data, and local data. The road design standards include road standard, road surface type, road template specifications, distance between road stations, design speed, vehicle specifications, and traffic volume. Economic data consist of the unit costs of road construction and maintenance activities and machine rate components of specified vehicles. Local data are soil swell and shrinkage factors, ground cover type, geological data, timber stand data, and the distance to local resources of the required road construction materials.

The designer selects a feasible trial route between the beginning and end points by establishing a series of control points on a 3D image of the terrain. The display and interactive features are provided by NewCyber3D (Redlands, CA). Using the trial route data as an initial alignment, the model automatically locates the horizontal and vertical curves, subject to the road design constraints (Figure 1). These include geometric specifications and environmental requirements. The geometric specifications are the maximum allowable road grade, the minimum radius of the horizontal curves, the minimum length of the vertical curves, the minimum distance between curves, and the minimum safe stopping distance for driver safety. Horizontal and vertical curves are not permitted to overlap each other. It is assumed that no vertical curve is necessary if the absolute value of the difference between consecutive grades is less than or equal to a specified percentage (e.g. £ 5%) (Kramer, 2001). The environmental requirements are minimum allowable road grade and rolling road grades to obtain proper drainage, a minimum distance from riparian zones to protect the stream channels, a minimum stream-crossing angle to reduce the damage to the riparian zones, and a maximum height of cuts and fills at any section to reduce soil movement.

Earthwork Optimization

The economic distribution of cut and fill quantities is determined using the linear programming method of Mayer and Stark (1981), considering possible borrow and landfill locations and various soil characteristics along the roadway. This method is used to overcome the limitation of the mass diagram on roadway sections with variable soil characteristics. It represents the earthwork allocation better than do the other methods and provides the optimal solution to the earthwork allocation (Mayer and Stark, 1981). In the method it is assumed that the unit

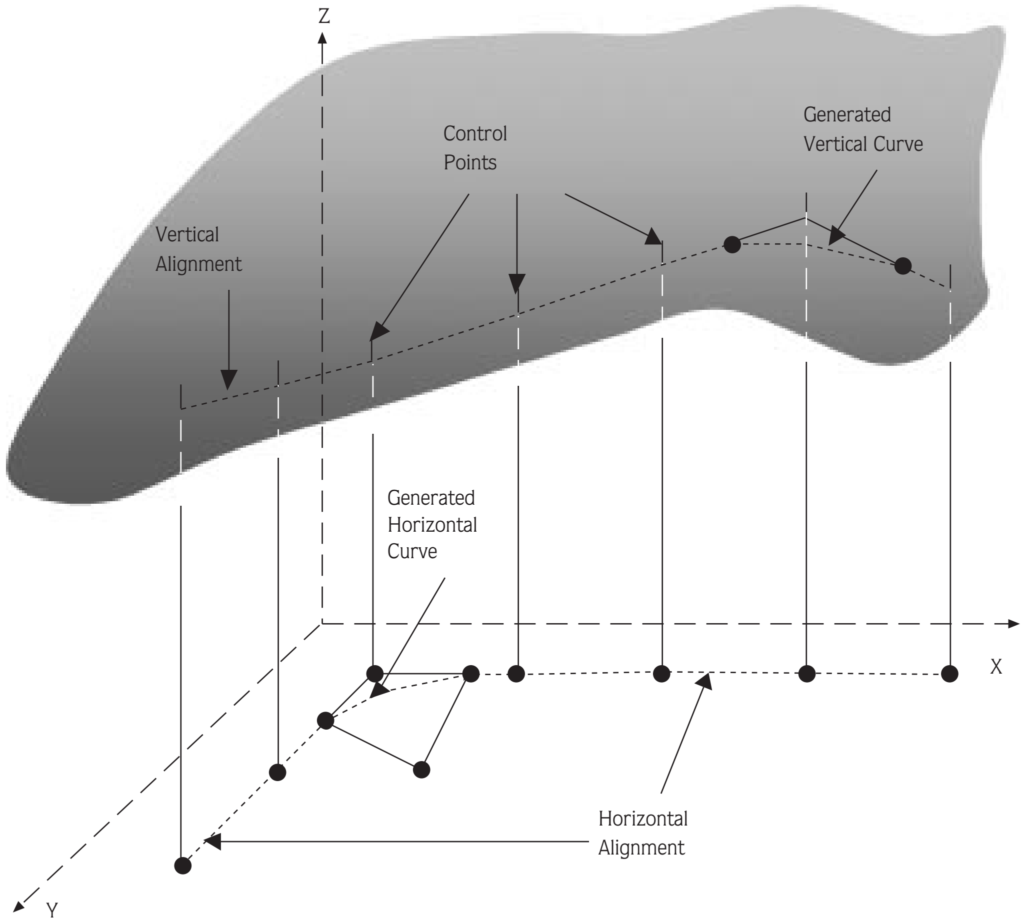

Figure 1. Generation of the vertical and horizontal alignments by locating control points.

costs do not vary with the amount of material moved. It is also assumed that the unit cost of hauling is linearly proportional to the hauling distance. The specific unit costs for earthwork activities including excavation, haul, and embankment are defined based on the soil type data for each road stage. The swell factor of the material moved from a cut section and the shrinkage factor of the material compacted into a fill section are considered to determine haul and fill quantities. The objective function is

$$Min\ Z = \sum_i \sum_j C(i,j)\ X(i,j) + \sum_i \sum_k C_D(i,k)\ X_D(i,k) + \sum_i \sum_j C_B(p,j)\ X_B(p,j)$$

where

$X(i,j)$ = the amount of cut moved from cut section i to fill section j

$X_D(i,k)$ = the amount of cut moved from cut section i to landfill area k

$X_B(p,j)$ = the amount of material moved from borrow area p to fill section j

$C(i,j)$ = the unit cost of moving and compacting the material moved from cut section i to

fill section j

$C_D(i,k)$ = the unit cost of moving the material from cut section i to landfill area k

$C_B(p,j)$ = the unit cost of moving and compacting the material moved from borrow area

p to fill section j

The objective function is subject to the following constraints:

The amount of cut moved from cut section i to fill section j plus the amount of cut moved from cut section i to landfill area k is equal to the available amount of cut at cut section i.

The adjusted amount of cut moved from cut section *i* to fill section *j* plus the adjusted amount of material moved from borrow area *p* to fill section *j* is equal to the amount of fill required at fill section *j*. The shrinkage factors for material moved from cut section *i* and borrow area *p* are considered to adjust the amount of material.

The adjusted amount of cut moved from cut section *i* to landfill area *k* is equal to or less than the capacity of landfill *k*. The swell factor for material moved from cut section *i* and wasted in landfill area *k* is considered to adjust the amount of material.

The amount of material moved from borrow area *p* to fill section *j* is equal to or less than the material available in borrow area *p*.

The unit cost of moving and compacting the material from cut section *i* to fill section *j* is estimated based on the unit cost of each operation including excavation, hauling, and compacting. It was assumed that the costs are linearly proportional to the quantities.

Vertical Alignment Optimization

After establishing the initial vertical alignment, new road alignment alternatives are generated by adjusting the vertical alignment to find the best path with the lowest total cost. Simulated annealing (SA), a combinatorial optimization technique, is used to guide the search considering technically feasible grades. For each alternative vertical alignment, the model calculates cross sections and earthwork volumes, and minimizes earthwork costs using linear programming, subject to geometric specifications and environmental requirements.

SA is based upon a metallurgical technique in which a solid material is heated, and then cooled back into an optimal state (Reeves, 1993). To produce the best product, the material should be cooled slowly but occasionally. Kirkpatrick et al. (1983) suggested that SA could form the basis of an optimization technique for combinatorial problems. SA has been applied in a wide variety of disciplines. It usually provides a good quality/near optimal solution and it has the ability to avoid becoming trapped at local minima. There are a number of generic decisions to solve a specific problem, including the initial temperature (t_0), the cooling rate (*a*), and the stopping condition. In most combinatorial optimization problems the maximum number of iterations is defined as a stopping condition, and an initial temperature is determined by a few experiments.

A trial road alignment generated by tracing the possible path using the computer cursor on the 3D image of the terrain is used as the initial solution, s_0. Then the model generates an alternative road alignment by changing the elevation of the initial solution at a randomly selected control point by a specified value. If this new alignment satisfies all the constraints, it is kept by the model as a new feasible solution, *s*. SA is illustrated in Figure 2. In this figure, *nrep* is the user-defined number of iterations before adjusting the temperature, and *x* is a random number between 0 and 1.

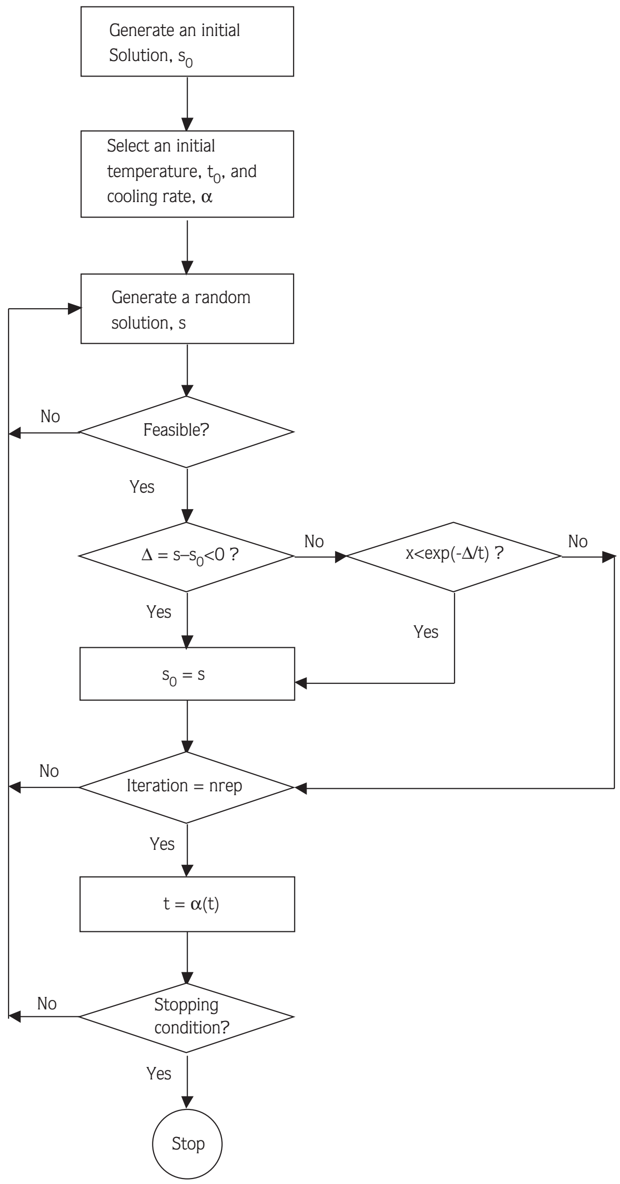

Figure 2. Logic behind vertical alignment optimization using the simulated annealing method.

To develop additional horizontal road alignments connecting the same beginning and end points, the designer traces out different feasible route paths. Then, for each selected route path, the model follows the same procedure to find the road alignment with the minimum cost by using optimization techniques. Thus, the designer can rapidly develop and then choose among the alternative road locations in an efficient way.

Results and Discussion

The model was applied to an example study area where a high-resolution DEM (1 m intervals) was made available using a LIDAR data set collected by Aerotec (Bessemer, AL). The study area was approximately 55 ha of predominantly forested land in the Capitol State Forest in western Washington. The site was mountainous with elevation varying from 270 to 355 m and a ground slope from 0 to 50 %. Soil, hydrology, and geology data were obtained from the Washington Department of Natural Resources. Road design standards (Tables 1-2) and economic data (in US dollars) are estimated based on the representative conditions in North America (Kramer, 2001; USDA Forest Service, 1999). Construction costs for the design example are summarized in Table 3.

A horizontal alignment was generated to connect 2 known end points. The vertical alignment with the minimum total discounted cost was found by using heuristic techniques (Reeves, 1993). Total cost included construction, maintenance, and transportation costs.

Table 1. Road design specifications used in the application.

Elements	Value
Width of road	4 m
Side slopes	Cut slope: 1:1
	Fill slope: 1.5:1
Minimum curve radius	18 m
Minimum length of a vertical curve	15 m
Minimum difference between consecutive grades	5%
Minimum distance between curves	10 m
Minimum road grade	± 2%
Maximum uphill road grade	12%
Maximum downhill road grade	-16%
Minimum distance between the road and a stream	10 m
Maximum cut and fill height at centerline	2 m
Design speed	55 km h^{-1}

Table 2. Specifications for surfacing material used in the application.

Layers	Surfacing Material
Base Course	If Grade £ 10%: Pit Run
	If Grade > 10%: Good Quality Rock (7.5 cm)
Traction Surface	If Grade £ 10%: No Traction Surface
	If Grade > 10%: Surface Rock (4 cm)

Table 3. Unit costs for road construction used in the application.

Items	Costs in $	Units
On site earthwork		
Excavation cost	1.6	m^3
Haul cost	1.3	m^3-km
Embankment cost	0.6	m^3
Disposal cost	0.1	m^3
Borrow material		
Excavation cost	1.8	m^3
Haul cost	1.3	m^3-km
Embankment cost	0.6	m^3
Surfacing		
Pit run cost	3.9	m^3
Good quality rock cost	7.9	m^3
Traction surface cost	11.8	m^3

During the search process, 182 feasible solutions were calculated out of 1200 automatically generated vertical alignment alternatives in about 15 min. This time includes the calculation time of earthwork allocation using a linear programming method for each alternative. It was indicated in previous studies that this method has provided the global minimum cost for earthwork allocation problems, and it is easy to apply (Easa, 1988a, 1988b). In a previous study (Ichihara et al., 1996), 420 alternative profiles were calculated in about 10 min to design forest roads using a 2-stage model. However, this model could not provide a solution to the route selection problem of forest roads and it only considered the construction cost.

The vertical road alignment that minimized the total cost located a horizontal curve with a radius of 62 m. The solution did not require a vertical curve since the absolute value of the difference between consecutive grades was not more than 5% (Kramer, 2001). The road section had a length of 252.38 m (Figure 3). The road gradient varied from 3% to 9% along the road section.

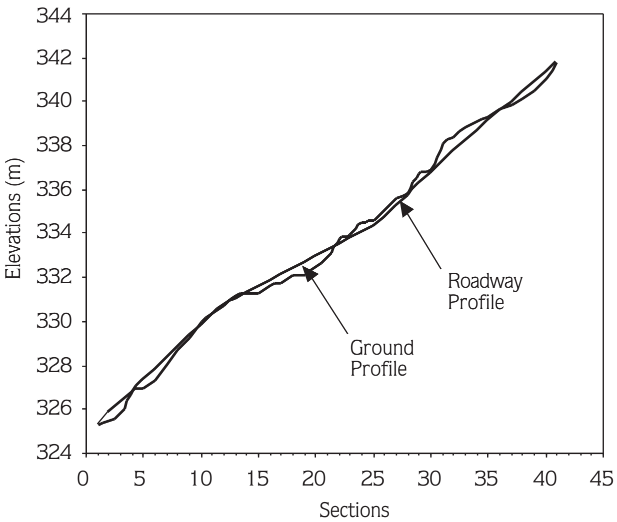

Figure 3. Profile view showing road gradient and vertical alignment for the application.

The lowest value of the objective function was obtained at iteration 89 with a unit cost of $24.70 per meter. Total construction cost ($17.48 per meter) was the largest cost component, followed by maintenance ($4.04 per meter) and transportation costs ($3.18 per meter). Surfacing cost (including riprap and watering costs) was the largest cost component ($9 per meter), followed by earthwork cost ($4.7 per meter). The model kept the road gradient below 10 % to take advantage of pit run rock for the base course. In addition, traction surface was not required when the road grade was less than 10% along the roadway.

Conclusions

An optimization model was developed to provide the forest road designer with a decision support system for evaluating alternative horizontal alignments by finding efficient vertical alignments. By allowing the designer to quickly examine various feasible route paths, design time is reduced in the early stage of the forest road design. Road feasibility is ensured by automatically considering geometric specifications, environmental impacts, and driver safety. The results from the brief example should not be generalized. However, the example is instructive in showing the tradeoffs that can occur, and these are not intuitive.

The model has several limitations and opportunities for further development. It is assumed that the unit costs of earthwork are constant. If the unit costs vary with the quantity of the cut and fill, the method suggested by Easa (1987) can be used. The model depends upon available GIS coverages of attribute data to represent ground conditions. LIDAR, one of the fastest growing systems in the field, can provide a high-resolution and accurate DEM. It is expected to provide even better accuracy in the near future. Future work could also provide refinements to the graphic interface and optimization of the horizontal alignment.

References

Ahmed, K.M., S.E. Reutebuch and T.A. Curtis. 2000. Accuracy of high-resolution airborne laser data with varying forest vegetation cover. In: Proceedings of the 2nd International Conference on Earth Observation and Environmental Information. November 11-14, Cairo, Egypt.

Akay, A.E. 2003. Minimizing Total Cost of Construction, Maintenance, and Transportation Costs with Computer-Aided Forest Road Design. PhD Thesis. Oregon State University, Corvallis, Oregon, pp. 229.

Chew, E.P., C.J. Goh and T.F. Fwa. 1989. Simultaneous optimization of horizontal and vertical alignment for highways. Transportation Research, 23B: 315-329.

Easa, S.M. 1987. Earthwork allocations with non-constant unit costs. ASCE Journal of Construction Engineering and Management, 113: 34-50.

Easa, S.M. 1988a. Selection of roadway grades that minimize earthwork cost using linear programming. Transportation Research, 22A: 121-136.

Easa, S.M. 1988b. Earthwork allocations with linear unit costs. Journal of Construction Engineering and Management, 114: 641-655.

Goh, C.J., E.P. Chew and T.F. Fwa. 1988. Discrete and continuous models for computation of optimal vertical highway alignment. Transportation Research, 22B: 399-409.

Ichihara, K., T. Tanaka, I. Sawaguchi, S. Umeda and K. Toyokawa. 1996. The method for designing the profile of forest roads supported by genetic algorithm. The Japanese Forestry Society, Journal of Forestry Research, 1: 45-49.

Kirkpatrick, S., C.D. Gerlatt and M.P. Vecchi. 1983. Optimization by simulated annealing, Science, 220: 671-680.

Kramer, B.W. 2001. Forest road contracting, construction, and maintenance for small forest woodland owners. Oregon State University, Forest Research Laboratory, Research Contribution 35, pp. 79.

Mayer, R. and R. Stark. 1981. Earthmoving logistics. Journal of Const. Div. 107(CO2): 297-312.

Pearce, J.K. 1974. Forest Engineering Handbook, a Guide for Logging Planning and Forest Road Engineering, Bureau of Land Management, Oregon State Office, US Department of the Interior. Divisions 100-800, pp. 220.

Reeves, C. 1993. Modern Heuristic Techniques for Combinatorial Problems. Department of Statistic and Operational Research School of Mathematical and Information Sciences, Coventry University, pp. 320.

Trietsch, D. 1987. A family of methods for preliminary highway alignment. Transportation Science, 21: 17-25.

Trypia, M. 1979. Minimizing cut and fill costs in road making. Computer-Aided Design. 11: 337-339.

USDA Forest Service, 1999. Cost estimate guide for road construction Region 6. Cost Guide Zone 5, Davis-Bacon Area 5, Oregon, pp. 96.