Incorporating Soil Surface Erosion Prediction into Forest Road Alignment Optimization

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ABSTRACT

A previous study introduced a forest road design model developed to simultaneously optimize horizontal and vertical alignments of forest roads using a Tabu Search optimization technique and a high-resolution Digital Elevation Model (DEM). In this study, surface erosion prediction was incorporated into the road design model, so that users can optimize horizontal and vertical alignments of forest roads while constrained by maximum allowable sediment delivery from roads to streams. The road alignment optimization model was applied to a part of the Capitol State Forest in western Washington state. The application confirms the potential of the model to determine forest road alignments in a way to reduce total road costs as well as sediment delivery to streams. This paper also discusses the effects of DEM resolution on forest road alignment optimization. The accuracy of generating ground profile and forest road alignments depends on the resolution and accuracy of the DEM. The study results suggest that a 10-m grid DEM might be inappropriate to use for the purpose of road design and alignment optimization due to the lower accuracy in its elevation representation.

Keywords: *forest road alignment, high-resolution digital elevation model, Tabu Search, road cost optimization, road erosion*

Introduction

Laying out forest roads has been a difficult task in managing forest resources. Forest engineers often face a challenge in finding good road locations on the ground among many possible alternatives. Several road design tools (e.g., RoadEng by SoftTree Inc.) have been developed to help forest engineers with road layout and design, but such tools are dedicated to drafting road traverse lines, profile and cross sections, and calculating earthwork volumes on fixed road alignments. Very few analytical tools exist for road alignment optimization, yet most of them optimize either only horizontal (Howard et al. 1968, Trietsch 1987) or vertical alignments (Kanzaki 1973, Goh et al. 1988). Simultaneous optimization of horizontal and vertical alignments has not been well investigated due to increased problem complexity. Our previous study (Aruga et al. 2005b) introduced a forest road design model that simultaneously optimizes horizontal and vertical alignments of forest roads using a high-resolution Digital Elevation Model (DEM) and a Tabu Search algorithm (Glover and Laguna 1993). Once an initial horizontal alignment of road is established by locating a series of intersection points, the model optimizes road alignments based on estimated construction and maintenance costs.

Although the Tabu Search algorithm successfully optimized horizontal and vertical alignments in the previous study (Aruga et al. 2005b), the road analysis was solely based on economic benefits and did not take into account any environmental impact of the road. Forest roads can substantially alter hydrologic and geomorphic response of forested watersheds (USDA 2001), and they are known as a primary sediment source for streams (Luce and Wemple 2001). Thus, forest road alignments should be optimized not only to minimize costs, but they should also be laid out in a way that future sediment delivery from roads is constrained.

Akay and Sessions (2005) developed a three-dimensional forest road alignment optimization model, TRACER, which uses a high-resolution DEM. Based on a user-defined horizontal alignment, TRACER is able to optimize vertical alignment of a forest road section, while calculating construction, maintenance, and transportation costs. It also estimates the average annual volume of sediment delivered to a stream from the road section using a road sedimentation model, SEDMODL. Murphy and Wing (2005) used SEDMODL2 (Boise Cascade Corp. and NCASI 2003), which is a successor of SEDMODL, to examine road sediment yields from dispersed versus clustered forest harvesting activity in the McDonald-Dunn Research Forest of Oregon State University.

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Sediment volume estimates of SEDMODL and SEDMODL2 are based on road erosion and traffic factors drawn from the Washington State Department of Natural Resources *Standard Method for Conducting Watershed Analysis* (WA State DNR 1997). Murphy and Wing (2005) summarize validation studies for SEDMODL and SEDMODL2. The results are mixed. The models overestimate sediment yields in several studies while providing relatively close estimates in others.

The method to predict sediment delivery used in SEDMODL2 was integrated into our road alignment optimization model. By generating exact road alignments and templates, the road alignment optimization model provides soil erosion parameters that are required in predicting sediment delivery from roads to streams. The model identifies locations and spacing of drainage structures based on Washington State's *Forest Practice Board Manual* (WA State DNR 2001) and predicts road-to-stream sediment delivery. The model then minimizes road construction and maintenance costs while keeping sediment yields from roads under a given allowable maximum level. In this paper, the new road alignment optimization model and its applications to a part of the Capitol State Forest in western Washington state is described. Also the effects of DEM resolutions on the ground profile and road alignments generated by the optimization model are examined. The effects are briefly discussed.

Methods

Once an initial horizontal alignment of road is established between given intersection points, the model generates alternative horizontal and vertical alignments while locating cross sections along the road prism. Based on each of the alternative road alignments, the model calculates earthwork volume and estimates road construction and maintenance costs as well as sediment yields. Then road alignments are optimized to minimize construction and maintenance costs while constraining sediment delivery from roads to streams using a Tabu Search optimization technique. Details on forest road designs, earthwork volume calculation, cost estimation, and optimization techniques with Tabu Search are documented in our previous paper (Aruga et al. 2005b). In this paper, the methods for locating ditch-relief culverts and estimating soil erosion are described along with how to integrate soil erosion into road alignment optimization.

Cross Sections

Cross sections are required to compute earthwork volumes and sediment yields. In this study, the following dimensions were used when designing cross sections (**Fig. 1**): 4.0 m road width and additional curve widening (e.g., 0.5 m), 0.8:1 (horizontal:vertical) cut slope, and 1:1 fill slope. Although a 1:1 fill slope might not be suitable in steep terrain, this study assumed that it is acceptable because the study area is relatively gentle (average ground slope is 21%) and fill slope heights are generally low. The road dimensions, such as cut and fill slope angles, could be easily modified in the model for other applications. When placing culverts, the model ensures at least 0.3-m fill over top of the culvert inlet (**Fig. 1**). A catch basin is constructed with 1 m bottom width between a ditch point and the toe of a cut slope.

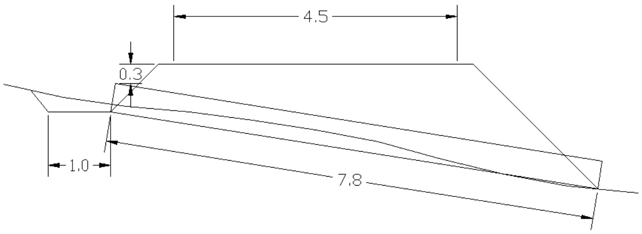

Figure 1. ~ *Cross section on a curve where additional curve widening of 0.5 m is applied to the standard road base of 4.0 m.*

Table 1. ~ *Determination of adequate drainage structure spacing as a function of road gradient in western Washington State (WA State DNR 2001).*

Road gradient	Maximum	Minimum
	- - - - - - - - - - - (m)	- - - - - - - - - - -
< 2%	300	150
2% to 6%	240	90
6% to 12%	210	60
> 12%	180	30

In the previous study (Aruga et al. 2005b), 0.075 to 0.12 m size rock (US\$7.9/m^3) is used for the base course with 0.25-m depth. Then, rock size and depth for traction surface is determined on road grades (Kramer 2001):

- 0.080-m-deep traction surface with 0.040-m rock when the road grade is less than 16 percent and
- 0.10-m-deep traction surface with 0.025-m rock when the grade is greater than or equal to 16 percent.

The unit costs of traction surface materials used in the analysis are US\$11.8/m^3 for traction surface rock (0.040 m) and US\$15.7/m^3 for finer traction surface rock (0.025 m). In addition to the road surfacing types used in the previous study (Aruga et al. 2005b), this study assumed pit-run material (US\$3.9/m^3) could be used as a base course without a traction surface if the road grade was less than 10 percent.

A ditch-relief culvert is located on the lowest point of each vertical curve or at a defined interval. Washington State's *Forest Practice Board Manual* (WA State DNR 2001) provides the maximum and minimum drainage structure spacing by road gradient for each region in the state (**Table 1**). Drainage structure spacing depends on the characteristics of the rainfall in the region. The optimization model estimates culvert spacing based on the guidelines shown in **Tables 1 and 2** (WA State DNR 2001). Culvert spacing starts at the maximum drainage structure spacing (**Table 1**) and further decreases depending on percent side-slope, average proximity from roads located

Table 2. ~ *Culvert spacing reduction factors as a function of topography, road, and environmental elements (WA State DNR 2001).*

Element	Sub element	Factor
		(%)
Percent side-slope	< 35%	0
	35 % to 50%	5
	50% to 60%	10
	60% to 70%	15
	> 70 %	20
Average proximity from roads located above stream to the stream	> 90 m	0
	60 m to 90 m	5
	30 m to 60 m	10
	15 m to 30 m	15
	< 15 m	20
Road use and condition	Well maintained	0
	Poorly maintained	5
Road surfacing	Paved	0
	> 015 m gravel	1
	< 0.15 m gravel	3
	Native material	5
Precipitation zone	< 635 mm	0
	< 1270 mm	5
	< 3048 mm	10
	> 3048 mm	15
Soil erosion potential	Low	0
	Moderate	5
	High	15
	Highly erodible and unstable	20

above stream to the stream, road use and condition, road surfacing, precipitation zone, and soil erosion potentials (**Table 2**). If the reduced culvert spacing is less than the minimum spacing (**Table 1**), the minimum spacing is used for a distance between culverts.

Road Erosion Calculations

SEDMODL2 (Boise Cascade Corp. and NCASI 2003) estimates erosion from roads using formulas developed from empirical relationships between geologic erosion rate, road surface type, road width and length, average road slope, cut slope cover density, cut slope height, road age, and average precipitation factor (**Table 3**). The average precipitation factor, RF, is calculated using the equation:

$$RF = 0.016[PR/25.4]^{1.5} \qquad [1]$$

where:

PR = average annual rainfall (mm).

The total soil erosion from each road segment, SE (tonnes/yr), is calculated based on the formulas:

$$SE = 0.9072 \times GE \times (TE + CE) \times AG \times PR \qquad [2]$$

Table 3. ~ *Soil erosion estimation factors (Boise Cascade Corp. and NCASI 2003).*

Element	Sub element	Factor
Tread surfacing	Asphalt	0.03
	Gravel	0.2
	Pit tun	0.5
	Native surface	1.0
Road width and traffic	Abandoned/blocked road	0.1
	Spur road	1.0
	Secondary road	2.0
	Primary road	10.0
Road slope	< 5%	0.2
	5% to 10%	1.0
	> 10%	2.5
Cut slope cover	100%	0.1023
	90%	0.1500
	80%	0.2003
	70%	0.2540
	60%	0.3116
	50%	0.3742
	40%	0.4435
	30%	0.5222
	20%	0.6155
	10%	0.7700
	0%	1.0000
Road age	0 to 1 year	10.0
	2 years	2.0
	> 2 years	1.0
Delivery	Directly to stream	1.0
	< 30 m	0.35
	< 60 m	0.1

where:

GE = the geologic erosion factor,

TE = total soil erosion from the tread of each road segment (tonnes/yr),

CE = total soil erosion from the cut slope of each road segment (tonnes/yr), and

AG = the road age factor.

TE and CE are calculated by the equations:

$$TE = SU \times WT \times GR \times L \qquad [3]$$

where:

SU = the tread surfacing factor,

WT = the road width and traffic factor,

GR = the road slope factor, and

L = segment length (m).

and:

$$CE = CC \times CH \times L \qquad [4]$$

where:

CC = the cut slope cover factor and

CH = cut slope height.

Then, the total sediment delivered to the stream network, TS (tonnes/yr), is estimated based on the delivery factor of soil erosion, DF.

$$TS = SE \times DF \qquad [5]$$

SEDMODL2 (Boise Cascade Corp. and NCASI 2003) makes the following assumptions to determine the length of road segments contributing to road-to-stream sediment delivery (**Table 4**):

- In-sloped roads: the entire length and width of the road segments located between the first upslope ditch-relief culvert and a stream crossing (**Fig. 2a**).
- Out-sloped roads: only 15-m road segments above a stream (**Fig. 2b**). No ditches and ditch-relief culverts on out-sloped forest roads.

Optimization Procedure

Our Tabu Search procedure involves a short-term memory phase followed by an intensification strategy as described in the previous paper (Aruga et al. 2005b). It begins with user-defined road intersection points which determine the initial horizontal alignment. Then, it creates various alternatives of road horizontal and vertical alignments (neighborhood solutions) by changing the location and height of each grade change point. All of the alternatives created are evaluated in terms of road construction and maintenance costs and estimated road-to-stream sediment delivery. The following objective function is used in optimizing road alignments in the Tabu Search:

$$Min \quad T_C = C + M_0 \qquad [6]$$

subject to

Sediment < Allowable sediment

where:

C = the construction cost and

M_0 = the discounted maintenance cost.

The total cost of each road section is determined considering construction and maintenance activities (Aruga et al. 2005b).

For each iteration of Tabu Search, a neighborhood, which is a set of new feasible solutions, is created by slightly changing the previous feasible solution. In this study, the model generates neighborhood solutions by changing the locations of curve intersection points, radii of horizontal curves, and the placement and heights of grade change points. For example, the model changes grade change point heights at an interval of 1 m within 5-m zones around elevations of grade change points (Aruga et al. 2005b) and evaluates those alternative alignments during the initial stage of optimization. Then, during the intensification stage, the model generates alternative road alignments by shifting grade change point heights at an interval of 0.1 m within ±1 m around the selected alignment in order to refine the alignment. Because of the DEM errors described below, we do not have to run the intensification stage when using 3.0-m, 4.5-m, and 10-m grid DEMs. Based on our computation experience, the initial optimization phase was terminated after 1,000 iterations, while the intensification stage stopped after 100 iterations (Aruga et al. 2005b).

Table 4. ~ *Road segment lengths/widths of different road drainage templates contributing to sediment yields (Boise Cascade Corp. and NCASI 2003).*

Road drainage template	Tread	Cut slope
In-sloped	Entire segment length, width	Entire segment length
Out-sloped	15 m, total width	15 m
Crowned	Half of total road width for entire segment length	Entire segment length

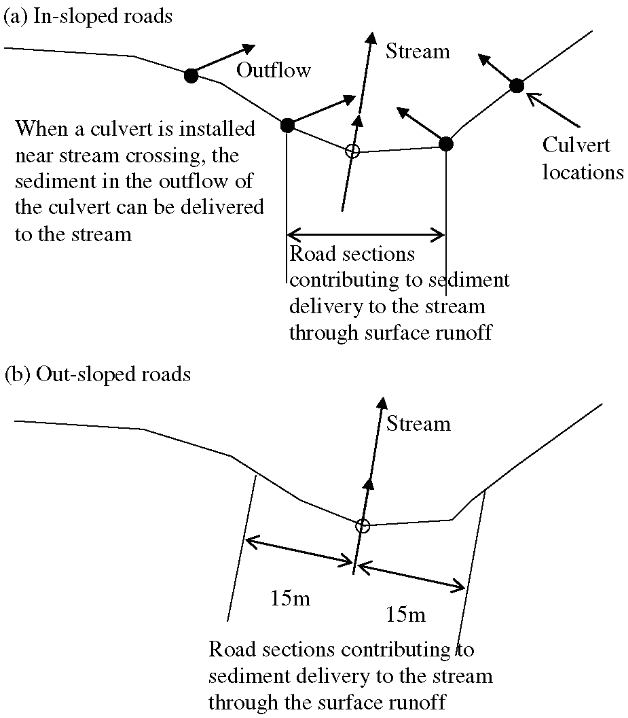

Figure 2. ~ *A plan view showing culvert locations, the outflow of culvert and road sections contributing to sediment delivery to the stream: (a) in-sloped roads and (b) out-sloped roads.*

Application

The road alignment optimization model developed in this study was applied to a part of the Capitol State Forest in western Washington state (**Fig. 3**). Most of the study area is cov-

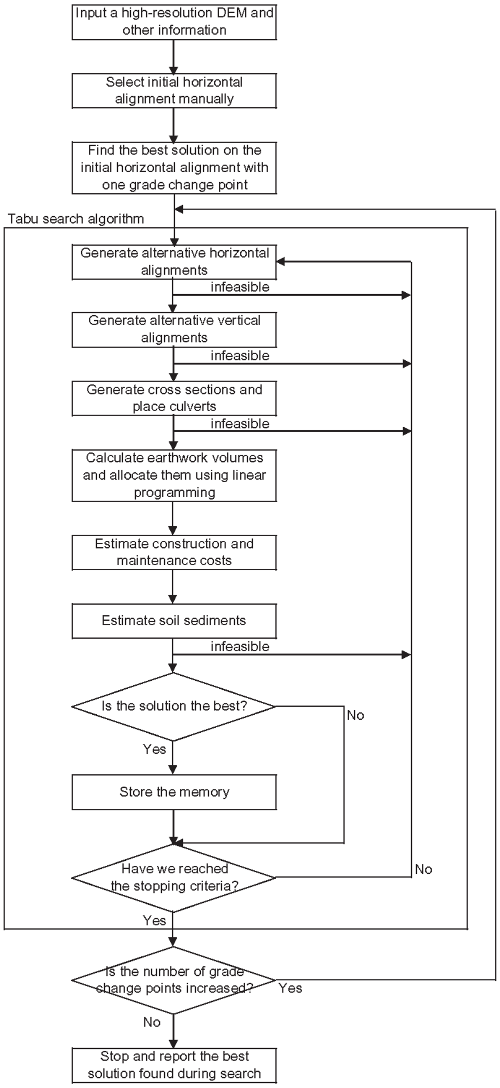

Figure 3. ~ *Flowchart of the model.*

Table 5. ~ *Flight parameters and scanning system setting (Reutebuch et al. 2003).*

	1999	2002
Flying height (m)	200	1,000
Flying speed (km/h)	90	--
Scanning swath width (m)	70	650
Forward tilt (°)	8	--
Footprint diameter (cm)	--	90 cm
Laser pulse density (pulses/m^2)	4	1
Laser pulse rate (points/s)	7,000	30,000

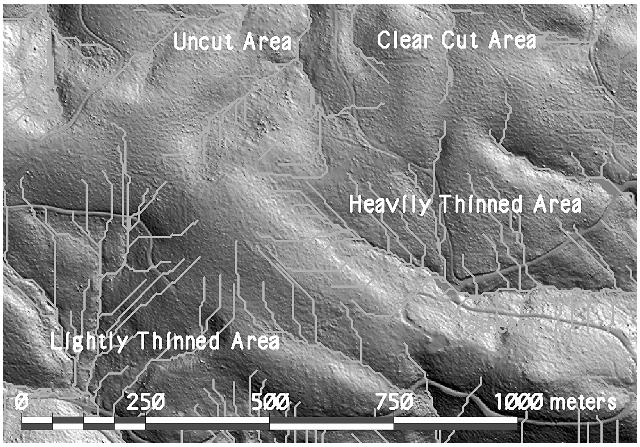

Figure 4. ~ *Shade relief map of 1.5-m grid DEM generated from LiDAR data in 1999.*

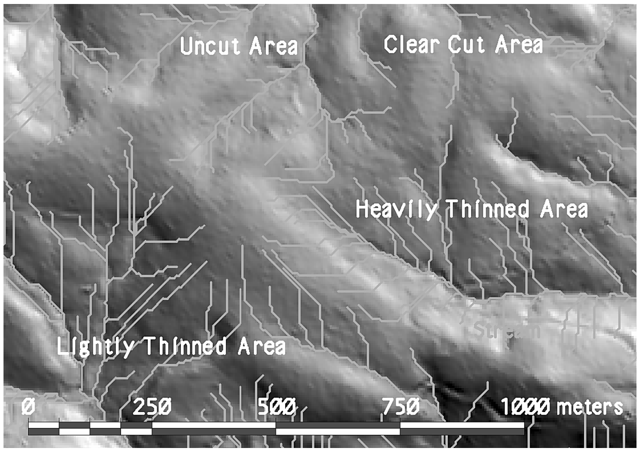

Figure 5. ~ *Shade relief map of 4.5-m grid DEM generated from LiDAR data in 1999.*

ered by 70-year-old coniferous forests. Elevation ranges from 150 to 400 m with an average ground slope of 21 percent. This site was mapped by a small footprint LiDAR system in the spring of 1999 and the LiDAR data was converted into a 1.52- by 1.52-m grid DEM (hereafter referred to as 1.5-m DEM) and 4.56- by 4.56-m grid DEM (4.5-m DEM) (**Table 5, Figs. 4 and 5**). Reutebuch et al. (2003) measured the vertical accuracy of the 1.5-m grid DEM by comparing the DEM with 348 points field surveyed using Total Station. As the result, the root mean square error (RMSE) was 0.43 m.

In addition, the 1.83- by 1.83-m grid DEM (1.8-m DEM) was obtained from the Puget Sound LiDAR Consortium (PSLC). PSLC mapped the site using a LiDAR system in 2002 (**Table 5**) and indicated that the vertical accuracy is 30 cm or less on a flat, open surface. We also obtained the 1/9 arc second DEM (3.43 by 2.35 m, hereafter referred to as 3.0-m DEM) and 1/3 arc second DEM (10.36 by 7.08 m, hereafter referred to as 10.0-m DEM) from the National Elevation Dataset developed by the U.S. Geological Survey. The metadata of 1/9 arc second grid DEM indicates that the vertical accuracy of 1/9 arc second grid DEM is 41 cm or less on a flat, open surface.

The road construction site where the model was applied is located in the Black River Watershed. Soil, geology, and hydrology data were obtained from the Washington State Department of Natural Resources. Soil types in this area include Olympic silt loam and Olympic clay loam. Geology in this

Table 6. ~ *Costs and total amount of sediment delivered from the entire road sections to streams on the seven optimized alignments .*

	Optimized alignment						
	1: Traction surface	2: Additional ditch-relief culvert	3: Out-sloped road	4: Out-sloped road with rut	5: Pit-run	6: Additional ditch-relief culvert with two different surface materials	7: Out-sloped road with two different surface materials
Total unit cost (US$/m)	48.7	51.2	44.7	44.7	32.3	40.5	35.6
Road length (m)	670	655	683	683	719	739	718
Total cost (US$)	32,701	33,522	30,542	30,542	23,253	29,940	25,598
Total sediment (tonne/yr)	0.955	0.239	0.216	0.961	1.314	0.200	0.163

area includes basalt flows and flow breccias, Crescent Formation. Four streams were identified in the area through the geographic information system (GIS) analysis followed by a field reconnaissance.

In order to use culvert spacing reduction factors in **Table 2**, the model computed percent side-slope and average road distance above each stream. The road use and condition factor of 0 percent was used in the model assuming the roads are well maintained. The road surfacing factor was set to 1 percent because the road surface consisted of 0.25 m depth base course with 0.080 m or 0.10 m depth traction surface, or 0.25 m depth pit-run without traction surface. Based on the precipitation of about 2,000 mm in the study site, the precipitation zone factor was set to 10 percent. The soil erosion potential was assumed to be low based on the geology in this site, so a soil erosion potential factor of 0 percent was used.

Road slope and delivery factors were computed in the model using estimated soil erosion factors (**Table 3**). Because geology in this area is basalt, a geologic erosion factor of 1.0 was used (Boise Cascade Corp. and NCASI 2003). Road tread surfacing factors for gravel and pit-run were 0.2 and 0.5, respectively. The road width and traffic factor was set to 1.0 because the road is to be built as a spur road. As 70 percent of cut slopes were assumed to be covered with vegetation, the cut slope cover factor was set at 0.2540. The road age factor was set to be 1.0, indicating the road is not new. The intention of this study was to estimate chronic sediment yields from roads rather than peak sediment immediately after new construction. A rainfall factor of 11 was calculated for the precipitation of 2,000 mm using Equation [**1**].

Results

The new road alignment optimization model was applied to the road section which was used in the previous study (Aruga et al. 2005b) in order to compare the results of optimized road alignments with and without the consideration of surface erosion. The same DEM resolution, 1.5 m, was also used. In the previous study (Aruga et al. 2005b), the entire road was assumed to be in-sloped and surfaced with high-quality base course rock and a traction surface. Sediment from entire road sections resulting from this condition was estimated at 0.955 tonnes/year (Column 1 in **Table 6**). Then, the model optimized horizontal and vertical alignments at different levels of sediment constraint. From our application, it was found that total road cost increases as the allowable amount of sediment decreases (**Fig. 6**). Obviously, the ability of the model to optimize road alignments with and without a sediment constraint can provide trade-off analyses between sediment yields and total road costs.

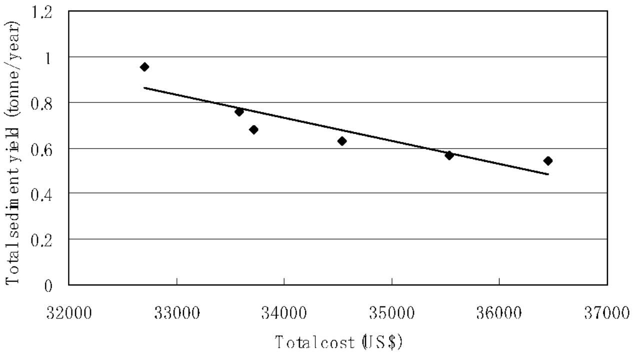

Figure 6. ~ *Relationship between total cost and total sediment yield.*

Discussion

A series of sensitivity analyses was conducted to test the model and address the impacts of culvert-to-stream distance, drainage types, surface materials, and DEM resolutions on the results of the model.

Culvert-to-Stream Distance

The distance between a stream crossing and the first upslope drainage structure is one of the major factors influencing volume of sediment delivery. When culverts are located near stream crossings, the direct sediment delivery to stream from surface runoff could be small, but the sediment delivery caused by culvert outflow could be substantial. The SEDMODL2 (Boise Cascade Corp. and NCASI 2003) assumes that 35 percent and 10 percent of the sediment in culvert outflow is delivered to stream when culverts are located within 30 m and 60 m, respectively, from the stream (**Table 3**). Therefore, it is important to evaluate the outflow area to ensure sediment-laden water is filtered prior to reaching any stream (**Fig. 2a**). For this reason, it is recommended that a culvert should be installed 15 to 30 m above all stream crossings (WA State DNR 2001).

Total costs and sediment yields on the road sections when additional ditch-relief culverts are installed at 15 m above streams (Column 2 in **Table 6**) were evaluated. Due to the additional culverts, the total construction cost becomes greater than the case without additional ditch-relief culverts. Placing culverts at 15 m above a stream intersection, however, dramatically reduced sediment delivery. Sediment yield from the road with additional ditch-relief culverts was about one-fourth of sediment yield from the road without additional ditch-relief culverts.

Road Drainage Types

Total costs and sediment yields on the road sections with the assumption that the entire road section is out-sloped (Column 3 in **Table 6**) were also evaluated. Earthwork volume for the out-sloped roads was far less than that for in-sloped roads due to no ditches and thus reduced subgrade width. Furthermore, drainage and riprap costs and their related maintenance costs were reduced because culverts were placed only at streams and road intersections without any ditch-relief culverts. The sediment estimation used in the model has limitations in that it relies on given soil erosion parameters and considers only 15 m of out-sloped roads near streams as a sediment delivery source. Even with these limitations, the results of road alignment optimization with sediment consideration imply the out-sloped road template could be an important tool in forest road design to minimize construction costs as well as sediment delivery.

Out-sloped roads, however, need to be carefully located and maintained after construction. Out-sloped roads should not be placed in sites where water flowing to the outside of the road is likely to directly enter a stream or where fill slopes are not stable. Results of this study show that when the road surface cannot be well maintained to prevent ruts, the sediment yield of out-sloped roads could increase to the same level as in-sloped roads (Column 4 in **Table 6**). Moreover, there is a safety issue for traffic on out-sloped roads; they have a higher risk for accidents caused by lateral sliding. Therefore, out-sloped roads should be considered only for low road gradient and low speed road sections.

Road Surface Materials

The road alignments were optimized under the assumption that pit-run (US\$3.9/m^3) is used for a base course when the road gradient is less than 10 percent instead of a higher quality base course (US\$7.9/m^3) with an additional traction surface. As a result, the total costs dropped to US\$23,253, but the estimated sediment amount increased to 1.314 tonnes/year (Column 5 in **Table 6**). This is mainly because the road tread surfacing factor of 0.5 was used for pit-run, which is higher than that of a traction surface (0.2). This implies that lower quality rock surfacing may not be appropriate near streams even though it reduces construction and maintenance costs.

In this study, two different surface materials were applied to the road with an additional ditch-relief culvert and out-sloped roads in order to examine whether it reduces both road construction costs and sediment delivery from roads (Columns 6 and 7 in **Table 6**). For in-sloped roads, a traction surface was only applied to road segments located between the first up-slope culvert and stream crossing. For out-sloped roads, a surface traction was applied only up to 15 m of road segments above stream crossing. Pit-run was applied otherwise. Using two different surface materials and placing culverts 15 m above a stream crossing on in-sloped roads reduced total road costs from US\$33,522 to \$29,940 and sediment yield from 0.239 to 0.200 tonnes/year (Columns 2 and 6 in **Table 6**). Similarly, using two different surface materials on out-sloped roads reduced total road costs from US\$30,542 to \$25,598 and sediment from 0.216 to 0.163 tonnes/year (Columns 3 and 7 in **Table 6**). This implies road construction costs can be reduced as well as sediment delivery from roads by applying additional traction surface only to roads near streams.

Effects of DEM Resolution on Forest Road Alignment Optimization

The vertical accuracy of the 1.5-m, 1.8-m, 3.0-m, 4.5-m, and 10-m grid DEMs were evaluated by comparing elevations of 165 survey points on six cross sections along an existing road (cross section lines 1 through 6 in **Fig. 7**) measured by Total Station. Because DEMs are grid data, a bilinear interpolation was applied to compute the elevation at the horizontal position of each survey checkpoint. The RMSE of the elevation difference between the 10-m grid DEM and Total Station Survey was 7.32 m (**Table 7**). The RMSEs of cross sections generated from 1.5-m, 1.8-m, 3.0-m, and 4.5-m grid DEMs were 0.14 m, 0.25 m, 1.12 m, and 0.70 m, respectively, which are relatively small. Although the 3.0-m and 4.5-m grid DEMs have small vertical

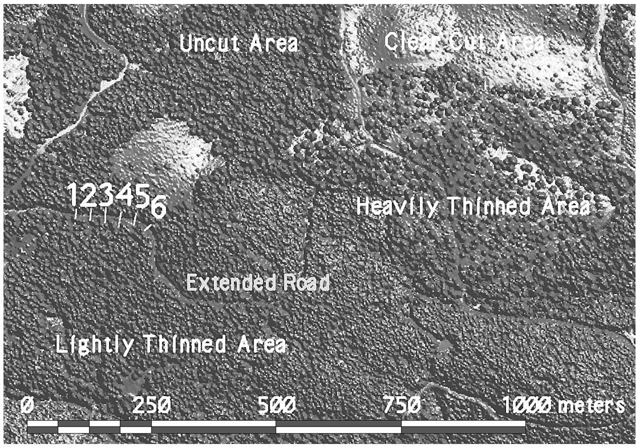

Figure 7. ~ *Shade relief map of Digital Surface Model generated from LiDAR data in 2002 (numbers 1 through 6 indicate Total Station survey points).*

Table 7. ~ *Comparison of cross sections generated from 1.5-m, 1.8-m, 3.0-m, 4.5 -m, and 10-m grid DEMs with those measured by Total Station.*

	1.5 m	1.8 m	3.0 m	4.5 m	10 m
	(m)				
RMSE[a]	0.14	0.24	1.12	0.70	7.32
Maximum	0.92	1.14	2.71	2.64	10.65
SD[b]	0.11	0.19	0.65	0.43	1.38

[a] RMSE = root mean square error
[b] SD = standard deviation

errors, the actual forest road template can be identified only on the cross sections generated from the 1.5-m and 1.8-m grid DEMs due to the small dimensions of road prisms (**Fig. 8**). Cut and fill slopes and road width do not clearly appear on the cross sections generated using DEMs that are lower resolution than 1.8 m.

The effects of DEM resolutions on the ground profile of the same horizontal alignment were evaluated. Elevations on the ground profile were generated at every 6 m in a horizontal distance. The distance of 6 m is used for the cross section interval because Aruga et al. (2005a) found that the earthwork volume can be estimated accurately when the horizontal distance between cross sections is less than 6 m in the study site. Ground profile elevations extracted from the 4.5-m and 10-m grid DEMs were compared with those from the 1.5-m grid DEM. The 1.8-m and 3.0-m grid DEMs were not compared with others because they were measured after road construction. The results show the ground profile generated from the 10-m grid DEM is quite different from other ground profiles (**Fig. 9**). The RMSE in the elevation difference between the 10-m and 1.5-m grid DEMs is 5.70 m (**Table 8**). The RMSE in the elevation difference between the 4.5-m and 1.5-m grid DEMs is 0.34 m. Interestingly, the comparisons indicate that the ground profile generated from the 4.5-m grid DEM is similar to that from the 1.5-m grid DEM although it is still difficult to identify detailed topography on the 4.5-m grid DEM (**Fig. 5**).

The effects of DEM resolutions on the results of road alignment optimization (**Table 9**) were also evaluated. Estimated road length and sediment amount using the 4.5-m grid DEM were similar to those using the 1.5-m grid DEM. When the 10-m grid DEM was used, the estimated total cost was slightly more than those with the 1.5-m and 4.5-m grid DEMs. Road length and total sediment yields estimated on the 10-m grid DEM, however, were quite different from those calculated on the 1.5-m and 4.5-m grid DEMs (**Table 9**). Moreover, the horizontal alignment generated from the 10-m grid DEM was different from those generated from the 1.5-m and 4.5-m grid DEMs. Subsequently, the vertical alignment generated from the 10-m grid DEM was also different from those generated from the 1.5-m and 4.5-m grid DEMs. Based on this study, it seems the grid resolution of 10 m is not high enough to capture detailed topography for road template de-

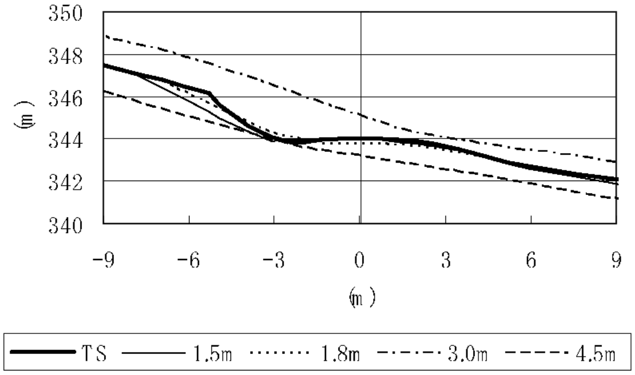

Figure 8. ~ *Cross section on Line 2 generated from 1.5-m, 1.8-m, 3.0-m, and 4.5-m grid DEMs and Total Station.*

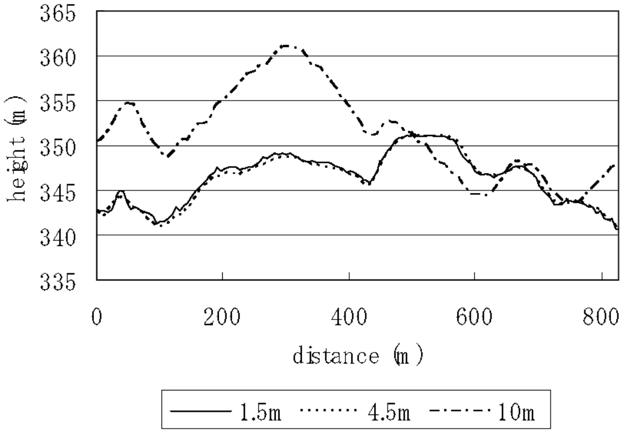

Figure 9. ~ *Ground profile on the three initial alignments: 1.5-m, 4.5-m, and 10-m grid DEM.*

Table 8. ~ *Comparison of ground profiles generated from 4.5-m and 10-m grid DEMs with 1.5-m grid DEM.*

	4.5 m	10 m
	(m)	
RMSE[a]	0.34	5.70
Maximum	0.92	12.34
SD[b]	0.23	3.86

[a] RMSE = root mean square error
[b] SD = standard deviation

Table 9. ~ *Costs and total road-to-stream sediment delivery from the total road section optimized using 1.5-m, 4.5-m, and 10-m grid DEMs.*

	1.5 m	4.5 m	10 m
		(m)	
Total unit cost (US$/m)	48.7	45.5	46.2
Road length (m)	670	671	776
Total cost (US$)	32,701	30,554	35,885
Total sediment (tonne/yr)	0.955	1.049	0.590

sign and, therefore, may not be appropriate for the road alignment optimization purposes.

Conclusions

In this study, a sediment constraint was incorporated into the road alignment optimization model previously developed. A soil sediment estimation method used in SEDMODL2 (Boise Cascade Corp. and NCASI 2003) is embedded in the model to estimate sediment yields from alternative road locations. Using the model, the effects of an additional ditch-relief culvert, an out-sloped road template, and road surface materials on road construction costs and road-to-stream sediment delivery were evaluated. Although out-sloped roads have some limitations since they might be inappropriate where road gradient is steep and fill slopes are unstable, this model suggests out-sloped roads can reduce both road costs and sediment yields if they are well designed and maintained. Placing an additional ditch-relief culvert above the stream can also be an alternative way to minimize sediment delivery.

Field verification in this study is very limited, and model outputs especially in sediment estimates heavily rely on the sediment model behavior that was chosen. The intention in this study is not to present an accurate estimate of sediment, but rather to demonstrate an automatic road location and alignment design approach that considers a sediment constraint. Selecting the right sediment model and providing accurate terrain data will be the key for successful field applications of this approach.

High-resolution DEMs such as 1.5-m and 1.8-m resolution DEMs can identify small changes in topography. The forest road design model fused with such high-resolution DEMs makes it possible to estimate sediment yields due to its ability to produce relatively accurate and precise road prisms. This also implies that high-resolution DEMs can be a substitute for field work when sediment delivery from existing roads needs to be estimated. Our analyses with different DEM resolutions indicate a 10-m grid resolution may not be high enough to capture detailed topography for road template design and alignment optimization. DEMs with resolutions higher than 10 m would be recommended for such analyses.

The forest road construction site in this study is located in stable area with gentle ground slopes. If roads are located in landslide prone areas or constructed in an inappropriate manner, soil erosion from mass failure can be a major source of sediment delivered to streams. Future application of the optimization model needs to include spatial considerations for unstable soils or wet areas that are not appropriate for road construction. Also there is a need to analyze road-caused sediment delivery on a watershed basis. Combined with GIS, the model developed in this study should be expanded to evaluate road systems in a large area for their economic and environmental impacts. We believe that such analyses will eventually help to develop alternative road locations and to prioritize road maintenance activities such as maintenance, reconstruction, and road removal.

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