Advantage

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Contents

Evaluation of forest access road designs for use with CTI-equipped log haul trucks phase II: seasoned access roads

Abstract

A forestry operation in northern Alberta constructs its temporary access roads with native, fine-grained materials and uses these roads during both frozen and unfrozen conditions. The log hauling fleet associated with this operation utilizes central tire inflation systems to reduce road damage and improve mobility. This second of three reports describes an evaluation of the design and construction of temporary access roads trafficked one year after construction; quantifies grading maintenance savings resulting from the use of road seasoning and optimized tire inflation pressures; and discusses the validation of a USDA Forest Service rutting model and its potential for use in other applications.

Keywords

Road transportation, Logging trucks, Tires, Central tire inflation system, Roads, Forest roads, Seasoned, Green, Compaction, Rutting, Performance, Evaluation, Alberta.

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Introduction

Since beginning forest operations in northeastern Alberta, Alberta-Pacific Forest Industries Inc. has had varied success with accessing its harvest blocks during unfrozen periods. Wet weather, scarce gravel sources, and moisture-sensitive, fine-grained soils have resulted in reduced trafficability and increased road maintenance. Alberta-Pacific asked the Forest Engineering Research Institute of Canada (FERIC) to review the construction of its summer-use, temporary forest access roads (i.e., those intended to be reclaimed within two years), and to suggest opportunities to reduce maintenance costs and improve access (i.e., reduce the need for truck assists and maintain haul speeds). Additionally the review was to take into account efficiencies possible through the use of central tire inflation (CTI) systems.

FERIC began its investigation by reviewing and summarizing available literature on the effect of variable tire pressures on road design and damage (Bradley 1997). During the summer of 1998, FERIC and Alberta-Pacific constructed two groups of three variations of the company's usual "V-ditch" temporary access road design and then left them to season for one year before using them for the trial. Alberta-Pacific's log hauling fleet, equipped with CTI systems, trafficked the first group of test sections using normal highway tire pressures and the second group using optimized tire pressures. This report documents the results of the field trial.

A first phase of the access road evaluation was conducted by FERIC and Alberta-Pacific in 1998. This phase of testing evaluated ten access road test sections constructed in July 1998 and trafficked in a freshly built, or green, condition in September 1998. Four of these test sections were constructed with a compactor in order to evaluate the cost-effectiveness of surface compaction on road performance. Half of the test road sections were trafficked with normal highway tire inflation pressures and half with optimized tire inflation pressures. The results of this first "green road" phase were published in 2001 in a companion document to this report (Bradley 2001). As well, a summary report will be published to provide practitioners with guidance and strategies to implement the results from both reports.

Objectives

The primary objective of this study was to evaluate Alberta-Pacific's temporary access road design and construction techniques, and was met through the completion of the following tasks:

- Quantify the cost of construction and maintenance of each road design.
- Determine the effectiveness of seasoning for improving road performance and compare with the previously studied green road methods.
- Quantify the influence of optimizing tire pressure on road performance.
- Suggest refinements to the access road designs.
- Validate the use of a USDA Forest Service rutting model in Canadian forestry applications by comparing its rut depth predictions with those observed during the trial.

Study methods

Road construction

Three variations of Alberta-Pacific's standard temporary access road design were evaluated in this trial: V-ditch (baseline case), 0.5 m Lift, and Lift-over-rootmat. In September 1998, six test road sections were constructed consecutively to form a 1000 m-long test road joined at either end to the 79-04 forest access road (Figure 1). The test road had consistent alignment, soil type, drainage conditions, weather, and traffic volume. Each of the three road designs was replicated twice, one set to be trafficked with normal highway tire pressures and one set with pressures optimized by CTI systems for the trucks' operating conditions. FERIC monitored the construction of the test road and assessed the construction cost of each road design. The finished road sections were surveyed to determine cross-section geometry and pre-trial surface profile and then the road was closed and allowed to "season" over the winter.

Seasoning is a term used to describe the process of road surface densification and

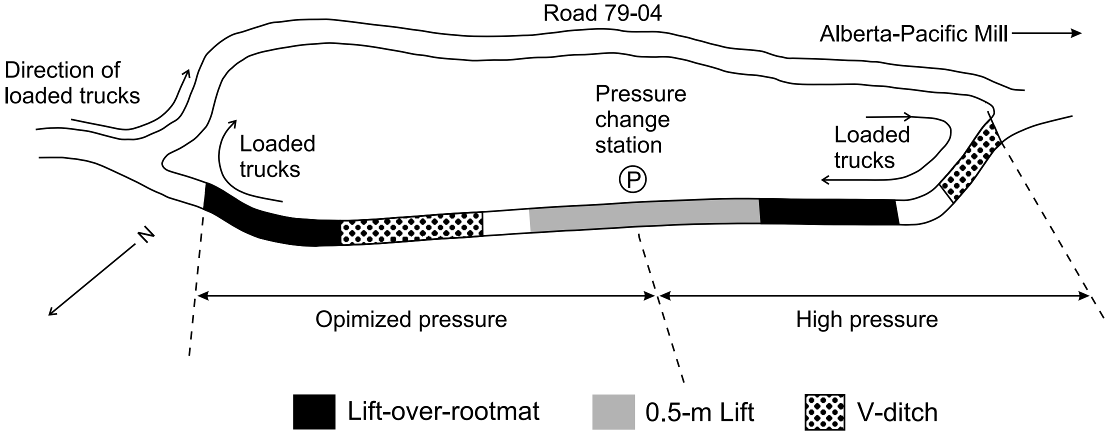

Figure 1. Plan view of seasoned test road showing test sections.

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strengthening that naturally occurs in untrafficked, earth-surfaced roads over time. This process begins with the disturbance and rearrangement of soils within the road prism by road construction equipment. Thereafter the surface soils are subject to drying and weathering forces. The upper soils of the road are desiccated by surface evaporation and drainage of the road prism into the ditches. Surface oxidation plays a significant role in crust formation by creating oxides and hydroxides of iron that act as cementing agents. Finally, precipitation percolating through the road prism can leach carbonate from the upper metre of material and thereby reduce the amount of silt-sized particles near the surface (Quigley 1978). These forces dry, consolidate, and cement the particles into a dense, strong, stiff crust. Strength increases are most noticeable in clay soils because the process of seasoning re-orients (flocculates) the clay particles and promotes physio-chemical bonding. Seasoning can continue for a long time (years in the case of clay soils) and is temporarily reversed by wetting (swelling) and frost heave.

Road construction costs

For comparison purposes, the basic cost of constructing each test section was estimated by summing the cost (activity time x charge-out rate) of all pieces of construction equipment used. The cost of large cuts and fills, operational delays, equipment transport, signs, and culverts are excluded. Nor do these estimates include costs incurred with the pre-construction process, such as planning, approvals, and layout. A relative comparison between road designs was made on the basis of *total cost*—i.e., the section's estimated basic cost of construction plus its grading cost during the trial. Based on this analysis, area-specific and use-specific revisions were suggested to the current road design process used by Alberta-Pacific.

Soil properties

FERIC measured soil strength, densities, and moisture contents during and after the construction process. Measurements of subgrade strength were gathered with a dynamic cone penetrometer (DCP) and an average penetration rate determined for the 20–60 cm depth. Surface density profiles and moisture contents were gathered, taking measurements along the centreline and in both wheel paths to quantify as-built, post-seasoning and post-trafficking conditions 9 months after construction. However, operational delays extended the interval by 3 months so the post-seasoning dry densities were estimated by straight-line extrapolation from 9 to 12 months. This extrapolation improved the estimate of the increases in dry density from seasoning and from trafficking. Soil samples were gathered and analyzed to identify soil type and to quantify basic soil properties, i.e., Atterberg Limits (Liquid Limit and Plasticity Index) and soil gradation.

Trafficking trial

The test road was arranged as a parallel route beside the existing 79-04 forest access road so that traffic could be directed onto either route (Figure 1). Loaded trucks took a circular route, entering the test road from the south to avoid starting on an adverse grade at the pressure change station. FERIC researchers inspected each loaded truck before it proceeded onto the test sections to ensure that its tire pressures were correctly adjusted. The optimized pressure settings were based on recommendations from the Tire and Rim Association (1999) (Appendix I).

The loaded trucks entered the test road at normal (high) tire pressures. After passing over the first group of three test sections, the trucks were stopped at a check point where their tires were deflated to optimized inflation levels before proceeding over the next three test sections.

FERIC monitored traffic over the test road during daytime hauling operations only. When researchers were not on site or were taking road measurements, traffic bypassed the test road. In order to evaluate the test designs under representative traffic conditions, both loaded and unloaded log trucks were directed over the test road; unloaded trucks bypassed the test road when loaded traffic was on it. Trafficking was intended to continue for 250 loads—sufficient to give a clear indication of road design performance. However, deteriorating weather conditions caused the trial to be prematurely stopped after 134 loads (5 320 t payload).

Axle weight distributions for the test loads were gathered with the assistance of Alberta-Pacific's scale staff. Each truck's axle weights were then converted to equivalent single axle loads (ESALs)[1] using equivalencies developed by the US Army Corps of Engineers (Barber et al. 1978) (Appendix I).

Alberta-Pacific's road grading maintenance is typically driven by the worst sections (i.e., those deeply rutted areas that slow traffic or necessitate tow assists). Similarly, when an extended portion of one of the test sections developed ruts averaging 15 cm deep (the trial's predetermined grading trigger depth), the test road was closed to traffic while that section was graded. Rut depth measurements were taken in both wheel paths of each test section at regular traffic intervals, and before and after grading.

Weather data for the test period were gathered from the nearest climate stations and expressed in terms of precipitation and fire weather index (FWI).[2]

Rut depth modeling

To estimate how much less damage is done when a truck's ESALs are reduced, the USDA Forest Service developed the Surface Thickness Program (STP) rutting model (Whitcomb et al. 1990), an empirical model that was validated in subsequent field trials (Truebe and Evans 1994). Data on tire pressure, axle loads, number of passes, and road strength were input into the earth-road model of STP to compare predicted rut depths with those observed in the test sections. Road strength was determined from the pre-trial DCP measurements converted to California Bearing Ratios (CBR) using an empirical formula developed by USDA Forest Service researchers (Truebe and Evans 1994).[3]

Once validated with the test road data, longer-term predictions of rutting were made for a V-ditched road. These rutting predictions were used as an input to an analysis of improving trucking efficiency by increasing payloads.

Results and discussion

Road designs and construction costs

Soil samples gathered from random locations along the test road were found to be predominantly silty sands (i.e., classified as silty very fine sands, sands, or silty sands and gravels having little plasticity) (Appendix II). Silty sands drain reasonably well and develop good compressive strength; they are considered reasonably stable when used in road embankments according to AASHTO (1990). When used as road surfacing, however, these soils rut easily because they lack cohesion and because the materials are physically less confined than when in an embankment. Hills in this region typically contain dry layers of sand and clay. When making cuts to reduce road grade, road builders sometimes access these materials and use the sand as embankment material in wet depressions and the clay to "clay-cap" the road surface.[4]

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[1] ESALs are a concept developed by road design engineers that allows one to quantify the road damage potential of any size and type of vehicle in terms of a standard unit—the ESAL. Working in ESALs allows the design of roads for any type of vehicle or combination of traffic. It also allows one to predict the influence on road life after changing some traffic parameter such as volume, axle loading, or tire pressure.

[2] FWI gives a good indication of drying conditions and is calculated from a variety of weather indices including daily precipitation, temperature, wind speed, and relative humidity, and from the previous day's FWI.

[3] CBR = $320/(DCP)^{0.943}$ where DCP is the penetration rate mm/blow. As is apparent from their inverse relationship, smaller DCP penetration rates correspond to stronger soils and higher CBR values. This conversion differs from that used in the green road analysis and was adopted to more closely match the CBR values used to generate the STP model's coefficients.

[4] Emery Gorman, Green Country Resource Managers, personal communication, July 1998.

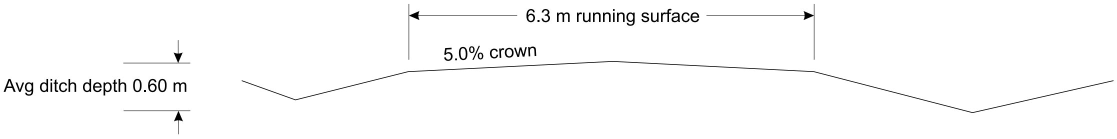

Figure 2. Schematic of a typical as-built V-ditch prism.

Figure 2 shows a typical, as-built, V-ditch test section, the most common type of access road built by Alberta-Pacific. This type of road is constructed using a bulldozer and is usually not compacted. The average cost for constructing both V-ditch test sections was $166/100 m, excluding all large cuts and fills, equipment transport, cross drains, and signs (Table 1). This result is approximately 57% more than the $106/100 m cost reported for the V-ditch test section on the green road constructed with the same types of equipment. This difference arises from the extra time required to remove or incorporate the cobbles and boulders found in the seasoned road sections.

The 0.5 m Lift design (Figure 3) would commonly be used in depressions and other wet areas where the roadway needs to be raised above the water table.[5] Lifted road sections also are usually not compacted. The average cost for constructing the two Lift sections was $349/100 m. This result agrees closely with the $373/100 m cost of constructing the Lift sections of the green road. The Lift sections were constructed with only 5 m-wide surfaces because of the difficulty with excavating sufficient fill from the ditches within the width constraints of the right-of-way.

The Lift-over-rootmat design is used successfully in Ontario in situations where subgrade soils are very wet or are absent (i.e., the root mat lies over bedrock) (Figure 4). Roots provide reinforcement and drainage to the lift material. When constructing roads of this type, stumps should be cut as low as possible, as tall stumps require more lift material to cover and may protrude through the running surface as trafficking progresses.

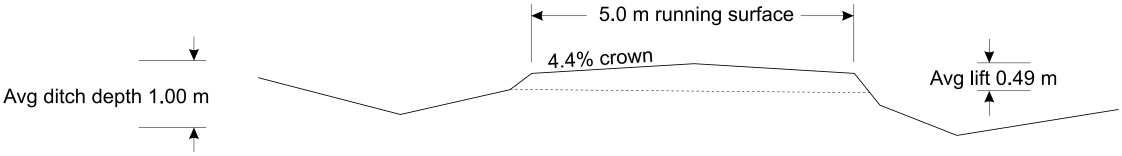

Figure 3. Schematic of a typical as-built Lift prism.

Table 1. Construction costs of the test sections

	Construction equipment used [a]			Total cost of construction	Constructed length	Total cost of construction	Average cost of construction
	D7H	E	G	($)	(km)	($/100 m)	($/100 m)
V-ditch (HP) [b]	X		X	207	0.146	142	166
V-ditch (OP) [b]	X		X	296	0.157	189	
Lift (HP)	X	X	X	481	0.138	349	349
Lift (OP)	X	X	X	481	0.138	349	
Lift-over-rootmat (HP)	X	X	X	600	0.160	375	394
Lift-over-rootmat (OP)	X	X	X	708	0.172	412	

[a] D7H = Caterpillar D7H bulldozer; E = Hitachi EX270LC excavator; G = Caterpillar 14G grader.
[b] HP = normal (high) pressures; OP = optimized (lowered) pressures.

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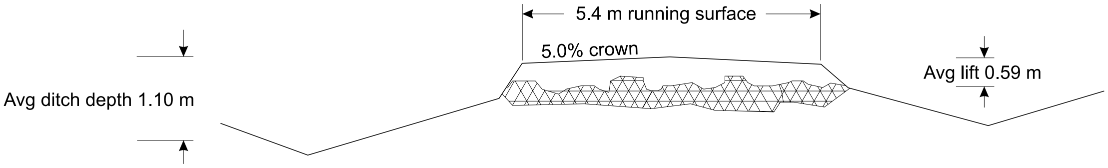
[5] Alberta-Pacific's experience with local soils is that 0.5 m of lift is adequate to ensure drainage. However, lifts need to be as high as 1 m in a part of its Forest Management Agreement area having predominantly clay soils.

Figure 4. Schematic of a typical as-built Lift-over-rootmat prism.



The average amount of lift was 0.59 m—about 10 cm more than for the Lift test sections.

At an average construction cost of $394/100 m, the two Lift-over-rootmat sections were the most expensive design built but were less costly than the equivalent sections on the green road ($419/100 m). This reduction in cost may reflect efficiencies developed by the excavator operator on the green road sections and used on these sections. Despite its higher cost, Lift-over-rootmat may be economic when compared to Alberta-Pacific's technique of bridging problematic wet areas with a corduroy (log) mat covered by fill.

Table 1 presents a summary of the cost of constructing the test sections; a detailed account of Alberta-Pacific's road construction process is given in Bradley (2001).

Optimizing road construction

To achieve optimal equipment productivity, the size, mass, and power of the equipment should be well matched to the requirements of the task. In the case of the seasoned test road, the Caterpillar D7H bulldozer lacked the power and size to easily clear some of the larger boulders from the grade. However, this same machine was reported to exceed the power and size requirements for working the fine-grained materials of the green test road. This suggests that this size of bulldozer would be well-suited for constructing road in Alberta-Pacific's varied terrain.

Construction techniques can contribute to seasoning by reducing the de-compaction that results from frost heave. For example, the grader left the test road with a rounded crown instead of finishing shaping before seasoning. This promoted seasoning in two ways: the rounded, unrutted shape shed water faster (thereby developing fewer ice crystals over winter and drying faster in the spring); and the materials that were most loosened by frost were graded off the running surface during final shaping prior to activation.

According to civil engineering professors Krebs and Walker in Transportation Research Board (1979), compaction of cohesive soils, near optimum moisture content, reduces both the loss of strength and the volume increase that occur when these soils become saturated by rainfall, capillary action, or frost action. From this, it can be surmised that surface compaction would also reduce the de-compaction resulting from frost heave, and hence contribute to the effectiveness of seasoning.

Care must be taken to ensure good drainage of roads left to season over winter, especially if these roads are constructed with highly erodible soils. Drainage plans should anticipate and allow for eroded material accumulating in ditches and cross-drains.[6] Measures such as constructing ditch grades at no less than 0.5% (to prevent silting up) and no more than 3–5% (to prevent scour), as well as frequent use of ditch blocks and diversion ditches to direct drainage into the nearby forest, should be considered. An inspection of the green road one year after construction found considerably less erosion of the ditch banks created by an excavator with a shaping blade compared to those V-ditched with a bulldozer. Erosion problems on seasoning roads are exacerbated by lack of monitoring by company personnel. Preventing the public from using seasoning

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[6] Alberta-Pacific has experimented with a maintenance crew using a trash pump to drain, as necessary, ditch water trapped by sediment accumulations rather than excavating to restore drainage. This may be feasible and economic for short-term hauls in areas with highly erodible soils and few water accumulation areas. David Lloyd, Alberta-Pacific, personal communication, June 1999.

roads is usually advisable because passenger vehicles may leave ruts in the soft surface and thereby accelerate erosion. Low ground pressure vehicles (e.g., pickup trucks equipped with tracks in place of wheels) can access drainage structures on closed, seasoning roads without causing excessive rutting.

Soil properties

Seasoning the test road before trafficking significantly increased soil densities. The average increase in dry density was 5, 9 and 10% at 10, 15, and 20 cm depths, respectively (Table 2). The density increase at the 10 cm depth was comparable to the 3–5% achieved by compaction on the green road. Conversely, while the increase in density from seasoning grew with depth, field compaction was most effective near the surface and had little effect at a 20 cm depth on the green road. The smaller increase observed close to the seasoned road's surface is attributed to the loosening of the soil by frost heave. Little variation was measured in dry density between the different test sections—all appeared to experience comparable seasoning.

The seasoned road section's subgrade strengths measured prior to trafficking were very consistent, with an average CBR of 20 (range 18–20). This was only slightly less than the average subgrade CBR[7] of 22 and 24 in the uncompacted and compacted green road sections, respectively. In general, CBR values increase with time as the road densifies; however, subgrade CBR will decrease during wet or damp conditions (Truebe and Evans 1994). Because both test roads remained relatively dry during the trafficking periods, the soil strengths are expected to have remained comparable, and should permit useful rutting comparisons.

Table 2. Test road dry density after construction and after one year of seasoning

	As-constructed: average dry density (g/cc)	Seasoned: average dry density (g/cc)	Increase (%)	Average increase (%)
10 cm depth				5
V-ditch	1.55	1.63	5	
Lift	1.57	1.64	4	
Lift-over-rootmat	1.57	1.67	6	
15 cm depth				9
V-ditch	1.55	1.69	9	
Lift	1.56	1.68	8	
Lift-over-rootmat	1.57	1.71	9	
20 cm depth				10
V-ditch	1.54	1.71	11	
Lift	1.56	1.70	9	
Lift-over-rootmat	1.58	1.73	9	

Trafficking trial

Weather conditions deteriorated throughout the trial, beginning with moderate fall conditions and ending with light snow flurries. The test road, however, stayed relatively dry throughout the trafficking period. The FWI reflected the cooling weather conditions observed during the trial. Beginning at about 15, the local FWI dropped to 10 with a 3-mm rain and to 5 by the end of the trial with the continued cooling of temperatures.

The average gross combined vehicle weight (GCVW) of the log hauling trucks during the trial was a highway legal 59.4 t (well under the legal allowable of 62.5 t), and average payload was 39.7 t (Appendix I). The normal high tire pressures (HP) and optimized tire pressures (OP) used by the loaded trucks during the trial are also shown in Appendix I. Only 11% of the trucks had CTI systems capable of reducing their steer tire pressures; the pressure differential between the trucks able to adjust the steer tire pressures and those that could not was typically less than 69 kPa (10 psi).

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[7] When estimated using the same DCP to CBR conversion as in the seasoned road analysis.

Figure 5. Influence of construction technique on road maintenance cost of Lift (HP) test sections.

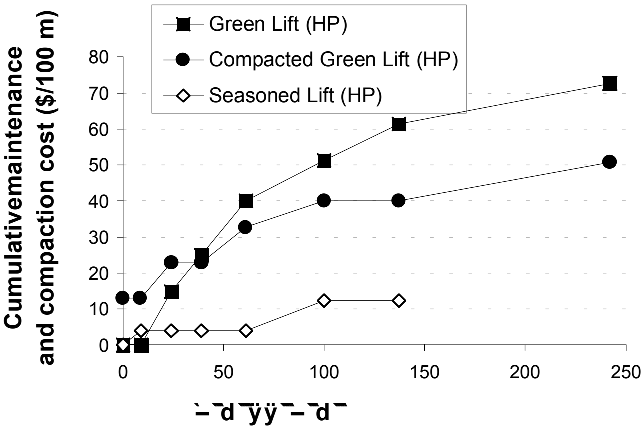


Figure 6. Influence of seasoning on road maintenance cost of Lift-over-rootmat (HP) test sections.

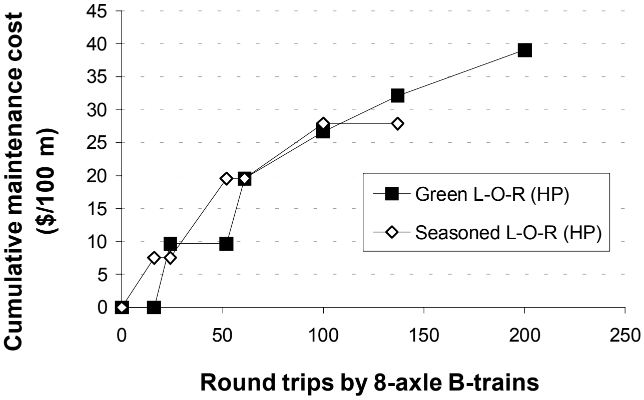


Figure 7. Influence of construction technique on road maintenance cost of Lift (OP) test sections.

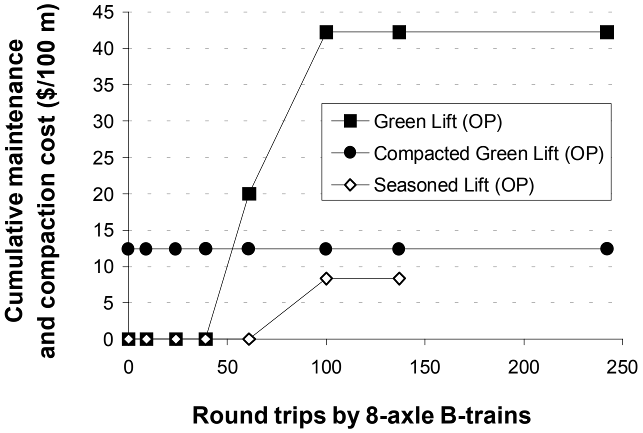
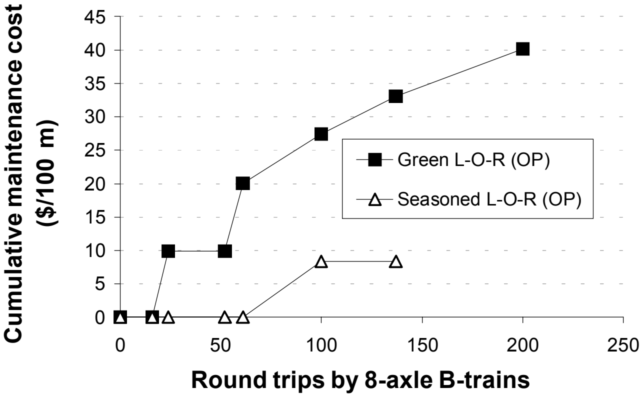


Figure 8. Influence of seasoning on road maintenance cost of Lift-over-rootmat (OP) test sections.



In an unfortunate accident, the entire test road was mistakenly graded after 97 round trips—before any of the sections had exceeded the trial's rut depth limit. Although the V-ditch and Lift-over-rootmat (OP) sections would not have required grading during the 250-pass break-in period, the accidental grading resulted in all of the sections' maintenance costs being increased by $8.33/100 m.

Effectiveness of seasoning and tire inflation on road maintenance cost

Figure 5 compares the cost effectiveness of seasoning versus compacting the Lift test sections by combining seasoned road cost data from this trial with green road cost data from the companion investigation of green access roads (Bradley 2001). Similarly, Figure 6 details the cost effectiveness of seasoning the Lift-over-rootmat test sections on which no machine compaction was employed. Figures 5 and 6 present data from the test sections trafficked by trucks employing normal, highway tire pressures. Figures 7 and 8 repeat these same comparisons for the test sections trafficked with optimized tire pressures.

Cumulative road costs in these figures include both the cost of maintenance grading and, when applicable, the cost of compaction but not any other construction costs (which were assumed equivalent for all Lift roads and therefore omitted for this comparison). The cost of compacting the test sections was approximately $130/km.[8] Pre-constructing roads for seasoning was assumed to cost no more than constructing roads to be used in a green condition.

The green Lift section subjected to high tire pressure traffic displayed the highest cumulative maintenance and

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[8] Based on actual compacting time only.

compaction cost. Seasoning, even more than compaction, resulted in maintenance savings for the Lift sections when compared to the green, un-compacted Lift (HP) sections. Similar trends were observed for the seasoned Lift sections trafficked with optimized tire pressures as those trafficked with normal, highway tire pressures, however, the relative improvement of seasoning over compaction was less.

Seasoning and surface compaction were both cost effective (i.e., less expensive than using a green road) after 40–60 round trips. Because the two trials were conducted under similar but not identical conditions (i.e., truck loadings, tire pressures, and FWI all differed slightly), relative rather than absolute comparisons are reported. The results indicate that roads subject to optimized tire pressure traffic will achieve similar maintenance savings whether they are seasoned or surface compacted. Which technique to use will depend largely on machine availability and construction lead time. Additional savings will likely result if Lift roads scheduled for seasoning are first compacted (i.e., constructed in 15 cm-deep lift layers that are compacted near optimum moisture content) but this technique was not evaluated during the trial. The results also indicate that Lift roads subject to high tire pressure traffic may incur significantly lower costs when seasoned than if surface compacted; however, further field trials are needed to quantify the amount.

Note:
When machine compacting fine-grained cohesive soils: *The pressure intensity from surface loads decreases rapidly with depth, especially in fine-grained, cohesive soils. When compacting these soils it is most efficient and effective to compact with as heavy a compactor as possible, however, heavy compactors may cause excessive sinkage and rutting, and may push soil ahead of the wheels. In response, the compactor must exert more energy to make the first passes or, alternately, it may be necessary to pre-compact with a lighter compactor (Transportation Research Board 1979).*

The results presented in Figure 6 indicate that seasoning appeared to generate little benefit for the section subject to high tire pressure traffic. However, seasoning the Lift-over-rootmat (OP) section did generate some maintenance savings (Figure 8). Maintenance costs for the road's break-in period[9] would likely have been less had the premature grading not occurred. Further field trials may identify greater savings.

The same principles apply to trafficking forest roads where high surface loads from log trucks cause densification throughout the break-in period, but under soft road conditions they can also generate long, deep ruts. Pre-compaction by seasoning (or with a compactor) may strengthen the road surface enough to prevent excessive sinkage, rutting and pushing. Riding down the raised edges of ruts with unloaded log trucks using optimized tire pressures provides another means to pre-compact the road surface prior to trafficking with loaded trucks.[10]

The improvement resulting from optimized tire pressures varied considerably with road design (Table 3). The baseline maintenance cost, for the V-ditch (HP) section, was $8.33/100 m (and $0.00157/t payload). The comparison of maintenance costs incurred during the trial indicates that $4.06/100 m less was spent on grading the Lift (OP) section than the Lift (HP) section. This savings of 33% resulted from the use of optimized tire pressures. And $19.53/100 m less was spent on grading the Lift-over-rootmat (OP) section than on the Lift-over-rootmat (HP) section—a 70% saving. The V-ditch sections showed no difference in grading maintenance cost and little

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[9] Based on the opinion of several Alberta-Pacific road contractors, a typical Alberta-Pacific temporary access road requires approximately 250 truck loads to break-in (i.e., reach a dense, stable condition).

[10] A forest operation near Grande Prairie densifies its forest roads by first trafficking with loaded CTI-equipped trucks followed later by loaded trucks using normal, highway tire pressures (Dennis Young, Weyerhaeuser Company Limited, personal communication, November 2001).

Table 3. Effect of optimizing tire pressure on grading maintenance costs incurred during the trial

Road design	(HP) Section maintenance cost ($/100 m)	(OP) Section maintenance cost ($/100 m)	Savings from use of optimized tire pressures ($/100 m)	(%)
V-ditch	8.33	8.33	0.00	0
Lift	12.39	8.33	4.06	33
Lift-over-rootmat	27.86	8.33	19.53	70

difference in rutting rate. The relative magnitude of these results is consistent with the results from the green road trial. In both trials optimizing tire pressures resulted in the greatest savings on Lift-over-rootmat sections and the least on V-ditch sections.

The accidental grading unnecessarily loosened the test road's surface thereby accelerating subsequent rut formation. This phenomenon is seen clearly in a USDA Forest Service trial (Truebe and Evans 1994) in which frequent light grading of test sections accelerated rut development (and grading frequency) well beyond what STP predicted had the road surface been left undisturbed to densify with traffic. Excessive rutting must not be allowed to develop as it can slow and/or endanger vehicles and direct moisture into the road, however, potential to economize on grading does exist. Shallow rutting can often be healed through the efforts of vehicles varying their wheel paths alone (Keller 1993; Bradley 1996) and, when necessary, with the judicious use of grading.[11]

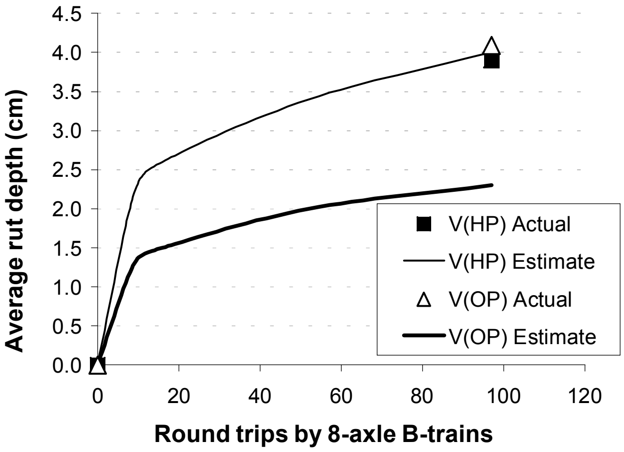

Figure 9. Actual vs. predicted rutting depths for the seasoned V-ditch test sections.

Rut depth modeling

Appendix I quantifies the theoretical change in access road damage resulting when a typical 8-axle B-train, loaded with the average trial load, optimizes its tire inflation pressures. This analysis shows that optimizing tire pressures causes a reduction of 4.63 ESALs per round trip. This corresponds to 55% slower rutting if the entire log hauling fleet optimizes its tire inflation pressures. It also means that grading frequency will be reduced by 55%, assuming that grading is only initiated when the average rut depth reaches a pre-determined trigger depth.

FERIC used the STP rutting model to predict rut development for the test sections prior to grading during the trial. The predictions were graphed and compared with observed, average rut measurements (Figures 9 and 10). Predictions were not attempted for the Lift-over-rootmat sections because the root layer imparts an unknown strength to the overlying material.

STP predicted the average rut depths for the V-ditch sections with reasonable reliability. Predictions of rut depth were within 1 mm of the V-ditch (HP) section average and within 18 mm of the V-ditch (OP) section after 97 round trips. Post-grading rut depth

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[11] Spot grading is a process by which candidate sections for grading are formally identified, based on some performance measures (e.g., road roughness, travel speeds) and scheduled for maintenance according to user-defined priorities. FERIC has recently released the "Opti-Grade" computer program to facilitate the process of spot grading (Brown and Provencher 2001).

predictions were not attempted because the road strength would have changed from the as-built condition but no DCP measurements were taken to quantify this change.

The average rut depth of the Lift (OP) section was overestimated by 63 mm after 97 round trips. After 9 round trips, localized deep ruts (averaging 48 mm) developed in the Lift (HP) section and it required grading. STP underestimated this rut growth by 24 mm, and the grading invalidated any longer term estimates for this section.

These results agree with the findings from the green road where estimates for the V-ditched sections were reliable but estimates for the Lift sections were not. As with the green road, the reason for the inaccuracy with the Lift section estimates may lie in the fact that the narrow top (only 5 m) and deep ditches of these sections discouraged drivers from varying their wheel paths. Although construction costs can be reduced by allowing narrower crown widths, this practice may be uneconomic if it increases maintenance costs. Additionally, Larcombe (1999) estimates that narrowing two-lane forest roads from 6 m to 5 m will reduce average travel speeds (by approximately 3 km/h under New Zealand conditions).

Given that STP reliably predicted V-ditch rut development, Figure 11 presents an example analysis of how STP might be employed by a forest operation to help evaluate ways of improving trucking efficiency. Assume a forest company is considering raising the payload of its 6-axle (i.e., tandem tractor/ tridem trailer) log trucks from 29 to 38 t, or replacing the fleet with high capacity B-trains capable of carrying 42.8 t payloads. In order to offset some of the added road damage (rutting) that may result, the company is also considering optimizing tire pressures on the trucks with CTI systems. The heavier loadings may necessitate bridge upgrading, but this was not considered in the analysis.

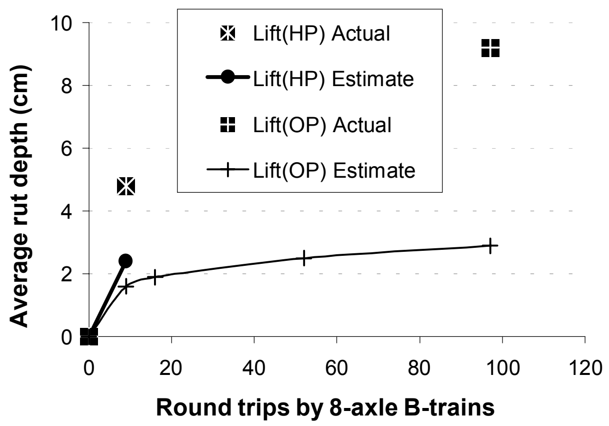

Figure 10. Actual vs. predicted rutting depths for the seasoned Lift test sections.

In the example, tire pressures were taken to be 655 kPa (95 psi) for all high-pressure inflation modes, with optimized pressures as per recommendations from the Tire & Rim Association for travel speeds up to 50 km/h.

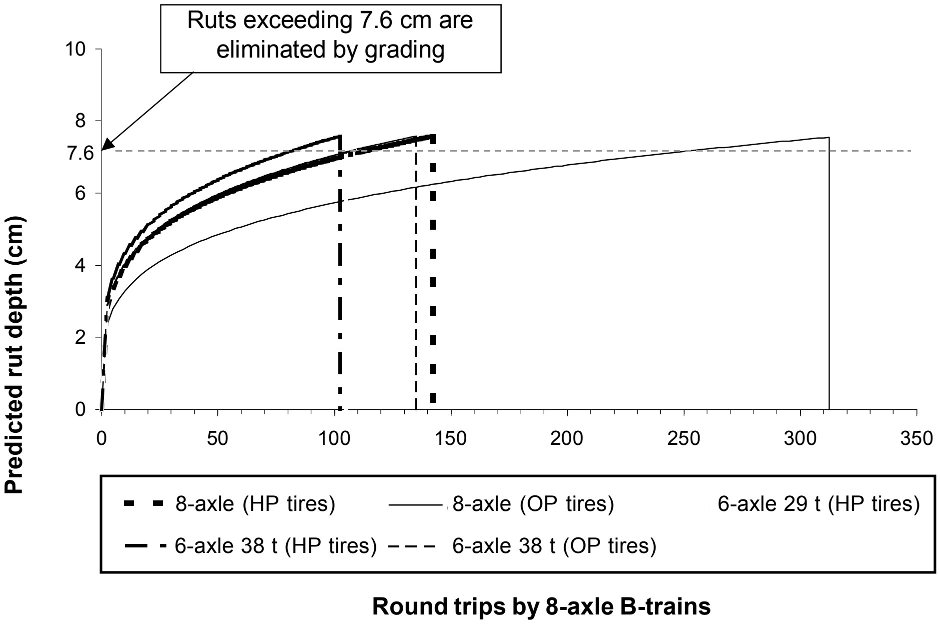

Figure 11. Influence of log truck configuration and inflation pressure on STP-estimated rutting.

With a payload of 29 t, a 6-axle truck's round trip ESAL equivalence is estimated to be 7.7 and 3.9 ESALs using high and optimized tire inflation modes, respectively. When loaded with a heavier, 38-t payload, a 6-axle truck's round trip ESAL equivalence increases to 10.4 and 7.9 ESALs for the high and optimized tire inflation modes. As with the majority of Alberta-Pacific's B-trains, none of the configurations optimized steering tire pressures. The subject road was a seasoned, V-ditched, forest access road with a subgrade CBR of 20 (i.e., equivalent to the average strength of the V-ditch test sections). Comparisons of road friendliness were based on how much payload could be transported before grading was initiated at a 7.6 cm rut depth, given that road strength remained constant.

Increasing the payload of the 6-axle trucks to 38 t resulted in no more road damage because the increase in damage per trip is compensated for by a reduction in the number of trips. If these heavily loaded 6-axles use optimized tire pressures, the predicted benefit is a 32% increase in grading interval. Switching to 8-axle B-trains further reduces the number of trips for a given payload, and thereby further increases the grading interval. Additional benefits of using the B-trains include less traffic congestion on the roads, smaller queuing delays, greater safety (compared to the 38 t 6-axles), and fewer trucks and drivers required.[11] Utilizing CTI systems on the B-trains, as Alberta-Pacific has done, offers the greatest advantage—an increase in grading interval of over 200%. While precipitation would reduce road strengths and grading intervals, and focus maintenance on the worst sections, the relative benefit from optimizing tire pressures generally increases on softer roads. The reduction in damage resulting from the use of optimized tire inflation pressures is less for stronger roads or for very low volume roads (Bradley 1997). Prior to implementation, forest companies should assess the economics of CTI systems; the benefits are numerous, however the investment in this technology can be sizeable. The cost of owning and operating CTI systems on Canadian 8-axle B-train log trucks, exclusive of profit, overhead and vehicle savings, was estimated to be \$3.34/h (Jokai and Bradley 2000).

The STP model appears to be a useful tool for modeling the effect of changes in traffic variables on rut development in seasoned and green V-ditched roads, for both of the soil types considered. Further testing is advisable to confirm its application for the wide variety of soil types and weather conditions found in Canadian log hauling operations. Once confidence with the model is established, however, many potential applications for its use exist.

Overall performance

Table 4 rates the performance of the seasoned road test sections that were subjected to optimized tire pressure traffic (i.e., under Alberta-Pacific haul conditions). The performance rating for the three

Table 4. Rating the performance of the optimized tire pressure road sections

Road design	Average construction cost ($/km)	Grading maintenance cost ($/km)	Combined road cost ($/km)	Performance rating
V-ditch	1 660	83	1 743	best
0.5 m lift	3 490	83	3 573	unsuitable
Lift-over-rootmat	3 940	83	4 023	least suitable

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[11] Attracting and keeping experienced, competent log truck drivers is a pressing concern for most Canadian forest operations.

designs was based upon the combined road cost and requirements for the given weather and soil conditions during the trial.

As with the green road analysis, the V-ditch section was rated as the best design based on its good performance and lowest combined cost. Both the 0.5-m Lift and Lift-over-rootmat sections experienced localized rutting problems, and their grading requirements were similar. The higher construction cost of the Lift-over-rootmat design earned it the "Least Suitable" ranking. As discussed, seasoning increased road surface densities by 5.5% (and by 9.8% at the 20 cm depth), and greatly improved the performance of these sections over green usage. Compacting increased surface densities of comparable V-ditch and Lift green road sections by 3–5% (and by less at the 20 cm depth), and resulted in slower rutting and, in the case of the Lift section, less maintenance.

The performance of the test designs and resulting performance ratings would likely have been different under other soil and/or drainage conditions. Had the sites been located in wet depressions, elevating the grade would have been more necessary and the Lift and Lift-over-rootmat designs might even have proven superior. Given that forest road maintenance is frequently driven by problem sections, employing better draining road designs in these sections is expected to reduce the occurrence of remedial repairs and the associated delays.

Conclusions

The construction costs of the three road designs were comparable to those reported for the green test road, with the V-ditch section being the least expensive and Lift-over-rootmat section being the most expensive. The average construction costs of the V-ditch, Lift and Lift-over-rootmat sections were \$166, \$349, and \$394/100 m, respectively. Total construction costs for each design can be estimated by including all site-specific construction-related costs (e.g., costs of major earth cuts or fills, equipment mobilization and demobilization, cross-drains and signs, or additional costs incurred due to early construction of the road to allow seasoning before use).

The cost of maintaining each test section through the break-in period was not determined because the test road was accidentally graded and weather deterioriated, prematurely ending the trial. However, STP predicts that the V-ditched sections would not normally have required grading through the break-in period. The V-ditched sections were observed to rut more slowly than either the Lift or the Lift-over-rootmat sections. Because forest access road maintenance is typically driven by problem sections, employing designs that drain well and provide strong roads through wet areas may significantly reduce both maintenance and hauling delay costs. V-ditched green road test sections experienced high levels of ditch erosion and sedimentation over winter. The cost of cleaning Alberta-Pacific's ditches and culverts (and repairing flooded roads) could be reduced if ditch walls are smoothed with an excavator-mounted shaping blade in areas with highly erodible, fine-grained soils.

Seasoning lasted for approximately one year from the time of construction and noticeably densified the test road—average dry densities were increased by 5, 9, and 10% at the 10, 15 and 20 cm depths, respectively. This densification of the road prior to trafficking improved the performance of the sections with built-up grades. The seasoned Lift (OP) and Lift-over-rootmat (OP) sections performed considerably better than did the comparable green test sections. The maintenance costs of the seasoned Lift (OP) and Lift-over-rootmat (OP) sections were less than that of the comparable (OP) green road sections after the first 40 and 20 truck loads, respectively. As with machine compaction, however, seasoning the V-ditch (OP) section resulted in no grading savings over green use. In conclusion, seasoning and surface compaction improved Lift and Lift-over-rootmat performance by a similar amount, and both should prove economic for all but very low volume roads. Conversely, the

V-ditched road design used by Alberta-Pacific does not appear to benefit enough from seasoning or compaction to warrant the added cost. Therefore, if operationally feasible, Lift and/or Lift-over-rootmat road sections should be pre-constructed through wet areas, using the logger's trails for machine access. However, loggers should be discouraged from trafficking these wet, seasoning, easily damaged sections. The following summer, V-ditched roads should be constructed on the well-drained ground between these wet areas, and the lifted road sections repaired as necessary.

Construction techniques can contribute to seasoning by reducing the de-compaction that results from frost heave, e.g., leaving roads to season over the winter with a rounded crown, and grading off the de-compacted surface materials in the final shaping. Seasoned roads should be constructed with due consideration for erosion and the potential disruption of drainage by sediment accumulation.

As with the green road analysis, the V-ditch (OP) section was rated as the best design based on its good performance and lowest combined cost ($1 743/km). Both the Lift (OP) and Lift-over-rootmat (OP) sections experienced localized rutting problems, and their grading requirements were similar. The higher combined cost of the Lift-over-rootmat (OP) section of $4 023/km (compared to $3 573 for the Lift section) earned it the "Least Suitable" ranking. The performance of the test designs and the resulting performance ratings would likely have been different under other soil and/or drainage conditions.

Optimizing tire pressures theoretically reduces the damage potential of the loaded test trucks by 55%. Damage reduction resulting from optimized tire pressures was most noticeable on weak, easily rutted sections. Optimizing tire pressures resulted in 33% and 70% less grading maintenance for the Lift and Lift-over-rootmat sections, respectively. There was no difference in maintenance, and little difference in rutting rate, between the V-ditch sections trafficked with optimized and high tire pressures. The relative magnitude of these results is consistent with the green road test in which the least benefit with optimized tire pressures was realized on the strong, dry V-ditch sections and the greatest benefit on the relatively uncompacted fill material of the Lift-over-rootmat sections. These findings agree well with theory that suggests that the benefits of reduced tire pressures are greatest under soft road conditions, where traction and flotation are most needed.

Alberta-Pacific's road contractors were familiar with constructing V-ditched roads and did so efficiently, creating roads with firm, full width running surfaces. However, both running surface quality and productivity were lower for roads with lifted running surfaces. This is because of inadequate lift compaction and difficulty with excavating enough material from the ditches to produce a road prism of sufficient height and width (while keeping within the constraints of the right-of-way width.) Because local experience suggests that lift heights of 0.5 m in silty soils and 1 m in clay soils are sufficient to provide drainage, and because sourcing sufficient lift material to produce the 0.5 m lifts of the test sections was difficult, it is concluded that lift height should be no more than 1 m (excepting fill sections). However, height reductions may be possible when constructing lifts with better draining materials.

STP is an empirical-based rutting model developed by the USDA Forest Service. The model reliably predicted rut development in the two seasoned V-ditch test sections but underestimated rut development for the seasoned Lift (OP) test section. Grading required after only 9 truck passes precluded making long-term rut predictions for the seasoned Lift (HP) section. The underestimation of rut depth on the Lift (OP) section may have resulted because of low soil densities, and because narrow road widths concentrated wheel paths—conditions significantly different from those used to develop the model. In order to apply STP to lifted road sections, road surface quality must be maintained and, possibly, the STP rut depth estimates factored upwards in the case of lifted sections.

Implementation

The results indicate that Lift and Lift-over-rootmat roads subject to optimized tire pressure traffic will achieve similar maintenance savings whether they are seasoned or surface compacted. Which technique to use will depend largely on machine availability and construction lead time. Companies utilizing optimized tire pressure fleets should develop guidelines for the most economic use of these techniques.

Performance comparisons should be made of Lift and Lift-over-rootmat road designs under wet subgrade conditions in order to establish where each may be most applicable. Excessive rutting was observed where running surface width had been narrowed during construction of lifted sections. A minimum running surface width of 6.0 m should be maintained to ensure that the trucks have adequate room to vary their wheel paths and heal existing ruts; this will also reduce the likelihood of accidents and maintain travel speeds through these sections.

Construction productivity and running surface quality for lift designs may be improved in a number of ways, including:

- Ensuring the full right-of-way width is logged.
- Placing organic debris from the ditch line into the area around the trees lining the right-of-way.
- Constructing with both a bulldozer and an excavator, and utilizing the strengths of each to best advantage (e.g., carrying and spreading lift materials with the bulldozer while using the excavator to ditch-sort out unacceptable materials and shape the ditch sides).

Additionally, several road contractors stressed the importance of preventing the lift material from being wetted by rain during construction because the moisture, once sealed in the road, may remain to degrade soil strength for the entire two-year life of the road. Operational measures that may prevent lift wetting include:

- Establishing a reliable rain warning system for in-woods operations.
- Using low ground pressure vehicles to transport road contractors to and from the road heading. This should make more time available to seal exposed lift materials by eliminating the need for contractors to immediately vacate a road heading in their own trucks when rain starts to make the fine-grained road surface slick and soft.
- Using lime or quick lime to dry and strengthen over-wet lift sections.

Rut depth measurements in this and other trials have found that grading can accelerate rut development by preventing the densification of the road's surface crust. Techniques such as healing ruts with unloaded CTI-equipped trucks and judicious spot grading will help extend grading intervals and fully capitalize on the surface densification that occurs with time and traffic. Tow-behind compaction attachments that reseal and compact road surfaces after grading should be considered. These units may also offer an economic way to pre-compact a road prior to seasoning and thereby reduce density losses due to frost heave.

Seasoning roads constructed with highly erodible soils (e.g., silts) can result in sediment blockages in ditches and cross-drains. Companies considering road seasoning should adopt practices that minimize erosion, and prevent sediment from reaching drainage structures and watercourses. Where erodible soil conditions exist and excessive sediment is unacceptable, an excavator using a shaping blade should be used to reshape the ditches of V-ditched roads. Blocking access to seasoning roads is recommended in order to reduce erosion caused by surface rutting from public vehicles. When travelling on soft, seasoning roads, drainage maintenance crews should avoid rutting the road surface—this may require the use of low ground pressure vehicles. A comparison should be made between the use of mobile pumping teams to drain ponded ditch water, and the use of excavators to continually re-establish drainage on temporary-use haul roads.

The STP rutting model appears to be a useful tool for modelling the effect of changes in traffic variables on rut development in V-ditched roads. Further testing is advisable to confirm its application for a wider variety of soil types and weather conditions, and for predicting rut growth after grading. Further testing is also advised to confirm and/or adjust the model for use with lifted sections.

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APPENDIX I

Tire inflation and axle loads of the test road traffic

Axle grouping	Loaded trucks Average tire inflation pressure (HP/OP) (kPa)	(psi)	Loaded trucks Average axle group load (t)	Unloaded trucks average axle group load (t)
Steer axle (1)	655/648	95/94	5.40	5.42
Drive axles (2)	648/372	94/54	16.72	6.27
Lead trailer axles (3)	641/379	93/55	21.67	7.97
Rear trailer axles (2)	641/379	93/55	15.57	0.00
Total			59.36 [a]	19.66 [b]

[a] GCW.

[b] Tare weight.

Effect of tire inflation and axle loading on axle load equivalencies for the test traffic

	Steer axle	Drive tan/axles	Lead trailer tri/axles	Rear trailer tan/axles	Total ESALs	ESALs per round trip	Change in ESALs per round trip (%)
Mode 1 — normal, highway tire pressures (HP)							
Loaded							
Pressure (kPa)	655	648	641	641			
Load (t)	5.4	16.7	21.7	15.6			
Equiv. factor	0.90	2.25	2.32	1.90	7.37		
Mode 2 — optimized tire pressures (OP)							
Loaded							
Pressure (kPa)	648	372	379	379			
Load (t)	5.4	16.7	21.7	15.6			
Equiv. factor	0.88	0.62	0.68	0.56	2.74		
Modes 1 and 2 (HP and OP)							
Unloaded							
Pressure (kPa)	648	372	379	379			
Load (t)	5.4	6.3	8.0	0.0			
Equiv. factor	0.87	0.08	0.09	0.00	1.04		
Average round trip ESALs of high pressure test traffic						8.41	
Average round trip ESALs of optimized pressure test traffic						3.78	(-55)

Payload (t)	39.7	Tare (t)	19.7	GCVW (t)	59.4

APPENDIX II

Summary of soil properties and classification

Sample location	Atterberg limits		Composition [a]		Unified soil classification	Classification as highway subgrade material [c]
	Liquid limit (%)	Plasticity index (%)	Sand (%)	Fines [b] (%)		
V-ditch (HP)	22.4	non-plastic	54	10	poorly graded sand, non-plastic (SP)	Good (A-2-4)
V-ditch (OP)	17.8	4.3	48	42	silty very fine sand, low plasticity (ML)	Fair to poor (A-4)
Lift (HP)	15.3	non-plastic	83	16	poorly graded sand, non-plastic (SP)	Good (A-2-4)
Lift (OP)	15.8	non-plastic	77	17 (13% silt)	poorly graded sand, non-plastic (SP)	Good (A-2-4)
Lift-over-rootmat (HP)	15.8	2.4	50	49 (27% silt)	silty very fine sand, low plasticity (ML)	Fair to poor (A-4)
Lift-over-rootmat (OP)	14.8	0.8	52	25	silty very fine sand, low plasticity (ML)	Good (A-2-4 or A-3)

[a] Gravel and cobbles make up the balance of the soil samples, e.g., V-ditch (HP) is 54% sand, 10% silt and clay, and 36% gravel and cobbles.
[b] Silt and clay content.
[c] Based on AASHTO (1990).

Appendix III

Glossary of terms

Atterberg Limits: Five indices that describe the response of soil to water. Two Atterberg Limits, the Liquid Limit and the Plastic Limit, are commonly used for soil identification and classification.

California Bearing Ratio (CBR): A widely accepted descriptor of soil strength that can be measured in the laboratory but is frequently estimated through correlations with more easily measured soil properties, e.g., Atterberg Limits or DCP values.CBR values are expressed as a percentage of the bearing strength of crushed rock.The values for very wet, fine-grained soils are in the range of 3–5%.

Dynamic Cone Penetrometer (DCP): A device used to gauge the shear strength of fine and medium-grained soils by quantifying the rate of penetration of a pointed rod into the soil. Higher penetration rates correspond to weaker soil conditions.

Equivalent Single Axle Load (ESAL): A standard unit used to describe the road damage potential of a vehicle's axles relative to the damage potential of a single axle with dual tires loaded to 18,000 lbs. The greater a vehicle's total ESALs, the greater its ability to generate rutting in unsurfaced forest roads.

Fire Weather Index (FWI): An estimate of forest dryness calculated from previous FWI and a variety of current weather measurements including precipitation, wind speed, temperature, and relative humidity.

Green road: A road intended for use immediately, or soon after, construction.

Lift road: Earth-surfaced, low volume road featuring a raised running surface. Local material, typically from the ditches, is placed on the stripped subgrade to create the final, lifted running surface.

Lift-over-rootmat road: Earth-surfaced, low volume road featuring a raised running surface. Local material, typically from the ditches, is placed on the existing mat of roots and low-cut stumps to create the final, lifted running surface.

Normal highway tire pressures: A tire inflation level normally used by loaded, on-highway (non-CTI) trucks. Many trucks used in Canadian forest operations use a cold inflation pressure of approximately 100 psi.

Optimized tire pressures: A tire inflation level adjusted (typically with a CTI system) to match the tire manufacturer's minimum recommended inflation for the specific operating conditions of load and speed.

Pre-compaction: The process of compacting a weak soil with light loads until it is capable of supporting heavier compaction equipment.

Pre-determined trigger depth: The pre-determined maximum acceptable depth for rutting on a particular type of forest road. Grading maintenance is initiated (triggered) when rutting on a section of road exceeds this depth.

Rut depth: The vertical difference between the lowest point in a wheel path (rut) and a straight line drawn perpendicular to the wheel path between the highest points of the material to either side of the rut.

Seasoned road: A low volume road constructed in advance of the intended use so that it will strengthen and stabilize through exposure to natural wetting and drying cycles.

Seasoning: The natural process of consolidation and strengthening experienced by unpaved roadway soils (especially fine-grained soils) in response to changes in water table level and weather.

Soil gradation: The composition, by weight, of the particle sizes that make up a soil. Soils identified as "fine-grained" are predominantly composed of very small particles (clay, silt and fine sand).

Surfacing Thickness Program (STP): An empirical model developed by the USDA Forest Service to estimate the thickness of road surfacing needed to limit rutting to a specified maximum depth, given inputs of soil strength and traffic-induced ESALs. The FERIC analyses use this model to estimate rut depth, for given as-built surface thicknesses and soil strengths, as well as traffic-induced ESALs.

V-ditch road: Earth-surfaced, low volume road with "V" shaped ditches. Typically constructed with a bulldozer, this road is shaped from the subgrade after the organic overburden has been stripped away.