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ESTIMATING SEDIMENT REDUCTION COST FOR LOW-VOLUME FOREST ROADS USING A LIDAR-DERIVED HIGH-RESOLUTION DEM

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Abstract. Traditional methods of designing forest roads using topographic maps and aerial photos are not always capable of leading to an optimal road alignment solution that minimizes the environmental effects of road construction. Forest road construction activities have the potential to cause more environmental impacts, especially excessive amount of sediment production, than perhaps any other forest management activity. In order to select an optimum road alignment that considers environmental constraints, mathematical optimization techniques are applied to a digital landscape in order to identify and evaluate a potentially large number of alignment solutions. A 3D forest road alignment optimization model TRACER was developed to assist road managers in designing a preliminary forest road alignment while minimizing total road cost and considering design specifications, environmental requirements, and driver safety. A 3D forest road alignment optimization model TRACER relies on a high resolution Digital Elevation Model for accurate representation of the terrain, while sediment production estimates are derived from a GIS-based SEDiment MODeL (SEDMODL). In this study, the 3D forest road alignment optimization model was used to generate two road alignments: 1) an optimum alignment with minimum total cost and, 2) a road alignment with minimum sediment delivery to streams. Both road alignment options were then analysed to better investigate the cost of sediment reduction associated with forest road construction.

Keywords: forest roads, optimal alignment, sediment prediction, Light Detection and Ranging, Digital Elevation Model.

1. Introduction

Designing an optimal forest road alignment involves economic and environmental considerations. Road construction and maintenance are generally the most expensive activities in the timber transportation process (Akay 2006) and typically surpass truck transportation costs. In addition, inadequately constructed and maintained forest roads have the potential to cause more environmental impacts than any other forest operation activity (Akay *et al.* 2008). Runoff from road construction activities removes forest vegetation from the road prism area, disturb the forest floor, and damage forest soil structure (Grace *et al.* 1998). Sediment delivered to streams from roads potentially leads to detrimental effects on water quality and aquatic life (Murphy, Wing 2005; Wing *et al.* 2000). Given these road construction considerations and increased public concerns about road effects on forest ecosystems, forest road managers have incentives to design economically viable and environmentally low-impact forest roads.

Because of the inherent trade-offs between economic and environmental considerations, selecting an optimal forest road alignment with the lowest total cost while protecting soil and water resources is a complex problem that is likely best addressed by computer-aided road design systems (Akay *et al.* 2005). Computer-aided road design systems generally employ mathematical optimization methods that allow users to examine a large number of feasible alternative alignments and then select an optimal solution from among the alternatives. There are a number of computer-aided forest road design systems that mainly search for the optimal road alignment with min road cost. There are, however, only a few studies that have sought an optimal road alignment that considers both economic and environmental constraints at the road project scale. Kirby and Rupe (1987) examined the cost of minimizing sediment considering road construction and harvest scheduling at the watershed scale using mixed integer programming, but did not consider trade-offs at the road project scale. Bettinger *et al.* (1998) developed a forest plan in which an algorithm determined the shortest travel path from each management unit to a mill. The road maintenance and obliteration choices were integrated with

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a harvest scheduling model and considered a sediment delivery constraint, however, the choices did not involve detailed road design.

Akay and Sessions (2005) developed a 3D forest road alignment optimization model (TRACER) that searches for the best vertical alignment that minimizes total road costs, while confirming sediment delivery to streams and driver safety. During the search process, vertical alignment alternatives were generated and evaluated using a hybrid simulated annealing/linear programming optimization technique. In a similar study conducted by Aruga *et al.* (2007), a forest road design model was developed to simultaneously optimize horizontal and vertical alignments of forest roads using a Tabu Search optimization technique. The model allowed users to select an optimal road alignment while constraining max allowable sediment yield. Application of this model led to reduced road construction costs and less sediment delivered to streams.

Forest road design models require a high resolution Digital Elevation Model (DEM) for accurate representation of the terrain. In recent years, Light Detection and Ranging (LiDAR) data based DEMs have been widely used in forest road design models (Akay, Sessions 2005; Aruga *et al.* 2005a, 2007). LiDAR technology, integrated with Global Positioning Systems (GPS), is a laser- based measurement system that calculates the three dimensional coordinates of objects based on laser pulse reflections (Akay *et al.* 2009). LiDAR sensors are mounted on aerial or terrestrial platforms. LiDAR operates by transmitting light pulses that travel until reaching an object and then are reflected back to the LiDAR sensor. The amount of time it takes the transmitted light pulse to return to the sensor is used to calculate a distance to the object. This distance is coupled with a GPS measurement to determine the three dimensional coordinates of the object. In forest areas, light pulses are reflected from different levels of vegetation canopy including top of vegetation surface (first return), intermediate surfaces (second and following returns), and the ground surface (last return) (Reutebuch *et al.* 2003). The first returns are used to generate a Digital Surface Model (DSM) of vegetation canopy (Takahashi *et al.* 2005) while the last returns provide high-resolution and accurate DEMs under forest canopy (Akay *et al.* 2009).

The primary objective in this study was to apply a 3D forest road optimization model to identify an optimal forest road alignment between two points given two application scenarios and based on a LiDAR-derived DEM. In the first scenario, a road alignment that minimizes the cost of road construction was developed. In the second, a road alignment that minimizes the delivery of sediment to surrounding streams was generated. In both scenarios, a 3D forest road alignment optimization model that was previously developed was employed (Akay, Sessions 2005). In order to estimate the cost of sediment reduction in forest road construction, the differences between the two scenario results regarding total cost and total sediment production were examined.

2. Material and methods

2.1. Study area and LiDAR data

The study area was selected from the McDonald-Dunn Research Forest of the College of Forestry at Oregon State University (OSU). The Research Forest is located about 15 min drive north of the OSU campus in Corvallis and consists of approx 4553 ha of predominantly forested land. Douglas-fir (*Pseudotsuga menziesii*) and bigleaf maple (*Acer macrophyllum*) are the dominant trees with the presence of grand fir (*Abies grandis*), western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*) (Akay *et al.* 2012). The elevation in the three watersheds that span the forest ranges from 122 m to 664 m with an average ground slope of 26%. In the McDonald-Dunn Research Forest, forested lands are located in the upper elevations while there are small holdings of agricultural areas, rural residential areas and urban developments in the lower elevations.

LiDAR data from the McDonald-Dunn Research Forest was collected in April 2008 with a Leica ALS50 Phase II laser system (Akay *et al.* 2012). The data consisted of three datasets including raw point data (1st returns, last returns, and all returns), vector data (ESRI shape file format), and raster data (1 m ESRI GRIDS of bare earth (DEM) and highest hit (DSM), and 1/5 m GeoTIFF of intensity image). The data resolution (average number of pulses emitted by the laser system) was 10.0 points/m^2 and 1.1 points/m^2 for

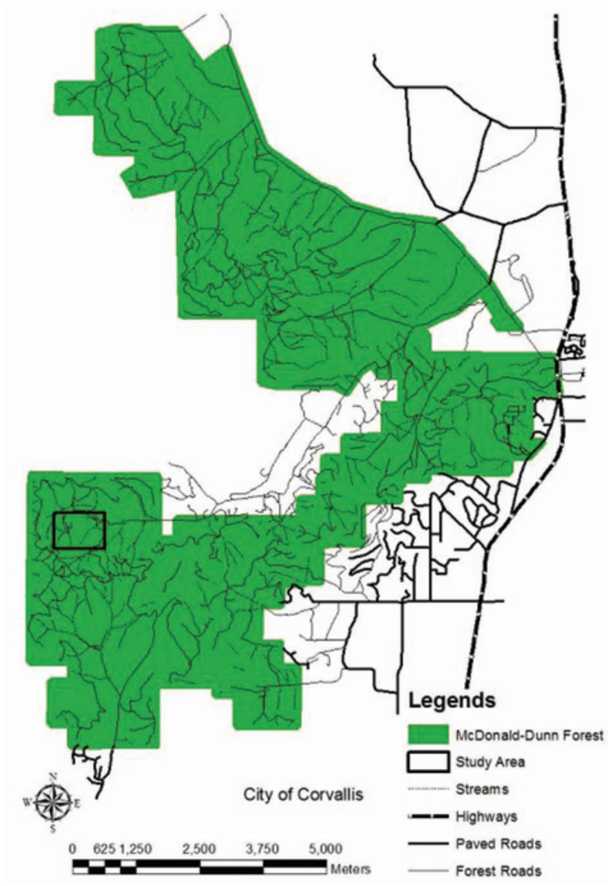

Fig. 1. McDonald-Dunn Research Forest and location of study area

average first return and average last return (ground) densities, respectively. Based on ground-truth measurements using real-time kinematic GPS measurements, the vertical accuracy was 0.02 m at one-sigma absolute deviation.

A study area of 70 ha (1000×700 m) was selected from McDonald-Dunn Research Forest (Fig. 1). LiDAR data from within the study area were extracted using ArcGIS 9.2 software. Soil and stream data layers of the study area drawn from the McDonald-Dunn Research Forest database were converted into a raster format (1×1 m). The soil and stream layers were re-projected to a match the Universal Transverse Mercator projection used for the LiDAR data.

Following all data spatial data pre-processing, the LiDAR data (DEM), soil, and stream layers were converted into an ASCII format for input into the 3D forest road alignment optimization model.

2.2. Road alignment optimization model

The 3D forest road alignment optimization model implemented in this study, TRACER, is developed to assist road managers with rapid evaluation of alternatives for the most economical path selection problem (Akay, Sessions 2005). The model selects the best potential road location path that minimizes the sum of construction, maintenance, and transportation costs while satisfying design specifications. A modern optimization technique (simulated annealing) is implemented to search for the best path (Akay 2006). Simulated annealing guides the search for the best path using a neighbourhood search of incremental changes to the vertical and horizontal alignment. To minimize earthwork allocation costs for each alternative path, a sub-optimization problem using linear programming (Mayer, Stark 1981) is solved. The linear programming approach, rather than the conventional mass diagram, was chosen since it has the advantages of being able to consider various soil characteristics along the roadway and possible borrow and landfill locations. In order to read soil type data real-time, the model requires a soil type layer.

TRACER employs graphic routines (NewCyber3D, CA) to display high-resolution two and 3D images of the terrain in real-time, based on DEM data. For locating the initial path, intersection points are manually selected using a mouse interactively on the terrain image. After locating the initial path, the model automatically locates cross-sections, computes earthwork, and calculates the horizontal and vertical road alignment locations while considering road design specifications, environmental requirements, and driver safety.

Road design specifications within TRACER include geometric specifications (i.e. road gradient, curvature constraints, design speed, etc.), local site specifications (i.e. soil characteristics, stand data, etc.), and economic data (i.e. unit costs for road construction, maintenance, and transport activities). The environmental considerations that are addressed by TRACER include min allowable road grade for proper drainage, distance from streams, and max height of cuts and fills for soil protection. In addition, stopping sight distance on horizontal curves is applied within TRACER road design criteria in order to ensure driver safety. Additional detail and technical information regarding TRACER are also available in Akay and Sessions (2005) and Akay (2006).

2.3. Road sediment delivery prediction

For road sedimentation applications, TRACER implements the equations used in the GIS-based model (SEDMODL) that estimates the average annual volume of sediment delivered to a stream from road networks (Akay *et al.* 2008). SEDMODL estimates the sediment delivered to a stream from each road section using empirical relationships between road surfacing, road use, road template, road grade, vegetative cover, and delivery of eroded sediment to the stream channel. Total sediment delivered from each road segment (ton per year) is predicted from two potential road sediment sources: road tread and cut-slope.

$$\text{Tread Sediment} = GE_r \cdot S_f \cdot T_f \cdot G_f \cdot P_f \cdot D_f \cdot L_r \cdot RW, \quad (1)$$

$$\text{Cutslope Sediment} = GE_r \cdot CS_f \cdot h_c \cdot D_f \cdot L_r, \quad (2)$$

where GE_r – geological erosion rate, kg/m^3-yr; S_f – surfacing factor; T_f – traffic factor; G_f – road grade factor; P_f – precipitation factor; D_f – delivery factor; L_r – length of the road segment, m; RW – road width, m; CS_f – cut-slope cover factor; h_c – cut-slope height, m.

Factors used in the tread and cut-slope sediment formulas are obtained from look-up tables in the SEDMODL documentation, which are generated from previous research from regions within Idaho, Washington, and Oregon (Akay *et al.* 2008). The geological erosion rate is based on dominant lithology and age. The sediment model provides the user with the surfacing factors of various surface types such as gravel (0.2), pitrun (0.5), and native surface (1.0) (Akay, Sessions 2005). Traffic factors of various road classes are given based on the average measurements taken during road erosion inventory studies (Reid, Dunne 1984). Based on these studies, traffic factors of primary, secondary, and spur roads are suggested as 10, 2, and 1, respectively. The road slope factors are assigned to each road stage based on the road grade classes. For road stages with grade of less than 5%, 5% to 10%, and greater than 10%, the road grade factors are 0.2, 1.0, and 2.5, respectively (Reing *et al.* 1991).

The precipitation factor in SEDMODL is computed based on the average annual precipitation falling within a watershed basin (Reid, Dunne 1984). The sediment model computes the erosion delivery factor for each road stage based on the proximity of roads to streams. It is assumed that a road segment that delivers directly to streams results a delivery factor of 1.00 (i.e. at stream crossings). A road segment within 30 m and 60 m of a stream results a delivery factor of 0.35% and 0.10%, respectively (i.e. at roads parallel to streams). The road segments that are located further than 60 m do not deliver sediment to streams (i.e. sediment do not reach the stream). In order to compute the stream distance, the model database requires a spatial stream database. The cut-slope cover factor as a percent of vegetative or rock cover on cut-slopes is also included in the sediment prediction equation based on local conditions within the watershed. Road width, length of the road stage, and cut-slope height in the model are computed based on road template information (Akay 2006).

2.4. Road alignment application

TRACER was applied to a sample landscape area with the goal of locating a single-lane forest road connecting two points while taking into account road design constraints, environmental considerations, and transportation safety. A 3D image of the terrain was generated from the LiDAR-derived DEM. Primary road design constraints for input into the road design model were adopted based on standard forest road design practices in Pacific Northwest (Table 1) (Akay, Sessions 2005). The cost elements of road construction and maintenance were determined based on the "Cost Estimate Guide for Road Construction" prepared by the USDA Forest Service.

Within TRACER, once an initial path was manually generated on the 3D view of the terrain, the optimization algorithm searched for all the feasible vertical alignments near the initial path and selected the optimal alignment that minimized the total road cost. For each alternative road alignment, TRACER estimated the total sediment yield. The road alignment with the least amount of sediment delivered to streams was selected for comparison to the initial least cost road alignment.

3. Results and discussion

The soil and stream layers generated using ArcGIS 9.2 (Fig. 2). The study area consisted of silty clay (SC) loam, gravelly silty clay (GSC) loam, and very cobbly (VC) loam. The geologic age and lithology combination in the study area was Tertiary/Basalt based on the geologic maps. The LiDAR-derived in the study area ranged from 227 m to 594 m, with an average elevation of 391 m (Fig. 3). The average ground slope was found to be 43%.

The initial road alignment generated manually resulted in a total road cost of 13 815 EUR. Using TRACER to design the optimal road alignment with min cost reduced the total road cost to 12 687 EUR. Thus, the road alignment optimization model reduced the total road cost about 8.17%. This percent reduction in cost is similar to that determined by previous research. In a similar study where Genetic Algorithm (GA) and Tabu Search (TS) were applied to determine the optimum forest road alignment, Aruga *et al.* (2005b) found that GA and TS reduced the total road cost by 11.54% and 8.84%, respectively.

For the road alignment that minimized sediment delivery, the road length was found to be slightly longer (352 m) than that of the optimal road alignment (350 m), while the average road gradient reduced from 11.6% to 9.9%. The total road cost was computed as 14 955 EUR, which indicated that minimizing the sediment delivery increased the total road cost by 17.88%.

In both road alignments, it was required to locate the horizontal curves with the radius of 25.18 m. However, vertical curves were not required since the absolute value of the difference between grades was less than 5.0% along the roadway (Fig. 4). The average side slopes for both alignment scenarios were computed as approx 22.0%.

Detailed cost summary for the values of main cost components were calculated for both design scenarios (Table 2). The largest cost component for both road alignments was construction cost, followed by maintenance and transportation costs. For the optimal road alignment with min total cost, earthwork cost (39.24%) and surfacing costs (35.86%) were the largest components of total road construction cost.

Table 1. Primary road design constraints for road design application

Constraints	Values
Min radius of horizontal curve	18 m
Min length of vertical curve	15 m
Min value of differences between grades	5%
Min gradient (for drainage)	±2%
Max gradient	18%
Max cut and fill height	2 m

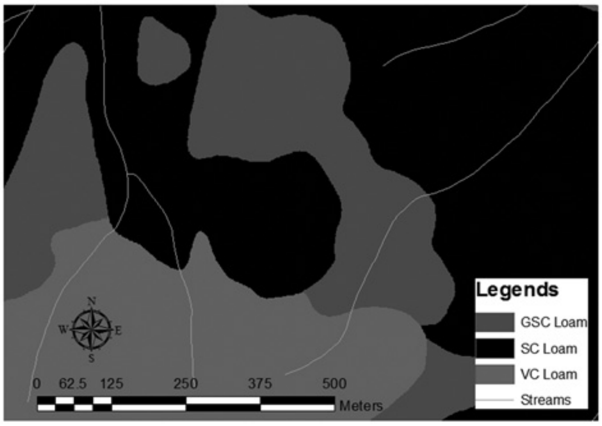

Fig. 2. The soil and stream layers in study area

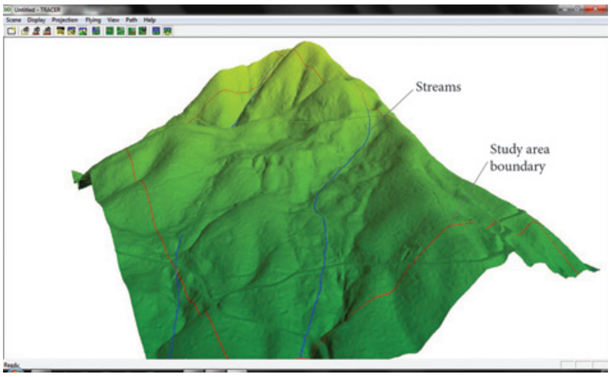

Fig. 3. 3D view of the study topography within TRACER's interface

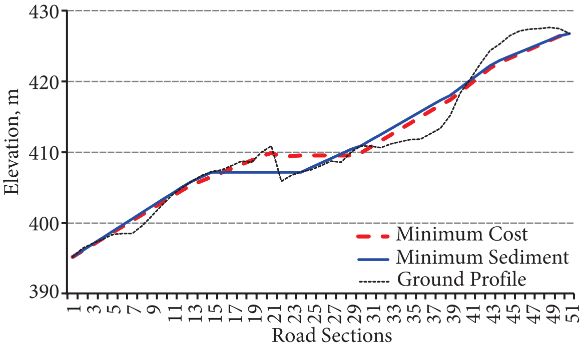

Fig. 4. Ground profile and road profiles for both design scenarios

Table 2. Main cost components for two road design scenarios

Cost components	Optimal road alignment, EUR	Alignment with min sediment, EUR
Construction		
Earthwork	4170	4901
Construction Staking	104	104
Clearing and Grubbing	578	595
Drainage	395	503
Seeding and Mulching	325	338
Surfacing	3812	5223
Water Supply and Watering	846	741
Riprap	399	399
Maintenance		
Rock Replacement	361	447
Blading	54	54
Culvert, Ditch, Brushing	816	816
Transportation	826	835

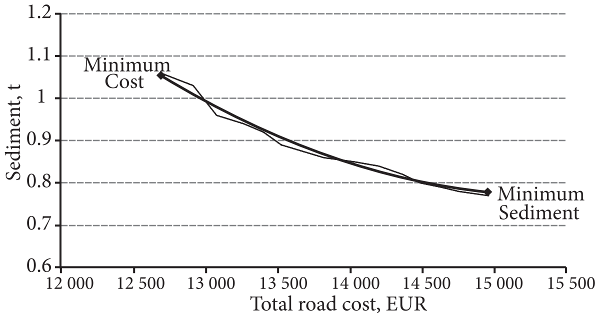

Fig. 5. The relationship trend between total road cost and sedimentation delivery

The results indicated that the road alignment with min sediment yield increased the earthwork cost and surfacing cost by 17.52% and 37.02%, respectively, because of changes on road length and gradient. The road maintenance cost also increased in the min sediment delivery scenario by about 6.96% primarily due to the increased rock replacement cost. Finally, the proportion of transportation cost was 6.51% and 5.58% of the total costs in both road alignments, respectively.

Sediment delivery to streams is considered a critical indicator of environmental impact of forest road construction practices (Grace *et al.* 1998). The optimal road alignment which minimized costs delivered average annual sediment of 1.06 t (3.03 t/km) to the streams. In the SEDMODL, the total sediment delivered from each road segment originates from two sediment sources: tread and cut-slope activities (Akay *et al.* 2008). The amount of tread and cut-slope sediment in the optimum road alignment results was 0.97 t and 0.09 t, respectively.

For the road alignment scenario that minimized sediment delivery, the sediment delivered to the streams from the road section decreased to 0.77 t (2.19 t/km), a 27.36% decrease compared to the sediment delivered by the cost minimized alignment. According to SEDMODL formulas, a road alignment with a gradient greater than 10% produces 2.5 times more sediment than a road alignment with 5–10% road gradient. Thus, the optimum road alignment produced about 38% more sediment delivery than the sediment minimized road alignment, mainly due to steeper road gradient. The amount of tread and cut-slope sediment by the sediment minimized road alignment was 0.70 t and 0.07 t, respectively. The slightly longer road alignment, gentler road gradient, and additional earthwork of the sediment minimized road alignment reduced the sediment delivery to the streams by about 0.29 t, while the total road cost increased by 2269 EUR, over the cost-minimized road alignment (Fig. 5). Therefore, the unit cost of minimizing sediment delivery to the stream in this example is approx 7823 EUR per ton of sediment.

The road alignment optimization model searched for the optimum solution based on a high-resolution DEM that was derived from LiDAR measurements. The accuracy of the LiDAR data directly affects the performance of the optimization model employed by TRACER, especially in earthwork allocation process. Aruga *et al.* (2005a) reported that using a LiDAR-based high-resolution DEM provided more accurate results in earthwork computations than using a DEM generated by ground surveying equipment. In this study, a 1 m by 1 m resolution DEM of the study area was generated based on LiDAR dataset with the vertical accuracy of 0.02 m (Akay *et al.* 2012).

4. Conclusions

The TRACER forest road alignment optimization model, previously developed to assist road managers in designing a preliminary road alignment, was implemented to estimate sediment volume and the cost of sediment reduction in forest road construction activities. The optimization model was applied to consider two road alignment scenarios. The model initially searched for feasible alignment alternatives with the search tolerances and selected the optimal alignment that minimized the total road cost, while constraining road design parameters, environmental considerations, and stopping sight distance. Then TRACER was used to identify the road alignment that delivered the least sediment yield to streams, while considering the same initial constraints. A GIS-based sediment prediction model was integrated into TRACER to estimate the sediment delivered to the streams from the road section.

1. The results from the model application indicated that the total cost of road construction and maintenance activities in the alignment generated by the optimization model that minimized costs was 1128 EUR less than the initial alignment that was manually digitized within TRACER.

2. In the second part of the application, the sediment delivery decreased by 27.36%, while the total cost was 2269 EUR more than that of the optimum min cost alignment.

3. The cost of reducing annual sediment delivery from forest road to the streams is approx 7823 EUR.

4. It was not aimed to generalize the results from this application to other areas given the unique environmental characteristics associated with specified study area. However, it was found that the forest road alignment optimization model was an effective decision support tool to investigate the trade-offs between economic and environmental considerations in locating forest road alignments.

5. Thus, this approach has great potential to provide benefits for road managers in identifying and evaluating potential road alignment options in areas within their own jurisdictions that are vulnerable to excessive sediment production.

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