Innovative Technology: Evaluation of the Softree RoadEng Vertical Optimizer

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Alexander Forrester, RPF, P.Eng, Roads and infrastructure

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REVIEWERS

Craig Speirs, President, Softree Technical Systems Inc.

David Mills, PEng, Principal, Softree Technical Systems Inc.

CONTACT

Dawson Markle, EIT
Researcher
Roads and Infrastructure Group
(604) 222-5735
dawson.markle@fpinnovations.ca

Disclosure for Commercial Application: If you require assistance to implement these research findings, please contact FPInnovations at info@fpinnovations.ca.

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1. EXECUTIVE SUMMARY

Building roads on steep slopes and difficult terrain is a necessary yet often challenging endeavor in the natural resource industry. The magnitude of earthworks required for forest road construction on steep slopes can require substantial time and cost. The traditional role of planners is to create a road design in road engineering software, and then manually change and optimize its layout to minimize end haul volumes, excavation, and borrow and spoil pit creation.

Softree Technical Services, Inc. and the University of British Columbia developed vertical optimizing software to save time designing resource roads and to minimize construction costs. In 2016, FPInnovations conducted an assessment of the benefits of using the vertical optimizer on steep resource road designs from B.C.

FPInnovations compared the road construction costs for eight resource road designs created in Softree RoadEng® versus the same designs after applying the Softree's vertical optimizer, Softree Optimal. The road designs were vertically optimized to two accepted resource road standards: the BC Ministry of Transportation and Infrastructure's low volume road design standard, and the BC Ministry of Forests, Lands, and Natural Resource Operations' Forest Road Engineering Guidebook road design standard. For the purpose of making relative comparisons, road construction unit costs were taken to be those default values specified in the optimizer.

The evaluation found that the Softree RoadEng® vertical optimization software produces road designs with lower total construction costs and reduced earthworks compared to manually completed designs. Additionally, the software is capable of producing a design in a matter of seconds or minutes, drastically reducing design time. Vertical optimization reduced the estimated construction cost by 13% to 22%, on average, depending on road design standard. Vertical optimization led to reductions in cut and haul costs, and in overhaul and end haul volumes. This was due to the optimizer being able to find more places to deposit fill material along the road. As a result, the optimizer was able to nearly completely eliminate the surplus of material at the end of the mass haul diagram.

FPInnovations also assessed the improvement to road users from optimized vertical alignments by simulating truck traffic over the design sections. FPInnovations' Otto software was used to simulate log hauling truck speeds, and fuel consumption for a loaded log hauling truck negotiating each road. Travel speeds were consistently faster for designs optimized to the LVR standard; however, speeds on roads optimized to the FREG standard were sometimes slower than with the original design.

In order to realize the complete value of the vertical optimized design, road construction should have on-site quality and grade control to ensure construction is performed to an acceptable safety and quality standard.

2. INTRODUCTION

Building forest roads in steep, challenging terrain can require considerable and sometimes unplanned earth work which can result in high construction costs and budget overruns. While the reason for this depends on many variables, minimizing cuts and fills through balanced designs that optimize the vertical alignment of the road may help control costs. Softree RoadEng® has recently released its latest road design software with the capability of automating vertical road alignment for this reason.

Softree Optimal is the vertical optimization software available within the Softree RoadEng® Location module. Using mathematical modeling, the software is able to optimize the vertical component of a road alignment, which can lead to reducing the time and cost associated with road design and construction (Speirs *et al.*, 2016). Case studies have shown that using this software in civil applications reduces the time required to determine a vertically optimized design. Further, the software allows comparison of multiple vertically optimized designs, allowing engineers and planners to select the right alignment for a given location. Using vertical optimization, Franklin County, USA, was able to reduce the overall cut, fill, and haul costs on a design by 23.3%, as well as limit the amount of time required to perform the vertical component of the design to two hours (Softree, 2016).

As part of FPInnovations' steep slopes initiative, techniques and technology are being sought to reduce earthworks, and overall costs, during the creation of roads in steep terrain. One method of doing this is to optimize the vertical alignment during the design of the road. Typically, earthworks associated with end haul construction are the most expensive. This is because all material removed from the slope must be loaded onto trucks and hauled to a spoil site where it can be placed in a stable deposit. In some cases, spoil sites may be many kilometres away. Designers can help reduce the overall costs of road construction by optimizing the vertical road alignment by considering the costs of excavation, hauling, borrow pit and spoil pit development, and slope constraints.

Finding an optimized vertical alignment may require hundreds of design iterations. Performing these iterations manually is time consuming and simply not feasible. Recognizing this, Softree developed automated software for determining an optimized vertical alignment. To better understand how the software can be utilized for developing resource roads in steep terrain, FPInnovations used the vertical optimizer to evaluate differences in costs and earthwork volumes between the original, manually developed, road designs and these same designs after vertical alignment optimization. This report presents a comparison of earthwork volumes, total construction costs, travel speed, and fuel consumption for a set of eight steep forest road designs that were prepared manually and then vertically optimized. Methods to maximize the utility of the vertical optimizer are also discussed.

3. METHODOLOGY

Vertical Optimization

FPInnovations evaluated eight forest road designs using the Softree RoadEng® vertical optimizer software. Road designs were provided to FPInnovations from several collaborators which include government, engineering consultants, and major licensees. This study is a part of the FPInnovations' Steep Slopes Initiative, as such road designs provided were located in areas with steep side slopes, and (or) had steep road grades. One design is from the B.C Interior, one from the coastal mainland, three from the region surrounding Port Alberni on Vancouver Island, and three from the northern part of Vancouver Island.

Each evaluation consisted of comparing the original, manually developed, road design (hereafter referred to as manual designs) to two vertically optimized versions of the design that were based on two different standards for vertical curvature. The first set of standards was based on the Ministry of Transportation and Infrastructure's supplement to TAC for low volume roads (2007). Throughout the report vertically optimized designs using these standards are referred to as LVR-based designs. K-values associated with this standard are for low volume roads with design speeds of 30 km/h, and a minimum stopping sight distance (SSD) of 30 m—a condition that is not uncommon for secondary and in-block forest roads.

The second set of standards is based on the Forest Road Engineering Guidebook (FLNRO 2002) which was the predecessor to the FLNRO (2016) Engineering Manual. Vertically optimized designs in this report that use these standards are referred to as FREG-based designs. FREG designs assume that roads are one lane wide, with two-way travel, design speeds of 20 km/h, and a minimum stopping sight distance of 40 m. Similar to the LVR-based design standard, these conditions are common on secondary and in-block forest roads. In general, forest roads in B.C. are designed to standards that reflect the FREG designs evaluated in this report. Table 1 demonstrates the values associated with each design standard.

Table 1. Design standards for LVR and FREG-based designs

	Design Standard	
	LVR	FREG
Sag K-value	4	2.1
Crest K-value	3	1.7
Stopping Sight Distance (m)	30	40
Design Speed (km/h)	30	20

To use the vertical optimizer software, the user must select or input various design constraints. For consistency between FPInnovations' evaluations, grade constraints for the vertical optimization were set to 28% for favorable grades and 18% for adverse grades.[1] While these grades are greater than recommended in the FLNRO Engineering Manual (2016), FPInnovations has observed that favourable grades as high as 28% are not uncommon for secondary and in-block forest roads.

In addition to the general road grade and vertical curve K-values, further constraints were established for each road that included specifications for end-haul, side-cast construction, waste-pit establishment, and borrow pit establishment. These individual constraints were unique to each road and were based on notes in the traverse and design files provided to FPInnovations or were from field observations.

[1] Favourable grades are those grades traversed while travelling in the loaded (towards the mill) direction; adverse grades are those grades traversed while travelling in the unloaded (towards the harvest site) direction.

Cost constraints for each design were set at the default values found in RoadEng® (Table 2). Note that all material excavation costs are $12/m^3$ and all material embankment (fill) costs are $4/m^3$. While these costs may be higher than typical forest road construction costs, they allow for the evaluation of relative cost differences between manual and vertically optimized designs.

Table 2. Softree RoadEng® default unit costs for earth moving

Earth moving	Hauling cost ($/ m^3/ km)	Loading cost ($/ m^3)	Maximum distance (m)
Overburden	8.00	0.00	150
Colluvium	4.00	0.60	1000
Gravel and sand	2.00	2.60	n/a

In relation to mass haul diagrams, freehaul refers to the average haul distance between cut locations and fill locations within the project work zone. Overhaul refers to earth moving for distances longer than the freehaul distance within the project work zone. End hauling refers to the earth moving of cut materials to a location beyond the project work zone.

Sometimes the manual designs in this evaluation lacked K-value standards for vertical curves or fill slopes had been designed even though the design notes specified a section for end-haul construction. To ensure a fair comparison between manual and vertically optimized methods, therefore, the manual designs were checked to determine if they violated constraints and standards set for the vertically optimized designs. The violations are noted in Appendix A. Additionally, the vertically optimized designs were constrained at the point of commencement (POC) and point of termination (POT) to match the manual design's elevation and road gradient.

Comparison of the vertically optimized designs to the manual designs was facilitated through evaluating each result found in the vertical optimization output table (Figure 1), and RoadEng®'s traditional data output table. The vertical optimization output table included results for total cost, cut cost, fill cost, haul cost, freehaul volume, overhaul volume, end haul volume, overflow volume, and underflow volume. RoadEng®'s traditional data table was used to evaluate differences in cut, fill, sidecast, waste, and net volumes (m^3) for each road.

Item	1) V-align 1	Units
Cost status	Determined	
Last Process	Unprocessed	
Total cost	397.26	1000's $
Cut cost	376.80	1000's $
Fill cost	8.40	1000's $
Haul cost	12.06	1000's $
Freehaul volume	5548.0	Cu. m.
Overhaul volume	4288.7	Cu. m.
Endhaul volume	69.9	Cu. m.
Alignment process time	-	seconds
Overflow	1407.7	Cu. m.
Underflow		Cu. m.

Figure 1. Screen capture of output from the RoadEng® vertical optimizer.

Results from the vertical optimization assessment were used to compare the relative difference between manual, LVR-based, and FREG-based designs. Since the actual cost data for each road was either not available or was overly complex to input into the format used by RoadEng®, only relative comparisons were performed. Additionally, due to the variability in costs between operations in various regions of B.C., RoadEng®'s default values were used to simplify the evaluation and results. For volume comparison, cut and fill volumes for the LVR- and FREG-based road designs were compared with the manual design to determine average differences in volume per distance of road constructed (m^3/km). For the other three earthworks outputs (freehaul, overhaul, and end haul), some road results were dropped from the evaluation due to a lack of data. This was a result of the variable constraints used for each road. For example, roads where borrow or waste pits were specified often did not have net earthworks volumes because the excess volumes were sent to a pit as waste. Again, these values are reported in m^3/ km and averaged across all roads to illustrate general results of the optimization.

In 10 of 14 cases, computing times for the vertical optimization were comparable regardless of optimization standard, and were under 15 seconds. The average time to find an optimal vertical alignment using the LVR standard was 55.9 seconds per km and only 7.4 seconds per km using the FREG standard. These results do not include roads ROAD 4 and ROAD 5 because these roads reached the maximum computing time limit of 600 seconds (arbitrarily set by the author) before the optimization iterations had finished.

Otto simulations for determining average speed and fuel consumption

Using FPInnovations' Otto software, an assessment of the average log truck haul speed and fuel consumption was completed for each road design. Results between the original, manual, designs and the LVR- and FREG-based optimized versions of these designs were then compared to determine whether using the vertical optimization software resulted in improved log hauling cycle times and fuel consumption savings.

4. RESULTS

Optimization results

Based on a dataset of eight steep resource road designs, use of vertical optimization software generated designs with lower construction costs that required less earth work. The vertical optimization software reduced the estimated total road construction costs by 13% ($50,230 per km), on average, for LVR-based designs (Table 3) and 22% ($66,402 per km), on average, for FREG-based designs (Table 4). Vertical optimization resulted in positive savings for seven of eight designs; however, one road design had an increase in total construction cost when optimized to the LVR standard and another when optimized to the FREG standard. Vertically optimizing the manual designs achieved these overall cost savings by reducing the number and volume of cut sections, reducing the volume of hauling, and increasing the number and volume of fill sections. In addition, vertically optimizing the manual designs tended to reduce the overhaul and end haul volumes while increasing the freehaul volumes. It should be noted that the longest road sections experienced large increases in overhaul volume with optimization instead of reductions and, in the case of the LVR standard optimization, this was enough to make the average overhaul volume a positive value (+30%). This is likely due to the optimizer being able to find more places to allocate the cut material within the project as opposed to end hauling.

Table 3. Optimized LVR-design comparison for earthworks, haul volumes, total construction costs

LVR-design, optimized									
Road	1	2	3	4	5	6	7	8	Average
Length (m)	0.56	1.11	1.56	2.05	2.29	2.52	2.46	4.67	2.15
Change in Cut Cost	-0.8%	-18.5%	-27.4%	-38.3%	-26.6%	-5.9%	37.9%	-43.4%	-15%
Change in Fill Cost	89.1%	263.3%	63.6%	295.8%	229.6%	330.6%	110.9%	117.2%	188%
Change in Volume of Freehaul	-6.2%	0.7%	110.3%	71.5%	116.3%	7.9%	109.3%	49.6%	57%
Change in Volume of Overhaul	-11.7%	-50.4%	-73.7%	-16.6%	-15.4%	-34.2%	158.3%	284.1%	30%
Change in Volume of End Haul	0.0%	-100.0%	-100.0%	-84.3%	-100.0%	100.0%	0.0%	-97.1%	-48%
Average Change in Cost of End Haul	9.4%	-38.8%	-75.6%	-61.3%	-83.0%	-11.1%	175.0%	-91.7%	-22%
Total Change in Construction Cost (%)	7.8%	-13.2%	-26.8%	-36.7%	-25.7%	-2.7%	44.1%	-48.5%	-13%
Total Change in Construction Cost ($/km)	$23,345	-$46,972	-$62,531	-$180,747	-$42,159	-$8,502	$3,489	-$87,762	-$50,230

A review of the constituent components of total construction cost identified changes in cut, fill, and end haul costs which are presented in the tables 3 and 4. There seems to be improvements for both LVR- and FREG-based vertically optimized designs as road length increases; however, as these roads are subject to various terrains, features, and designers, it is difficult to demonstrate a strong relationship between cost and road length. This finding was due to an overall reduction in earth works and, therefore, lower costs for cutting and hauling material. The exception was fill costs, where there was an increase as road length increased. The optimization found more opportunities to create fills instead of end hauling, leading to higher fill costs relative to manual designs but lower haul costs and end haul volumes.

Table 4. Optimized FREG-design comparison for earthworks, haul volumes, total construction costs

FREG-design, optimized									
Road	1	2	3	4	5	6	7	8	Average
Length (m)	0.56	1.11	1.56	2.05	2.29	2.52	2.46	4.67	2.15
Change in Cut Cost	-13%	-14%	-38%	-45%	-36%	-18%	3%	-31%	-24%
Change in Fill Cost	80%	49%	57%	248%	189%	301%	71%	162%	144%
Change in Volume of Freehaul	-20%	-15%	80%	87%	97%	2%	77%	40%	44%
Change in Volume of Overhaul	-11%	-12%	-78%	-39%	-32%	-43%	-26%	148%	-12%
Change in Volume of End Haul	0%	-100%	-100%	-84%	-100%	100%	0%	-99%	-48%
Average Change in Cost of End Haul	-4%	-24%	-79%	-69%	-87%	-25%	50%	-87%	-41%
Total Change in Construction Cost	-4%	-13%	-36%	-44%	-36%	-15%	9%	-36%	-22%
Total Change in Construction Cost ($/km)	-$11,976	-$46,289	-$85,106	-$217,769	-$58,077	-$46,770	$691	-$65,919	-$66,402

The changes in freehaul and overhaul from optimization are shown as well. In general, freehaul volumes increased from optimization whereas overhaul volumes increased with the LVR-design and decreased with the FREG-design. End hauled volumes were reduced, in general, with four road designs having a complete elimination of end hauling. With the vertical optimizer it is possible to identify end haul sections automatically based on side slope angles, whereas manual designs tend to set end haul sections through manual overrides or templates in RoadEng®. As a result the optimizer is able to find more opportunities for fill material and, therefore, reduce the overall end haul volume.

Earthworks results

As part of the evaluation, FPInnovations considered how overall earth work volumes were affected by using the vertical optimizer. It was found that for all of the earth work parameters evaluated, except for fills, there were notable decreases in the amount of volumes for the optimized designs when compared to manual designs (Table 5). This agrees with results from the vertical optimizer's data output as it appears the optimizer was able to find more locations for fill material which reduced the volume of sidecast, waste, and net earthwork. For this evaluation, net earthwork volume was considered to be the surplus or deficit of material remaining in the mass haul diagram at the end of the road design. Results also show that the amount of cut volume was reduced. When reviewing the net volume in Table 5, the reason for such high savings is that there was no, or very little, remaining volume at the end of the mass haul diagram for most vertically optimized designs. This resulted in the high relative differences in volumes.

Table 5. Average earthwork differences: Manual and optimized designs for eight road designs

	Average Difference	
	Optimized to FREG standard	Optimized to LVR standard
Cut volume	-27.8%	-16.9%
Fill volume	38.3%	42.3%
Sidecast volume [a]	-81.4%	-77.7%
Waste volume [b]	-60.5%	-44.8%
Net earthwork volume [c]	-99.9%	-99.4%

[a] Sidecast volume averaged for six roads where sidecast constraint was used
[b] Waste volume averaged for five roads where a waste pit was identified
[c] Net earthwork volume averaged for five roads that did not have a balanced original design

Travel speed comparison for optimized designs

Average unloaded travel speeds in the unloaded direction were marginally faster for the LVR-optimized designs than for the manual design in seven of eight cases (Figure 2), and average loaded travel speed results in the loaded direction were relatively comparable for all designs (**Erreur ! Source du renvoi introuvable.**). However, average speeds for both the unloaded and the loaded simulations were marginally slower for the FREG-optimized designs than for the manual designs in five of eight cases. The differences in predicted travel speed were minor between the original manually developed designs and the vertically optimized designs (to the FREG and LVR design standards). Because of the minor speed differences and the short lengths of road involved no inference on cycle times can be made. The results are presented, therefore, to illustrate a potential method to compare road designs.

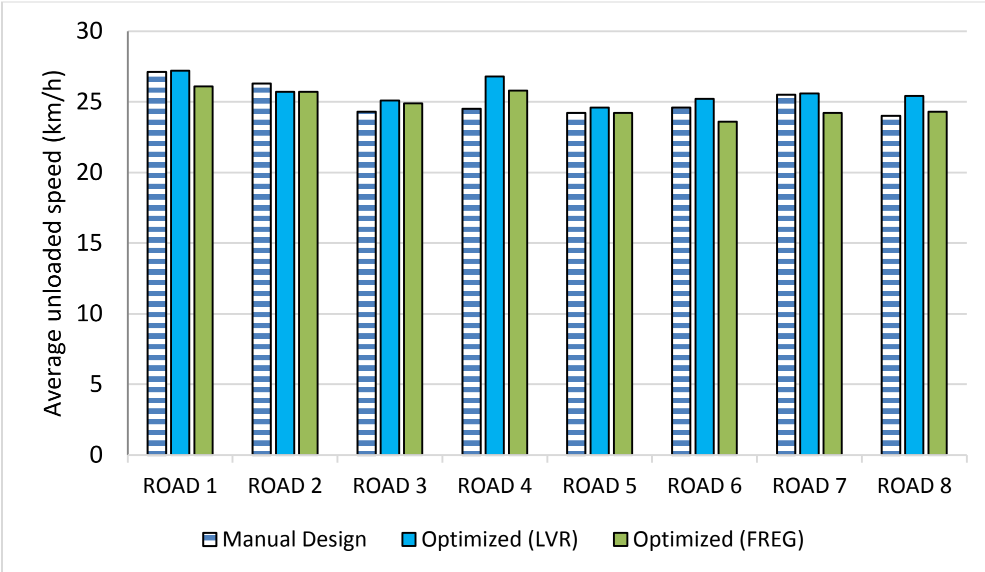

Figure 2. Average speed comparison of unloaded trucks in the unloaded direction, by road design.

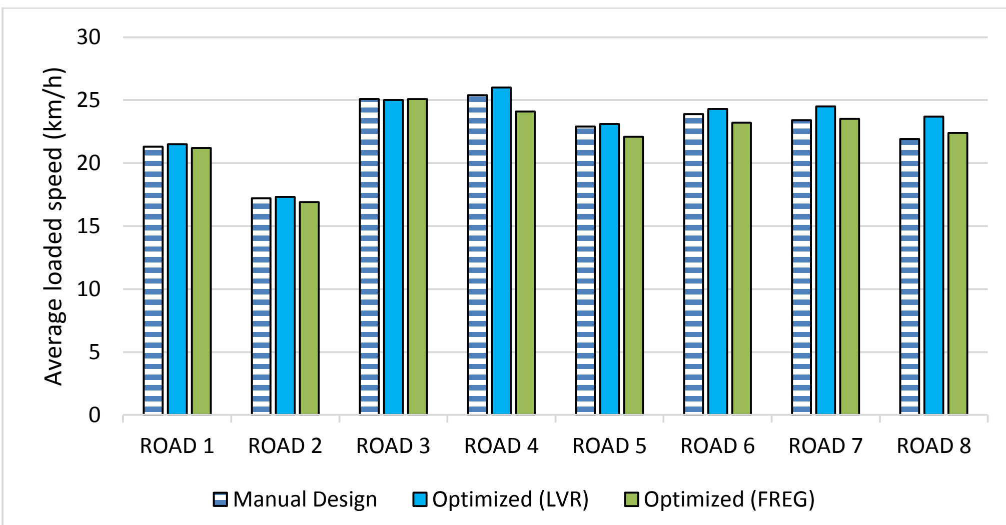

Figure 3. Average speed comparison of loaded trucks in the loaded direction, by road design.

Fuel consumption comparison for optimized designs

Average fuel consumption results for the manually designed roads and the LVR- and FREG-based vertically optimized roads were comparable, with a mixture of minor reductions and increases. Predicted fuel consumption for unloaded trucks was within 25 litres per 100 km for all three road designs; the result for loaded trucks was similar. Also, because the majority of simulations featured loaded trucks traveling downhill, predicted fuel consumption was much lower than usual (e.g., under 50 litres per 100 km). Overall, fuel consumption improvements were observed with vertical design optimization and further studies are needed to accurately quantify the benefit.

5. CONCLUSIONS

FPI's study of Softree Optimal revealed two main findings. First, Softree Optimizer typically yields results that are more cost effective and reduce haul volumes when compared to a manual design. Second, once constraints have been determined, the vertical optimizer software saves design time. While results of this study relied on default values found in the optimizer program, it does provide insight into the relative savings created by optimizing vertical alignment. In addition, it was observed that the amount of time required to perform a vertically optimized design was less than that required to perform a manual one. This result is based on user experience with the software, as the original designs were provided to FPInnovations already complete.

As shown in the results, vertically optimized designs yielded an average cost savings of 13% ($50,230/km) when using low volume road (LVR) standards derived from (MOTI 2007) and 22% ($66,402/km) when using standards derived from the forest road engineering guideline (FREG) from (FLNRO 2002). It should be noted that the longest road evaluated was 4.70 km long, and it is unknown whether there is a maximum road length after which cost savings would begin to diminish. Increased savings for cut and haul costs were found as road length increased, while fill cost savings decreased. This finding appears to be a function of reducing the amount of end haul sections on the roads. This can be attributed to the vertical optimizer finding more opportunity for fill volume, which decreases the amount of volume left over for end haul when compared to a manual design. Similar savings to RoadEng® may be obtainable via manual methods; however, finding the optimal alignment via manual design would likely be onerous and time consuming for designers.

Time savings results from the study are somewhat subjective, as it is unknown how long the original designs took. Results do show that in some cases an optimal alignment was found in less than 5 seconds, and based on the experience of FPInnovations' researchers, it would take much longer to manually design the vertical alignment of these road sections. Additionally, the average per kilometer design time shows that designers will not be required to spend as much time manually moving vertical intersection points (IP) on roads during the design process to find an efficient vertical alignment. Although computing time for the vertical optimizer is short, it should be noted that inputting constraints and cost data before running the vertical optimizer requires some additional time. This is an important step in the optimization process, and requires due-diligence by the designer to ensure all the constraints are appropriate to meet design specifications and budgetary assumptions for the road. It is likely that even with the additional time it takes to input constraints and cost data, however, the vertical optimizer will reduce the overall time required to design a roads vertical alignment compared to manual designs.

FPInnovations performed simulations using Otto to determine whether vertically optimized roads resulted in improved average travel speeds or reduced fuel consumption. LVR-optimized road designs showed marginally improved travel times, however, it is unclear if this was a result of optimization or because these optimized designs had a higher standard of vertical curvature K-values and this allowed trucks to travel at faster speeds. Given the slow travel speeds on this class of road, no significant improvements in fuel consumption were found for the vertically optimized roads.

Realizing these savings in the real world may be challenging because quality control for vertical alignment is often not a priority during forest road construction. It is costly to have a qualified surveyor on site to establish grade stakes, and often the ground conditions assumed in the design vary from those found in field. In general, forest roads are designed to reflect the FREG design standards evaluated in this report. The analysis of eight forest road designs found that total construction cost was reduced by 22%, on average, but varied from a 9% increase to a 44% reduction. Assuming an average savings of 22% is achievable with vertical optimization, $110,000 in cost savings might be expected on a $500,000 annual road program. These savings could be used for up-front subsurface investigations to ensure a more accurate design, and active quality control during construction to ensure designs are followed.

Active quality control on site will ensure that forest roads are built to acceptable safety standards and satisfy professional practice requirements outline by the Association of British Columbia Forest Professionals and the Association of Professional Engineers and Geoscientists of British Columbia Joint Practices Board (Joint Practices Board 2012). Additional operational savings and benefits from vertical optimization may be realized through more efficient cycle times, reduced fuel consumption, and higher truck productivity.

Presently, the vertical optimizer is available only as an extension within RoadEng®; however, Softree intends to make the optimizer available for Civil 3D in the future. Softree Optimal is currently available as a package in a “starter bundle” which includes RoadEng® and a year of Softree support for $4500. Softree Optimal is available for $2300 by itself.

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Head Office

Pointe-Claire
570, Saint-Jean Blvd
Pointe-Claire, QC
Canada H9R 3J9
T 514 630-4100

Vancouver
2665 East Mall
Vancouver, BC.
Canada V6T 1Z4
T 604 224-3221

Québec
319, rue Franquet
Québec, QC
Canada G1P 4R4
T 418 659-2647

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