Optimizing Road Maintenance Intervals

Yves Provencher, *Forest Engineering Research Institute of Canada*

The elements that affect the performance of a forest road are discussed. Poor drainage of the rolling surface, the use of materials that do not conform with standards, or poor grading technique (or all three) can accelerate degradation of the road and require premature rehabilitation of its surface. The costs of road maintenance are compared on the basis of surfacing materials used. Different methods of managing grading are evaluated using a model developed within the framework of this project for predicting the performance of roads. One alternative of scheduling grading at fixed times, the method generally used in the industry, is proposed: localized grading with a flexible schedule. Examples demonstrate that this management method ensures good road quality and can result in savings of more than 30 percent on grading costs.

The costs of transporting wood are closely tied to the transport distance between the forest and the mill. The average transport distance for wood is now more than 100 km in eastern Canada (*1*). To meet their revenue goals, which are a function of productivity (trips/day), and to minimize vehicle maintenance costs, truck drivers require an excellent rolling surface. Forestry companies are thus interested in maintaining the surface of their road networks in good condition.

Grading operations are now part of the day-to-day operations of forestry road managers and have now become almost automatic; grading is done every day, every week, or twice per month. However, roads do not deteriorate at the same rate over their entire length and over time, which makes the practice of treating roads identically throughout a season questionable. Rationalization of resource use, a constraint now faced by the forest industry, requires a profound review of the justifications for all expenses. The practice of scheduling road grading at fixed intervals is not exempt from this examination.

A model for predicting road performances is now under development at the Forest Engineering Research Institute of Canada (FERIC) as part of a larger project aimed at improving forest road design methods. This model is used in the optimization of grading frequency. In this paper, the fixed-schedule management of grading that is common in the industry is compared, economically and qualitatively, with the concept of a flexible prescription based on localized grading with a flexible schedule.

Study Objectives

Management of the grading frequency on a flexible schedule permits the identification of poor road sections, so that more maintenance efforts can be directed at them. It also reduces grading time by ignoring the sections of road that still perform well.

To understand the progression of road roughness over time and prescribe a grading interval adapted to the road's condition, FERIC has modeled road surface performance; the road's utilization, design, and maintenance appeared to be important in terms of optimizing the frequency of grading.

The objectives of the grading study were to

- Quantify the progression of the road roughness over time as a function of different patterns of grading, all else being equal;
- Determine the types of road surface damage that were observed and to explain their causes;
- Establish relationships between the most important measurable factors that affect the roughness of unsurfaced roads so as to model the evolution of roughness; and
- Evaluate different grading management scenarios in terms of their economic viability.

Modeling Performance of Road Surface

The objective of the model currently under development at FERIC is to establish the performance of the road surface in terms of its construction characteristics (e.g., material, construction techniques, drainage) and its utilization (e.g., volume of traffic, axle weights) under Canadian climatic conditions. When completed, the model will provide the information necessary to justify intervention strategies for the maintenance and rehabilitation of roads. The model will also be able to predict the performance of proposed roads and will thus contribute to the design of road surfaces that perform better.

The many variables that affect the performance of a road make it difficult to establish an empirical model that describes the overall deterioration process of a forest road. There are, however, complex models that consider every factor that influences the deterioration of road surfaces. The principal models (e.g., HDM-III) arose from studies conducted in developing countries and financed by the World Bank (*2,3*). Without questioning the correctness of the results of these studies, it is important to remember that the general conditions in these countries are radically different from those in Canada. Work was conducted in Saskatchewan to adapt HDM-III to North American conditions, but the results were not conclusive. Other than climate, the study identified the materials used and, most important of all, the loads and sizes of the vehicles traveling on the roads and their travel speeds as the biggest problems (*4*).

Description of Trials

On a portion of road that received an even amount of traffic throughout its length, nine straight, 1-km-long portions of road were marked and divided into three groups. Each group was managed with a different grading frequency. The forestry company that cooperated with FERIC in these trials graded the road twice weekly during its normal operations, and this treatment was used as the control. The two other grading frequencies selected were weekly and twice monthly. A road sign with a shape that indicated the frequency of grading assigned to that segment was used to identify each segment of road.

Soil samples were taken at an interval of 200 m and granulometric analyses were conducted in the laboratory to determine if variations in performance among segments could be attributed to differences in surface materials. The roughness of the road surface was determined three or four times per day in each segment during the entire study, which was carried out between June and August 1992. The measuring device used was a pickup truck towing a light tandem-axle trailer equipped with accelerometers. The ensemble was linked to a data acquisition computer in the truck.

Information from a weigh scale located at one end of the main road was used to determine the traffic flow. A radar device with a precision of +1 km/hr was used to measure the speeds of heavy vehicles on one segment of road with different levels of roughness. The device was hidden so that the drivers would not know they were being observed to prevent the measurements from affecting their driving habits.

Summary of Observations

Road Surface Materials

The grain-size distributions within and between road segments were not significantly different (Figure 1). This conclusion permits us to eliminate differences in the

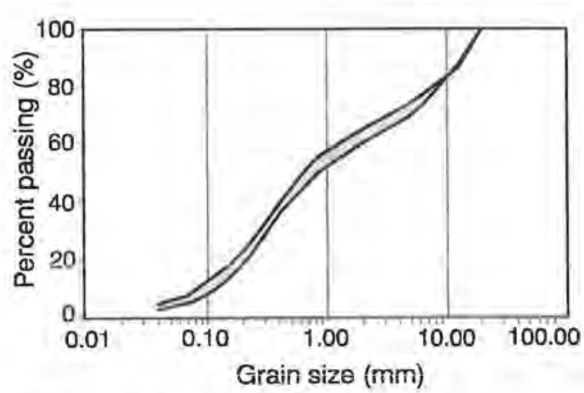

FIGURE 1 Range (*shaded zone*) in grain-size distribution of materials present in nine road segments.

road materials as an influence on the observed performance of various road segments.

Volume of Traffic

The volume of traffic was effectively constant during the entire study period and averaged 30 loaded vehicles per day. This figure is based on off-highway vehicles with loaded weights of 110 tons and empty weights on return trips of 38 tons. The trailers each had three tandem axles.

Vehicle Performance

It was not possible to detect any measurable effect of roughness on truck speed, even though this relationship undeniably exists. This observation may have several explanations:

- The roughness of the segments was perhaps not sufficiently high to affect the handling of the trucks significantly.
- The drivers knew that the rough sections were no longer than 1 km and thus chose to endure a high level of noise or vibration that would not last long.
- The high variation in travel speed observed among drivers obscured any influence resulting from the state of the road itself.
- Available power could have been the limiting factor in travel speed, as FERIC demonstrated earlier (*5*). This study demonstrated that the speed of off-highway trucks when loaded was only slightly affected by road conditions.
- Some drivers may have discovered that they were being monitored and modified their driving habits.

Many scales are used to describe the condition of a road surface. From among these, FERIC chose the International Roughness Index (IRI) developed by the World Bank (*6*). This index was developed to estimate the comfort of using the road as a function of the condition of the road's surface. The index is expressed in meters per kilometer and represents the sum of the vertical displacements of the suspension (in meters) over the distance driven (in kilometers). This index typically varies between 0 and 20, where 4 is typical of a good gravel road and 14 represents a level at which travel speed would be greatly reduced. Figure 2 shows the IRI scale and descriptions of the road surface condition at various IRI values. Figure 3 shows the development of roughness (IRI) as a function of total traffic on the road segments studied.

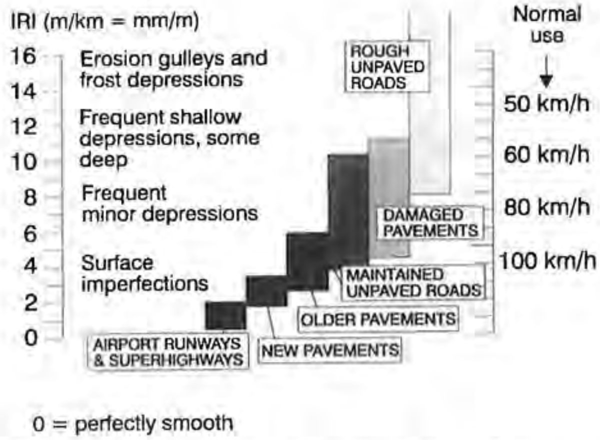

FIGURE 2 International Roughness Index (IRI) scale [after Sayer et al. (*6*)].

Figure 4 uses data from one of the road segments studied to show the typical development of roughness. Because the study was of relatively short duration compared with the useful life of a road, we cannot comment on permanent degradation of the road surface. The grader was able to restore the road surface to its original condition after each grading operation, which would not have been the case if the study's duration had been longer. In a longer study, road degradation because of loss of surface materials or deterioration of the subbase would begin to complicate the grader's task. At a certain point, permanent degradation would be sufficient to require a major rehabilitation of the road to restore its original surface quality. From Figure 5, which shows the progression of roughness over a longer time frame as a function of the frequency of grading, we can state that the frequency of grading affects the rate of both degradation of the road surface and the occurrence of permanent deterioration. Thus,

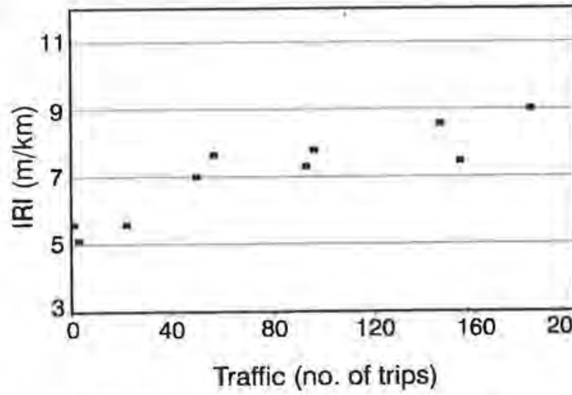

FIGURE 3 Development of roughness as a function of traffic in road sections studied.

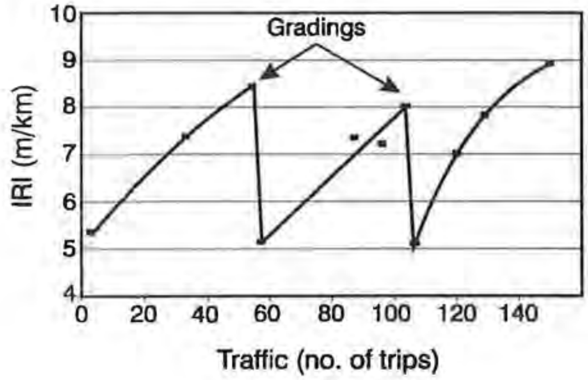

FIGURE 4 Cycle of development of road surface roughness in one segment studied.

the longer road surface restorations are delayed beyond the point when they become necessary, the less effective the repairs will be and the sooner a full rehabilitation will be required.

Model Development

Observations of the road segments studied permitted the establishment of relationships between roughness and the amount of traffic. Figure 6 presents two curves that show the development of roughness as a function of traffic on two different road segments. The increase of roughness follows a quadratic curve identified through regression analysis; that is, after an initially rapid increase, the level tends to stabilize as it approaches an asymptotic limit. The only difference between the two road segments was in their slopes: the segment with the fastest increase in roughness was also the segment with the steepest slope. Since the roughness of the road segments measured just after each passage of the grader remained at an IRI value of between 4 and 5 over the course of the trial, no permanent deterioration of the road was detected.

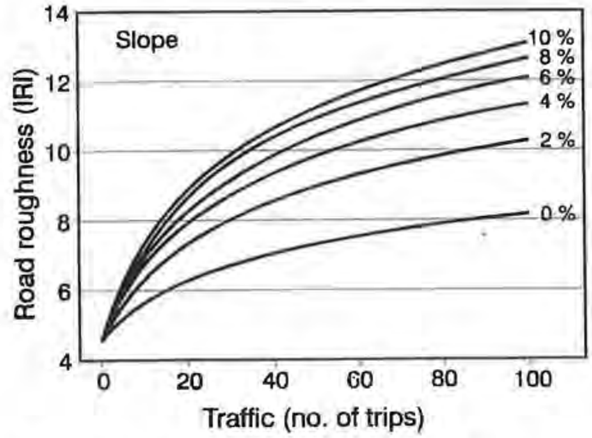

FIGURE 6 Comparison of development of road surface roughness as affected by topography (slope of road).

These observations shed some light on the role of slopes in the process of road deterioration. By isolating the variable "slope" from the field results, we developed a vulnerability index that permits us to consider the likelihood of damage to the segment's surface as a function of its slope and respective lengths (Figure 7). This index led to the establishment of a family of curve that describes the development of roughness as a function of topography (7). Using these curves, we developed a model for calculating roughness as a function of the amount of traffic and of topography. This model permitted the estimation of IRI for a road given its slope and the number of trips made by trucks since the last grading. This model is empirical, however, and only valid for the road conditions encountered during this study. The model will ultimately be extended to allow its general use for other road types.

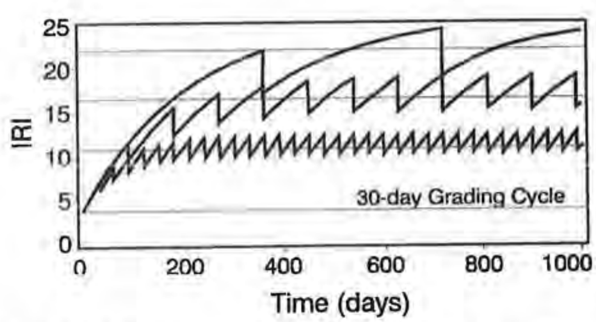

FIGURE 5 Long-term degradation of road surface (3).

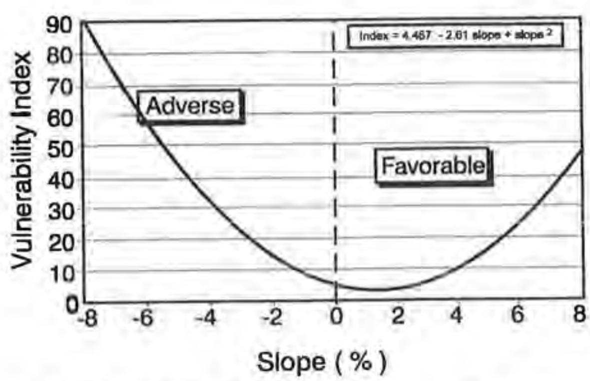

FIGURE 7 Relationship between road's slope and its vulnerability index.

The scope of the study did not permit an evaluation of the effect of road roughness on the maintenance of trucks traveling on the road, and few studies have been done on this issue. The most detailed study that currently exists, a study of the operating costs of articulated vehicles as a function of road roughness, indicated a cost increase of about 4 percent for each increase of one unit in IRI (*2*).

Prescription for Frequency of Grading

Grading operations are conducted with two principal goals: to restore the road's surface to a level adequate for efficient vehicle travel with the goal of augmenting driver productivity and minimizing maintenance costs and to conserve the integrity of the road surface by returning displaced materials back to the road's surface. Optimizing the prescription for grading frequency consists of determining the most opportune time at which to grade the road to minimize the total transportation and road maintenance costs (Figure 8). A too-high frequency of grading unduly increases grading costs, and too-infrequent grading increases both transportation costs and long-term road repair (rehabilitation) costs. As demonstrated in the previous section, too-infrequent interventions will make the full restoration of the road surface by grading difficult if not impossible because a greater deterioration of the surface materials will occur between gradings. The roughness of the road after successive gradings increases continuously until regraveling of the road is required.

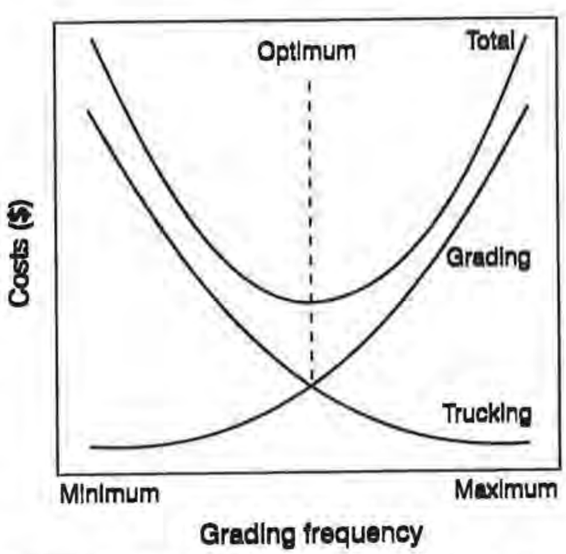

FIGURE 8 Optimization of road maintenance and trucking costs.

Economic criteria for grading intervention are generally better than criteria based on acceptance of the road by the users (*3*). This conclusion implies that if the interventions are motivated only by complaints from the users, the total maintenance and utilization costs will be higher than if more technical criteria are used.

Intervention at Fixed Intervals

The method of intervention at fixed intervals implies scheduling the time and location of the grading in advance. This method is becoming more popular because of the almost universal use of contractors to perform grading in the forest industry. In this method, a contract that stipulates the times and locations of grading is negotiated at the beginning of the season, and this scheduling restricts all subsequent interaction between the user of the road and the contractor responsible for its maintenance. Road grading does not lend itself well to annual contracts because, in contrast with other forestry activities, the work to be done is less predictable and, above all, has a direct effect on subsequent operations, that is, transportation. The intensity of grading work required depends on the volume of traffic and the type of vehicles, which are predictable to some extent, but climatic (weather) conditions, which also affect the road, cannot be predicted. To respond adequately to the needs of trucking, interaction between the forestry company and the road maintenance contractor is desirable.

Intervention in Response to Traffic or Volume of Wood Transported

The volume of traffic is the most significant cause of road-surface degradation. A program of grading based on this criterion for intervention will thus be more effective than one based on time alone. Except for heavy trucks, which are generally tallied at weigh-scales, it is difficult to know the precise number of vehicles that travel on the road. A program of road grading based on the number of heavy vehicles that pass over the road (e.g., grading once per 100 trucks) nonetheless cannot take topography, atmospheric (weather) conditions, and the amount of traffic by light vehicles into account.

Intervention in Response to Road Surface Conditions

The two methods of setting a grading prescription that have been discussed use one or more of the elements that affect the quality of the road surface to predict the best time for the use of a grader. The decision to intervene is based on indicators of the road's condition (i.e., time and traffic) and not on the state of the road itself. Intervention based solely on the road's actual condition assures better quality control because it is based on reality rather than on estimates.

Localized Grading with a Flexible Schedule

The preceding sections presented various decision criteria used in prescribing a grading frequency. Indicators such as time or traffic can be employed but do not translate exactly into measures of the road's surface condition. These indicators can lead to an imprecise estimate of grading needs and, thus, increase road maintenance and/or transportation costs. The method of intervention based on the actual road conditions responds to these deficiencies, but, because no road is homogeneous across its entire length, the road condition will necessarily vary. The information gathered will, therefore, only be representative of the road sections evaluated. Managing the frequency of grading as a function of the actual road condition will thus have to be refined based on the road segments to be treated. The potential of this improved method, "localized grading with a flexible schedule," will be evaluated in this paper. This method consists of grading deteriorated road segments according to criteria that define when intervention should occur. The goal is to optimize the frequency of grading in terms of the location at which grading will take place. The following sections present some details on implementing a management method and evaluating the economics of the method.

Implementation

The success of the concept of localized grading with a flexible schedule rests on two essential elements: an adequate evaluation of the road's surface conditions and establishing an effective communication network between the maintenance manager and the field staff who will conduct the grading.

Evaluation of Road Conditions

The surface evaluation must provide the grader operator with a strategic tool that indicates which road segments need to be graded. Heavy trucks are less sensitive to roughness than light vehicles. Therefore, an evaluation based on the ride quality of light vehicles will generally satisfy the requirements of heavy vehicles. A "windshield evaluation" (i.e., observing the road through the windows of a pickup truck) and an appreciation of the quality of the ride, both performed from a light vehicle, are considered adequate to ensure a good-quality road surface for heavy vehicles.

There is a rich literature on rating road surfaces (*8, 9, 3*). However, since these studies were targeted at public roads, they were generally more meticulous in their rating methods than would be required for road surfaces used by heavy vehicles. Forest roads also present more variable characteristics than public roads, so their degradation rates will vary more. Furthermore, a small error in the roughness evaluation will not cause a serious problem because forest roads are graded frequently, usually many times per month. The amplitude of the potential savings is related to a reduction in the large number of grader passes over the various stretches rather than to large savings on a single pass. Therefore, there is no need for a complex scientific method of rating the roads; local guidelines are generally adequate.

The surface rating of a particular road segment must be accurate in terms of the criteria for intervention and must be identified in terms of the proper location on the road segment. The road network must be divided into sections and subsections that present homogeneous characteristics in terms of road class, topography, structure, traffic, construction material and method, and drainage. The sections and subsections obtained must then be well identified so that both the grader operator and the person carrying out the road surface rating can easily locate them. This work may seem demanding but it is done only when the management system is being implemented. The ongoing work of the road surface evaluation begins once the road has been divided into sections.

Road Surface Evaluation

The evaluation is performed from a light vehicle (e.g., a pickup truck) moving at 50 km/hr. Surface damage in each section is identified and rated according to its relative seriousness. The data are then integrated to provide an estimate of the level of deterioration for each section. Based on these results, a grading scenario is elaborated. This scenario can easily be computerized so that, once the inspection results are recorded, it is automatically produced. After some time, the grading scenario may even develop a cyclical pattern so that sporadic inspections may be sufficient to verify the road's surface condition.

Economic Analysis

The economic analysis of localized grading with a flexible schedule was performed with the road performance model developed during the present study. The results of this analysis will be compared for the three grading scenarios in the study. This method minimizes the risk of errors that could be introduced by the model because the nature of the model is such that the errors, if any, should be proportional for all three scenarios. Each of the model's results will be compared with field results obtained during the trials to test their accuracy.

The approach in this section is as follows: Initially, we used the model to determine the performance of various road segments, each with specific characteristics. Next, we used the forest company's surface quality tolerance criteria to apply a new grading prescription to the road. Finally, the machine time required for grading was calculated to establish the basis for an economic comparison. The results of these exercises are then presented and discussed.

Use of Predictive Model for Road Surface Performance

Figure 9 presents the development of roughness obtained with the model for two road segments with slopes of 3 and 5 percent, respectively. The roughness of the segment with a slope of 5 percent increases more rapidly than that of the segment with only a 3 percent slope. If the tolerance level is set at an IRI level of 11 (which is generally the case for Class 1 road and was specifically the case for the company with which the study was undertaken), Figure 9 shows that, for the same level of traffic, the segment with a 3 percent slope will only be graded twice for every three gradings of the segment with the 5 percent slope.

It is possible to repeat the preceding exercise for a series of slopes in order to calculate the grading time required per kilometer as a function of topography and traffic. The attractiveness of this exercise will increase when the cost of grading is expressed in terms of dollars per 100 truck trips. Figure 10 presents the costs of grading 1 km of road as a function of slope for a road that is graded as soon as an IRI value of 11 is reached. The horizontal line at a value of $25/km per 100 trips shows the cost of grading if the road is graded every 60 vehicles (one of the cases studied).

Comparative Studies

Two situations will be compared in this section. The first represents grading on a fixed schedule, an actual situation involving off-highway trucks on a private forestry road. The second case is a simulation of localized grading with a flexible schedule on the same road and with the same traffic as for the fixed-schedule grading. The program used to model the performance of the road was validated on this road, so the results offer good reliability. The exercise was carried out for 500 trips, a time during which the state of the road surface attained a certain stability.

The 100-km road was divided into 20 homogeneous segments. Table 1 summarizes the road's profile. The IRI values for the 20 segments were recalculated after increments of 20 truck trips. In the case of grading on a fixed schedule, the road was graded every 60 trips, which corresponded to an IRI near 11 for the most difficult segments. The logistics for the variable (localized) grading were as follows: As was the case for scheduled grading, grading was triggered at an IRI value of 11. As soon as any segment reached an IRI value of 11, all segments with an IRI value of between 9 and 11 were graded and all other segments were ignored.

Table 2 compares the two methods of grading management. In addition, it includes a column labeled "im-

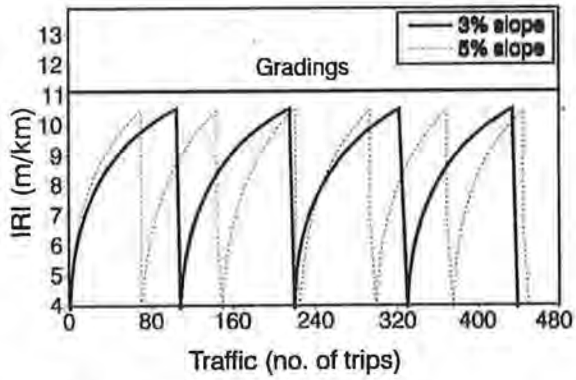

FIGURE 9 Variation in need for grading as a function of slope of road segment (solid lines = 3 percent slope; dotted lines = 5 percent slope).

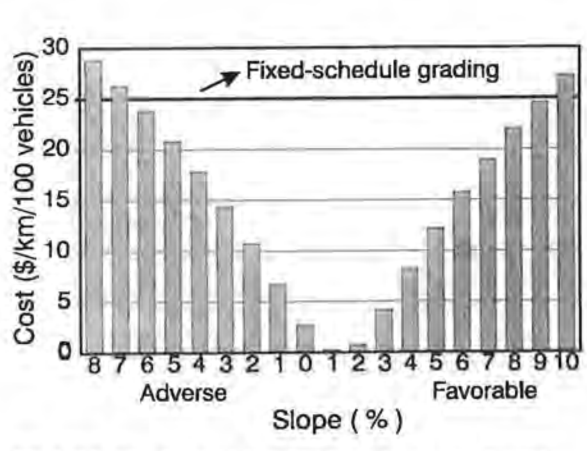

FIGURE 10 Cost of localized grading with flexible schedule for various slopes.

TABLE 1 Topographic Sequence for Road Studied

	Section																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Length (km)	16	2	7	3	2	1	7	2	1	19	5	2	1	1	5	6	11	3	5	1
Slope (%)	1	-3	2	5	-4	8	-1	4	5	0	-2	6	-6	-6	-8	2	-1	3	-2	7

proved road," which contains information for a situation in which slopes of 7 or 8 percent were reduced to 6 percent. The costs of grading were calculated based on the following assumptions:

- The cost assigned to the grader and operator was $75 (Can.)/hr.
- Productivity was estimated at 5 km/hr for grading and 40 km/hr for travel between road segments.
- Management on the basis of localized grading with a flexible schedule permitted a reduction in time, thus in grading cost, of 35 percent.

With these assumptions, the grader traveled the same distance in each case, but when grading was performed only as needed, only 542 km was actually graded versus 900 km using a fixed schedule. The calculations also showed that using a flexible grading schedule permitted a saving of almost $4700 as a result of reduced machine time during the period simulated (about 2 weeks). An additional saving on operating costs of the grader will occur as a result of these time savings. By grading only those segments that were the most damaged, the average level of roughness of the entire road increased only slightly, but no segment exceeded the prescribed IRI threshold of 11.

Tracking the development of roughness on the different road segments demonstrated that two road segments, with slopes of 7 and 8 percent, were shown to be the triggers for grading in almost every case. Another benefit of localized grading with a flexible schedule was that it quickly identified problem segments of the road as in the case of the segments with slopes of 7 or 8 percent. Such a tool offers two important advantages: It can help justify special budgets for improving road segments, but it also guarantees that these sums are used optimally by allocating them to the segments that trigger grading.

The next step was intended to evaluate the impact on grading costs of reducing slopes from 7 or 8 percent to 6 percent. The same decision criteria were used, and the results are presented in Table 2 in the column "improved road." The first thing to note is that the number of gradings was reduced from nine to eight with the result that the grader traveled 100 km less. Of the travel distance, only 518 km was graded, a time savings of 40 percent in comparison with the time required for grading on a fixed schedule, which amounted to a cost saving of $5200 over the period of the study. The saving was $250 per week more than that realized from the treatment alone with no road improvement. By eliminating extreme slopes, the road became more homogeneous, so the grader was used less frequently but treated a larger proportion of the road on each pass. Reducing the amount of grading increased the overall surface roughness by only 10 percent.

CONCLUSIONS

The frequency of grading can increase fivefold from one company to the next depending on the materials used for road construction. Moreover, a FERIC survey showed that the same company can decrease its grading costs by half if the road surfaces are composed of crushed rock instead of natural gravel (5).

The influences of traffic and topography on the performance of roads were demonstrated. For example, an adverse slope of 5 percent degrades 50 percent more rapidly than a slope of 3 percent. The work in this study led to the creation of a predictive model for the performance of road surfaces. This model, though only valid under a limited number of road conditions, proved its usefulness in the development of a new concept of grad-

TABLE 2 Comparison of Grading Performance for Three Regimes

	Fixed schedule	Flexible schedule	Improved road[a]
No. of trucks	500	500	500
No. of gradings	9	9	8
Time (hours)	180	117.4	110.7
Distance (km)			
- Traveled	900	900	800
- Graded	900	542	518
Costs ($)	13 500	8 800	8 300
Average IRI	6.46	6.99	7.14

[a] Slopes of 7 or 8% were reduced to 6%.

ing management—localized grading with a flexible schedule. Such a predictive tool could be used for optimizing grading operations or studying the economics of reducing a road's slope. The next phase of the model's development will be to generalize its application to any type of unsurfaced road.

Localized grading with a flexible schedule can reduce grading costs by focusing efforts on the portions of the road that need it most, usually the most difficult segments. The result is a road with a more homogeneous surface condition; that is, no segment will exceed a prescribed roughness. The quality of the road surface thus obtained is adequate over the entire road network. The examples presented in this paper demonstrate that savings of at least 30 percent can potentially be obtained by using a flexible schedule without neglecting the overall condition of the road. Assuming that a road is graded about 26 weeks per year in Canada, the saving can easily reach $61,100/year ($2350/week). Further savings are possible if the road is improved to reduce high slopes, which trigger gradings by degrading faster than other slopes, and as a result of decreased operating costs for the grader. This information proves that road maintenance efforts must be targeted strategically on an ongoing basis rather than scheduled systematically over a given period.

Measurements were taken of travel speeds, but no significant differences were found over the range of road roughness encountered in the study.

FERIC is continuing to develop the predictive model of road performance in order to better understand the process of deterioration. Our eventual goal is to provide the forest industry with a decision-making tool that will permit the construction of higher-quality roads that will better resist intensive use.

REFERENCES

1. Provencher, Y., and J. Favreau. *Statistical Information on Forest Roads.* Field Note No. Roads and Bridges-32. Forest Engineering Research Institute of Canada (FERIC), Pointe-Claire, Quebec, 1993.
2. GEIPOT. *Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization (PICR).* Final Report, 12 vols. Empresa Brasilleira de Planejamento de Transportes (GEIPOT), Ministry of Transport, Brasilia, 1982.
3. Paterson, W. D. O. *Road Deterioration and Maintenance Effects: Model for Planning and Management.* Highway Design and Maintenance Standards Series. Johns Hopkins University Press, Baltimore, Md., 1987, 454 pp.
4. Bein, P., J. Cox, and M. Clark. *Relevance of HDM3 Road User Cost Model to Canadian Heavy Vehicles.* Presented at Second International Symposium on Heavy Vehicle Weights and Dimensions, Kelowna, B.C., Canada, 1989.
5. Provencher, Y. *Crushed Rocks on Roads: An Economical Option?* Field Note No. Roads and Bridges-21. Forest Engineering Research Institute of Canada (FERIC), Pointe-Claire, Quebec, 1990.
6. Sayers, M. W., T. D. Gillespie, and W. D. O. Paterson. *Guidelines for Conducting and Calibrating Road Roughness Measurements.* World Bank Paper No. 46. The World Bank, Washington, D.C., 1981.
7. Méthot, L. *Modèle de prévision de la déterioration de la chaussée.* Master's thesis (in preparation). Faculté de foresterie et de géomatique, Université Laval, Ste-Foy, Quebec, 1994.
8. Eaton, R. A., S. Gerard, and D. W. Cate. *Rating Unsurfaced Roads: A Field Manual for Measuring Maintenance Problems.* Special Report 87-15. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, N.H., 1987, 35 pp.
9. Chong, G. J., and G. A. Wong. *Manual for Condition Rating of Gravel Surface Roads.* MTO SP-025. Ministry of Transportation of Ontario, Downsview, 1989, 61 pp.