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MANAGING THE REHABILITATION OF FOREST ROADS USING HISTORICAL DAILY ROUGHNESS DATA COLLECTED BY THE OPTI-GRADE® SYSTEM

MONTRÉAL, AOÛT 2002

Mark Brown

Gestion de la réfection des chemins forestiers à l'aide de données historiques quotidiennes sur la rugosité recueillies avec le système Opti-Grade*

Pour gérer l'entretien des chemins forestiers, l'Institut canadien de recherches en génie forestier (FERIC) a mis en application Opti-Grade, un système de gestion de nivelage, qui a permis aux entreprises forestières d'économiser entre 15 et 35 % de leurs coûts d'entretien des chemins. En plus d'être un outil de gestion de l'entretien journalier, les donnés d'Opti-Grade peuvent être utilisées pour améliorer la gestion de la réfection des chemins forestiers.

Pour confirmer la fiabilité des données du système Opti-Grade on a étudié la répétabilité des mesures obtenues. Divers systèmes de gestion de chaussée disponibles ont été évalués pour être utilisés avec les données du système Opti-Grade pour gérer la réfection des chemins. Comme aucun système ne convenait parfaitement aux besoins de l'industrie forestière, on a décidé d'élaborer un système de gestion de la réfection des chemins capable d'isoler les tronçons de chemins à réparer et de déterminer la date d'exécution de ces travaux.

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IT WAS THE TOPIC OF PRESENTATION BEFORE

THE JURY AND PUBLIC

JUNE 27, 2002

AT L'ÉCOLE DE TECHNOLOGIE SUPÉRIEURE

GESTION DE LA RÉFECTION DES CHEMINS FORESTIERS À L'AIDE DE DONNÉES HISTORIQUES QUOTIDIENNES SUR LA RUGOSITÉ RECUEILLIES AVEC LE SYSTÈME OPTI-GRADE®

Mark Brown

Sommaire

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MANAGING THE REHABILITATION OF FOREST ROADS USING HISTORICAL DAILY ROUGHNESS DATA COLLECTED BY THE OPTI-GRADE® SYSTEM

Mark Brown

Abstract

The forest industry represents an important contributor to the Canadian economy, generating $44.2 billion worth of exports per year and providing direct jobs to more than 350 000 Canadians. As with most industries in the world that are dealing with the issue of globalization, the Canadian forest industry faces increased competition for international markets, and this competition generates an ever-increasing need to control costs and spend budgets efficiently to obtain the best-possible results. One important area of operational costs for the forest industry involves forest roads, which represent about 15% of total in-woods operational costs.

The key to controlling road costs lies in obtaining timely information on the roads, and this concept underlies the implementation of any pavement management system. In the case of forest roads, years of evolution within the industry have not been accompanied by efforts to obtain and update information about road conditions and management. When trucks and thus roads were first introduced in the forest industry, they were used solely for short-distance transport, so road networks were small and those in charge of maintenance could easily keep track of the condition and management of their roads. As it became necessary to extend the road networks for longer transportation distances and as road managers took on responsibility for multiple tasks in addition to road management, their personal knowledge of the roads inevitably decreased greatly. Consequently, the maintenance of road networks fell into a patterned approach in which every section of the road received the same maintenance, regardless of that section's performance. Similarly, road rehabilitation suffers from a less than optimal approach; with no way to justify the need for a budget to perform road rehabilitation and no way to objectively identify where rehabilitation is required, road rehabilitation is only performed when money is left over in the budget.

To deal with these road maintenance issues, the Forest Engineering Research Institute of Canada (FERIC) has recently implemented an effective, simple, low-cost system called Opti-Grade. This system consists of a hardware component and a software component. The hardware is installed on a haul vehicle that travels regularly across the road network, and once it has been installed, it continuously measures road roughness. This data is then transferred daily to the software, which analyzes it based on user-defined criteria to identify where grading is required. This focused approach to road maintenance has allowed the eighteen Canadian forestry operations that have

implemented Opti-Grade in 2001 to save between 15 and 35% on their road maintenance costs. However, although Opti-Grade has significantly improved road maintenance, additional efforts must be made to improve forest road rehabilitation management.

The large database of road roughness values being created and stored by Opti-Grade provides a natural basis for a future road rehabilitation management system (RMS). To confirm the reliability of Opti-Grade's data for use in such an RMS, the repeatability of the Opti-Grade system's measurements was tested and it was confirmed that the level of repeatability was adequate. Through a literature search, various currently available pavement management systems suitable for rehabilitation management in the forest industry based on Opti-Grade data were identified and evaluated. It was concluded that no existing system was well suited to the needs of the forest industry and the use of Opti-Grade data. Therefore, a RMS was developed that would identify where and when rehabilitation should be performed.

The Opti-Grade data suggest that the roughness of forest roads is very variable over short times and distances and thus, this data is not directly usable for the development of road performance curves. Instead, it was determined that the best method for modeling road performance based on Opti-Grade data would be based on Markov chains. To do this analysis, sections of the road network were divided into families, based on road geometry. This typically gives three or four families per road network. Markov matrices are then developed based on the Opti-Grade data for each segment of road within a family; subsequently, a Markov matrix is devised for each age group within a family of roads. Using these predictive models, the road user and maintenance costs are simulated using Monte Carlo simulations summed to determine the total annual cost for each age group of road. The total 5-year costs of six different scenarios are provided to the manager; the chosen scenarios involved doing no rehabilitation, and performing rehabilitation in years 1 through 5. The road manager can then generate a 5-year road rehabilitation plan in which the location and time of the rehabilitation has been economically optimized.

GESTION DE LA RÉFECTION DES CHEMINS FORESTIERS À L'AIDE DE DONNÉES HISTORIQUES QUOTIDIENNES SUR LA RUGOSITÉ RECUEILLIES AVEC LE SYSTÈME OPTI-GRADE®

Mark Brown

Résumé

L'industrie forestière constitue un volet important de l'économie canadienne, avec 44,2 milliards $ d'exportations par année et plus de 350 000 emplois directs au Canada. Dans un contexte de mondialisation, l'industrie forestière canadienne, à l'instar de la plupart des industries dans le monde, fait face à une concurrence accrue sur les marchés internationaux. Compte tenu de cette concurrence, les industries doivent sans cesse limiter leurs coûts et utiliser efficacement leurs budgets de façon à optimiser leurs activités. Dans l'industrie forestière, les chemins forestiers constituent l'un des postes importants du budget d'exploitation — environ 15 % des dépenses totales en forêt.

La meilleure façon de limiter les coûts inhérents aux chemins forestiers consiste à obtenir en temps opportun de l'information sur ceux-ci ; or, ce concept sous-tend la mise en œuvre d'un système de gestion des chaussées. Dans le cas des chemins forestiers, l'industrie n'a jamais, au fil de son évolution, consenti les efforts nécessaires pour recueillir de l'information sur l'état et la gestion des chemins et pour mettre cette information à jour. Quand les camions et les chemins ont fait leur apparition dans l'industrie forestière, ils ne servaient qu'au transport sur de courtes distances ; le réseau forestier était de faible envergure, et les responsables de son entretien pouvaient facilement faire le suivi de l'état et de la gestion des chemins. Lorsqu'on a étendu le réseau forestier pour couvrir de plus longues distances, les gestionnaires de chemins, qui se sont vus confier plusieurs autres tâches en plus de la gestion des chemins, ne pouvaient plus être aussi bien informés de l'état du réseau. Ils ont donc dû adopter une approche globale en matière d'entretien selon laquelle chaque section de chemin forestier reçoit le même entretien, peu importe son état. La réfection des chemins est, elle aussi gérée selon une approche quelque peu désuète. Comme on ne dispose pas de moyens pour justifier l'allocation de fonds pour la réfection des chemins et que l'on ne peut déterminer objectivement les endroits à réparer, la réfection des chemins n'est effectuée qu'à partir des surplus budgétaires.

Pour régler les problèmes associés à l'entretien des chemins, l'Institut canadien de recherches en génie forestier (FERIC) a récemment mis en application un système efficace, simple et peu coûteux appelé Opti-Grade, qui est constitué d'un composant matériel et d'un composant logiciel. Le composant matériel, installé sur un véhicule de transport qui sillonne régulièrement le réseau forestier, mesure sans interruption la rugosité des chemins. Les données recueillies sont transférées chaque jour au composant logiciel, qui les analyse en fonction de critères définis par l'utilisateur pour établir les

endroits nécessitant un nivellement. Cette approche ciblée en matière d'entretien des chemins a permis à dix-huit entreprises forestières canadiennes, qui ont mis en application le système Opti-Grade au cours de la dernière année, d'économiser entre 15 et 35 % de leurs coûts d'entretien des chemins. Cependant, même si le système Opti-Grade a amélioré l'entretien des chemins de façon significative, il faut consentir d'autres efforts pour améliorer la gestion de la réfection des chemins forestiers.

L'importante base de données sur la rugosité des chemins créée avec le système Opti-Grade constitue un point de départ logique pour un futur système de gestion de la réfection des chemins. Pour confirmer la fiabilité des données du système Opti-Grade avant de les appliquer à un système de gestion de la réfection des chemins, on a étudié la répétabilité des mesures obtenues et on constaté que le niveau de la répétabilité était adéquat. En examinant la littérature à ce sujet, on a ensuite relevé et évalué les divers systèmes de gestion de chaussée disponibles que l'on pourrait utiliser pour effectuer la gestion de la réfection des chemins avec les données du système Opti-Grade. Comme aucun système ne convenait parfaitement aux besoins de l'industrie forestière et aux données du système Opti-Grade, on a décidé d'élaborer un système de gestion de la réfection des chemins capable d'isoler les tronçons de chemins à réparer et de déterminer la date d'exécution de ces travaux.

Les données du système Opti-Grade indiquent que la rugosité des chemins forestiers varie passablement sur de courtes périodes et de courtes distances. On ne peut donc utiliser directement ces données pour l'élaboration de courbes de rendement des chemins. On a par ailleurs déterminé que la meilleure méthode pour modéliser le rendement des chemins à partir des données du système Opti-Grade était d'utiliser l'analyse en chaînes de Markov. Pour effectuer cette analyse, on a divisé des segments de chemin en familles d'après la géométrie des chemins. Les résultats obtenus sont d'ordinaire trois ou quatre familles par réseau de chemins. On a ensuite élaboré des matrices de Markov à partir des données du système Opti-Grade pour chaque segment de chemin d'une même famille, puis on a conçu une matrice de Markov pour chaque catégorie d'âge d'une même famille des chemins. Grâce à ces modèles de prévision, on simule les coûts en entretien et en utilisation des chemins à l'aide de la méthode de Monte Carlo, puis on additionne les résultats pour déterminer le coût total annuel pour chaque catégorie d'âge de chemin. Les coûts totaux sur 5 ans de six scénarios différents sont ensuite fournis au gestionnaire. Les scénarios retenus sont les suivants : ne faire aucune réfection ou effectuer des travaux de réfection au cours de l'année 1, 2, 3, 4 ou 5. Le gestionnaire du réseau forestier peut alors produire un plan quinquennal de réfection des chemins dans lequel les secteurs et la période de réfection ont été optimisés sur le plan économique.

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Abitibi-Consolidated Inc.
Tembec Inc.

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INTRODUCTION

Objective

Faced with growing road networks, the Canadian forest industry has begun implementing modern road management principles. A significant step has been the development by the Forest Engineering research Institute of Canada (FERIC) of a low-cost tool (Opti-Grade) for measuring road roughness; Opti-Grade provides a daily reading of the distortion of sections of the road and allows the scheduling of routine daily maintenance activities. The purposes of this project are to:

- Establish the forest industry's need for an effective, easy to use, practical road evaluation and management system;
- Develop the key basic components of an effective system for managing road rehabilitation activities that is suitable for use by the Canadian forest industry.

Scope

This thesis is being developed with cooperation from FERIC. FERIC is a non-profit institute that provides research and development services to the Canadian forest industry and the federal and provincial governments. FERIC membership, which is voluntary, represents more than 70% of the entire Canadian forest industry, with more than 100 forest company members and 11 governmental partners (provincial, territorial, and federal). The goal of FERIC is to improve the efficiency, effectiveness, and safety of forest operations, including all operations involved in delivery of wood fiber to mills and the re-establishment of forests. Research on forest roads and transportation operations represents a significant portion of this mandate, and account for about 20% of the total $9,731,000 research budget. FERIC's membership meets annually to define FERIC's short- and long-term research goals and develop the annual work program.

In the mid-1990s, FERIC's membership identified road maintenance management as a priority and it was added to the work program. The research and development on this topic lead to the introduction of Opti-Grade, a road roughness evaluation and maintenance management tool (discussed in more detail in chapter 2 of this thesis), which entered beta testing in July 2000 and was released for a broader commercial launch to FERIC members in March 2001. By December 2001, 18 FERIC members (including five of the six largest members) had implemented Opti-Grade in five provinces across Canada.

With the implementation of Opti-Grade, the forest industry now has a tool to evaluate road roughness daily and to use this information to direct when and where daily maintenance activities (grading) should take place. What continues to be missing from this forest road management system is a process to make use of the now available information on road roughness and maintenance activities in the management of rehabilitation activities, this is outlined in figure 1. Though proper interventions are key to successful road rehabilitation, this thesis does not address the question of what type of intervention should be performed. This thesis will address the issue of rehabilitation management by developing the key basic components of a decision-support tool that will identify when and where road rehabilitation should take place.

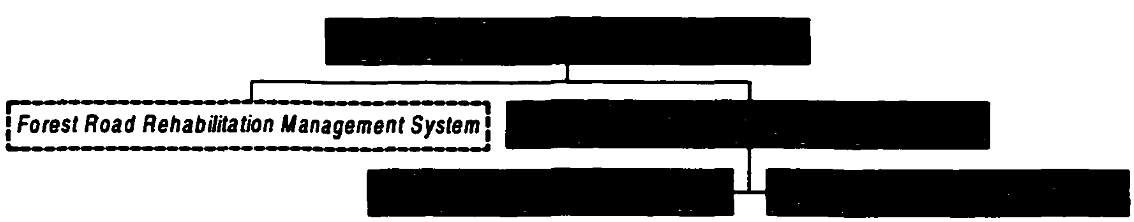

Figure 1 Organizational chart of Forest road management

Need

The importance of forest roads

The forest industry is a major contributor to the Canadian economy, with $44.2 billion in exports and a $19.4 billion contribution to the GDP. The forest industry directly provides jobs to more than 350 000 Canadians (Anon., 2000). The forest operations that deliver raw material, wood fiber, from the forest to the mills are a key component of this industry. These operations include harvesting, transportation, reforestation, and road construction and management. Representing almost 15% of the total operational costs, roads are a significant portion of any forest company's budget.

Forest roads range from the simplest and lowest-cost roads in the world to some of the most complex unbound roads in the world. The nature of the industry forces road construction to be done in a wide range of situations and using a wide range of materials. The forest industry has no control over where trees grow, and to harvest the maximum value from the forest, they must access as much of the forest as possible. As a result, forest roads range from main trunk roads, built to high standards using high-quality road material and technologies such as geosynthetics and chemical stabilization, to low-grade access roads built solely from native materials, with every type of unbound road in between these extremes.

Traditionally, forest roads have been lumped into the category of low-volume roads and treated as such by road experts. However, although the traffic levels on these roads may seem relatively low, the vehicle weights place these roads in a unique category (Figure 2). Traffic on forests roads is made up almost exclusively of heavy trucks that range from 57 000 kg on seven axles up to 180 000 kg on six axles. This constant, heavy traffic creates management and maintenance challenges for forestry road network managers.

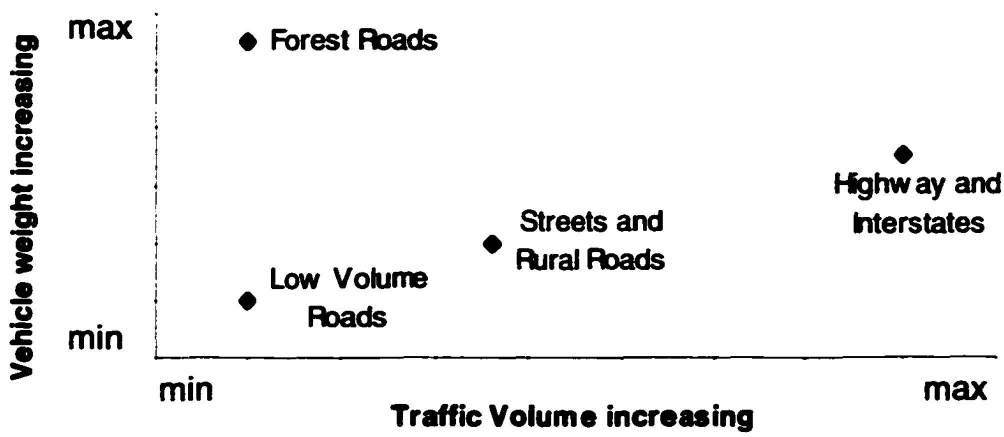

Figure 2 How forest roads relate to other types of road

The introduction of trucks to the forest industry initially solved the problem of hauling logs over short distances to the mill from nearby harvest areas or to rivers, where the logs would be floated longer distances to the mill. In this situation, truck transportation was a minor part of forest operations. With the phasing out of river drives and increasing distances from the mill to forest operations, truck transportation has become a crucial part of forestry operations, and as a result, road construction and maintenance have achieved considerably greater importance.

Need for better evaluation and road maintenance

Until recently the management of the forest road network could easily be done based on direct, subjective observations by road managers (i.e., subject to strong bias). As the road networks grew and budgets shrank, this intimate knowledge of the road network became difficult or impossible to maintain and the subjectiveness of observations became a significant obstacle to creating a more rational operation. Managers became more concerned with keeping construction crews working effectively and keeping haul operations coordinated. As such, routine maintenance of the active road network became a secondary priority and every segment of the road received the same treatment at the same frequency, regardless of its condition. Given the inability to obtain timely, high-quality information on the state of the road network, this approach has become the accepted method for maintaining forest road networks.

This approach maintains an acceptable overall condition for the road network, but is inefficient. Traffic levels on 80- to 500-km-long roads may be identical, but the terrain, geometry, road-building materials, and road ages may vary widely. In the traditional approach, the same maintenance investment is being made in several different families of road, regardless of their condition and rate of deterioration, and all sections are reprofiled at the same rate. Because grader time is limited and the industry is constantly under pressure to reduce costs and optimize resources, sections that are treated for no good reason consume resources that would be better spent elsewhere.

To overcome this inefficiency, managers must obtain better information on road conditions. With unbound roads exposed to the typical traffic levels experienced in the forest industry, this means that road condition should be evaluated at least daily. The manual evaluation methods traditionally used on low-volume roads are too time-consuming for daily evaluations to be possible (Eaton et al., 1988). In addition, high-tech road scanners used on higher-value surfaced roads are too expensive to be used daily in forestry (Assaf, 2001), as shown below. For the Canadian forest industry, grading costs range between $50 and $70 per kilometre for daily maintenance activities. FERIC has found that the traditional approach to grader management treats about 20% of the road network per day or per treatment. Moreover, up to 30% of the treated road doesn't require treatment. This 30% ($60 × 0.2 × 0.3 = $3.60) represents the cost of a poor decision, and if the unnecessary grading could be reduced to 5% ($60 × 0.2 × 0.05

= \$0.60) or less by obtaining better knowledge of the road, then the lack of this information costs \$3 per kilometre (\$3.60 – \$0.60 = \$3.00). Since this is only a potential cost, a company willing to perform measurements to provide the necessary information could only economically justify an approach that costs less than \$3/km, and would likely only be convinced to adopt a method that costs significantly less.

Need for better road rehabilitation management

For road managers, the lack of information on road condition affects more than routine road management; it also affects road rehabilitation, and rehabilitation is often planned with little knowledge of road performance. Without keeping records of road conditions over the course of the haul season, it becomes difficult to recall which sections were in poor condition or received the most maintenance over the 6 to 10 months the road was active. Without these records, road managers have no systematic, technically and economically rational way to justify or request budgets for road rehabilitation. Consequently, road rehabilitation becomes a low priority at budget time, and often receives whatever funding remains after all other needs have been funded. In good years, this budget can be significant, but in bad years, it can fall to zero.

When funding is provided, road rehabilitation is limited almost exclusively to regravelling a segment with crushed material. The first and most common candidates for this rehabilitation are sections that prompted the most complaints from road users. The second candidates are sections that have gone the longest since they were last regravelled, an approach that fits the "blanket treatment" mentality used for routine daily maintenance. In both cases, the approach is not wrong so much as it is inefficient. To better manage the rehabilitation of forest roads, managers need good information. Although information on the road's history and condition is valuable, information that can support economic decisions is more effective in obtaining funding. Road managers must be able to show a direct benefit from spending money on road rehabilitation.

Because forestry road managers must decide frequently on what maintenance to perform, information on road conditions must be gathered quickly. In the past, this assessment was done subjectively; road managers and road users traveled the roads at 70 km/h and recorded areas that caused them the most difficulty, if they did assessments at all. Graders would then be directed to sections of the road based on these rough, subjective assessments or, more commonly, would simply start work where the previous shift had finished, regardless of the road condition.

Summary

This introduction has demonstrated that there is a need for better road evaluation, maintenance management, and rehabilitation management in the forest industry. With the introduction of Opti-Grade by FERIC, the first two of these three issues have been successfully addressed. To add to the advantage that has been gained by using Opti-Grade, a decision-support tool to help with rehabilitation management must still be implemented. The next chapter will examine how Pavement Management Systems are presented in the literature and evaluate existing systems to determine whether they would be appropriate for introduction to the forest industry.

CHAPTER 1

PAVEMENT MANAGEMENT SYSTEMS AND LITERATURE REVIEW

This chapter briefly describes how Pavement Management Systems (PMS) are typically described in the literature. Based on the description of a PMS, an outline of the industry's need for an appropriate PMS for forest roads is presented. In this chapter, a literature review is presented that examines the possibility of implementing an existing system from another area of PMS application.

1.1 Pavement Management Systems (PMS)

The basic concept of a PMS has remained largely unchanged since its initial conception in the 1950s, and the following two definitions effectively describe the basic concept:

"A pavement management system is designed to provide objective information and useful data for analysis so that highway managers can make more consistent, cost-effective, and defensible decisions related to the preservation of a pavement network." (Anon., 1990)

"A pavement management system (PMS) is a set of tools or methods that assist decision makers in finding optimum strategies for providing and maintaining pavements in a serviceable condition over a given period of time." (Haas et al., 1994)

Although the older systems have little in common with today's high-tech systems, they still follow the basic principle of combining data collection to determine the current condition of the road with existing knowledge of the road and its history, a financial and economic analysis, and engineering knowledge; this combination lets managers determine the most effective management approach for maintaining the road in an acceptable condition. In the past, measurements were done manually; today, they are performed using high-speed electronic scanners that provide more extensive and up-to-date information. In the past, the historical information might have been found in paper files or on large specialized computers, whereas today's massive amounts of data are managed using databases on personal computers. Road managers still evaluate the best information available to determine where maintenance dollars are most needed. This same basic principle must be applied in forestry.

Based on FERIC's experience with forest roads, a PMS that will be useful in forestry operations must address the following unique situations faced by forestry road managers:

- The traffic levels and the rate at which road conditions change on forest roads require daily routine maintenance decisions, so information must be provided at this rate.
- Managers in charge of road maintenance have little time or money to spend on road management activities and often lack even the basic engineering knowledge required to do more than a basic evaluation of any information they collect.

Thus, although the criteria used by existing methods for evaluating unsurfaced roads are valuable, the suggested methods have limited application in forestry. One example from U.S. Army Corp of Engineers, Eaton et al. (1988) suggests a two-pass measurement done every 1 to 2 years. However, even a quick first pass to examine 200 km of road from a vehicle moving at around 40 km/h would take nearly 5 hours for data collection alone, plus an additional 3 hours to return to the office to analyze the data. As a result, this approach offers some valuable ideas that would assist annual decisions, but would still prove to be very time-consuming for the forest industry and would leave daily decisions unsupported by current data on the road. This example clearly demonstrates why applying knowledge of low-volume roads to forest roads fails to meet the needs of forestry road managers.

With this in mind, model developers have attempted to evaluate the situation from the point of view of a forestry professional rather than that of a road engineer. Douglas and McCormack (1997) tackled the question of how to apply pavement management knowledge to forest roads. They found that the basic principles of road management can be applied in forestry, but that the level of detail in the information collected on road condition needed to be reduced. For one thing, the skid resistance of a gravel road is very difficult to measure and varies greatly across the road network and over time; moreover, because this parameter offers little information of value to road managers, it could be omitted from a forestry PMS. For another, the technology, knowledge, and cost associated with measuring road structural capacity create a barrier to applying pavement management principles; although these measurements offer very important information about the road from an engineer's point of view, a forestry roads manager feels that the structure is adequate if the haul trucks don't sink into the road. With this in mind, an effective PMS for the forest industry would need to consider road roughness and surface distresses, most of which can be accurately predicted with a measure of surface roughness.

With the Douglas and McCormack assessment in mind, the components of an effective PMS for the forest industry would include several steps:

Inventory and categorize the road network

- Build a historical database using available information: road age, road class, construction methods, traffic levels, geometry, time since last rehabilitation
- Categorize segments of the network into families; the forest industry is most likely to use road geometry (e.g., curved vs. straight sections) as the basis for these families

Establish a daily roughness measurement system

The measurement system must be:

- Inexpensive (less than $2/km)

- Fast
- Simple
- Objective
- Accurate and repeatable
- Reliable

Manage daily road maintenance

- Use daily roughness measurements to produce objective grading schedules that target the roughest sections each day.
- Store the daily road condition as additional information for each road segment.
- Record what grading was actually done on the network in the database each day.

Manage road rehabilitation

- When decisions must be made about rehabilitation, analyze each section of road using the data stored since the last analysis to identify problem sections.
- From all the data available for a given family of road segments, establish how the road will perform based on the time elapsed since the last rehabilitation.
- Determine the cost of various management scenarios for the near future (rehabilitation interventions at different times).
- Select the lowest-cost scenario for each road segment in the family.
- Perform a detailed evaluation of candidate segments for rehabilitation to determine what course of action would best correct the road problems (e.g., load-bearing capacity, type and severity of defects).
- When a solution for the section has been identified, confirm that the expected savings justify the planned activity; if so, perform the rehabilitation.
- Track the performance of the rehabilitated section to confirm its performance and update the models within the family based on the results.

1.2 Potential pavement management systems

Given the criteria for a pavement management system to be used in the forest industry the next step is to determine, if there is a feasible system currently available that can be easily adapted to the needs. The following section will look at some existing road management tools and evaluate their applicability to the needs of the forest industry.

1.2.1 The Highway Design and Maintenance Standards Model (HDM)

The HDM model software performs cost estimates and economic evaluations of different policy options, including different timing strategies (Paterson et al., 1987). HDM is intended to help developing nations better use their road budgets to maintain and manage national road networks. Therefore, it is a very comprehensive model based on extensive studies in the regions where HDM is meant to be applied. It presents users with a wide range of potential inputs, including nine vehicle types and 30 maintenance standards. Each run of the model can evaluate up to 20 different road links, each of which can have up to 10 sections with different design standards and environmental conditions (Paterson et al., 1987). HDM is a powerful model and thus, is very complex. It was developed for use over widespread road networks within nations by users with the ability and knowledge to calibrate the model and supply it with the required information.

The major concern with HDM lies in its complexity. The intended user in the Canadian forest industry deals with relatively small road networks (400 km) that are very localized, within a single climatic zone. Thus, the model's power and complexity are both excessive for the industry's needs. The knowledge and training required from a group of what are almost exclusively non-engineers would impede acceptance of HDM. Moreover, the HDM model is intended to standardize decision-making processes and to accept standard inputs, including the international roughness index (IRI) as a measure of roughness. Given that Opti-Grade, currently the roughness measurement tool of choice for the Canadian forest industry (Mercier and Brown, 2002), does not currently deliver

IRI values, significant investment would be required to develop appropriate conversion factors. As well, a significant investment of time, money, and research personnel would also have to be made to confirm whether the mathematical models used by HDM apply to Canadian forestry. Given that the model's focus was on roads in the warmer climates of developing nations and the very different cost issues in these nations, revising these models would not be a trivial undertaking.

The complexity of HDM suggests that it provides more features than the Canadian forest industry requires. Although recent releases of HDM (e.g., version 4) have attempted to adapt its models for use in northern climates, significant effort and investment would still be required to adjust the model for use by the Canadian forest industry. These factors suggest that HDM is not currently a good choice for that industry.

1.2.2 U.S. Army Corp of Engineers, Rating Unsurfaced Roads

The methods described by the U.S. Army Corp of Engineers (USACE) (Eaton et al., 1988) for rating unsurfaced roads are intended for more traditional low-volume roads. The target road for their model is one that is graded three or four times per year, with maintenance planning or scheduling done once per year. Given the traffic levels on forest roads in Canada, grading is more commonly done once or twice per week, and maintenance is planned at least weekly and often daily. Moreover, rehabilitation is planned on an annual basis. Given the increased frequency of maintenance work on forest roads, the time required to sample each road group as described in the USACE method would be significant.

The method for rating unsurfaced roads does a good job of identifying the sections of road that are in the worst condition and the specific problems in these sections. Unfortunately, this approach assumes that managers have a sufficient budget for the road maintenance and rehabilitation operation, and that their only task is how best to spend this budget. In reality, tight budgets in the forest industry require managers to justify every dollar spent. Any system that would help industry roads managers allocate a budget to road rehabilitation must justify itself through savings in future maintenance costs and sometimes user costs. As a result, the USACE method lacks some of the required features to be used as a management tool.

The USACE method has been used for many years and is still being used. The method was presented in 1992 as Unsurfaced Road Maintenance Management by the Cold Regions Research and Engineering Laboratory (CRREL; Eaton and Beaucham, 1992) and has been followed by other systems around the world, including the Australian "unsealed roads manual" (Anon, 1993) and New Zealand's "Forest Roading Manual" (Larcombe, 1996). Given its strengths, the method has some value for the Canadian forest industry. However, the time required by the method's visual evaluations could be reduced by focusing the measurements on sections of the road that require rehabilitation based on roughness measurements and on economic analysis with Opti-Grade. The method could then be adjusted to diagnose the best intervention given a rating of each defect type rather then prioritizing interventions based a total "deduct" value as the system currently does.

1.2.3 Traditional Pavement Management Systems (PMS)

For the purpose of this report, traditional PMS are defined as systems used by road agencies to manage public road networks. This group includes two subgroups: systems used by developed countries to manage mainly surfaced roads and highways, and systems designed for low-volume roads.

PMS for surfaced roads

The majority of PMS for surfaced roads follow one of two approaches. The first, which is becoming less common, is the "treat the worst first" approach (Beaulieu, 2001). Approaches in this category evaluate all road segments based on various measurements and rate each road segment based on what measurements are available and how the data have been recorded; these values include Riding Comfort Index, Surface Distress Index, Structural Adequacy Index, Pavement Condition Index, and Pavement Quality Index (Haas et al., 1994). The worst segments are then scheduled first for rehabilitation. Managers allocate estimated budgets between segments until they exhaust the available budget. This approach fails when there is a shortfall in the available budget and work remains to be performed. Segments of road that have not yet deteriorated severely receive no attention, so their deterioration accelerates and more of the road network degrades to unacceptable levels each year. This failure led managers to adopt a second, more common approach.

In this second approach, road agencies began using a network-level "lifecycle cost" approach. This approach evaluates the same road measurements and determines the current state of the road. Managers then model how these roads will perform over the coming years based on their agency's experience with the road. This modeling may use the "family" approach, in which similar road segments of different ages are grouped to form a single family (e.g., based on construction method, environment, traffic, and/or rehabilitation). With similar road segments at different ages, road managers can safely assume that a 5-year-old segment left untreated for 5 years will perform like a 10-year-old segment in the same family if traffic levels and environmental conditions don't change significantly. These models can also predict future conditions after rehabilitation. Rehabilitated segments then move into a new family based on their rehabilitation history, and how they will perform in the future can be predicted. Given the ability to predict future road conditions, different scenarios can then be modeled. In this approach, road managers search for the best net benefit over the entire network that they can achieve with a given budget. This requires a consideration of user costs, maintenance costs, future rehabilitation costs, and (in many cases) political costs based on the road's future performance. As a result, rehabilitation may be performed on an important segment of the network that is currently in moderately good condition while smaller or less important segments in much poorer condition are left untreated.

Variations of these two approaches are used by most road agencies that manage major networks of surfaced roads around the world. To keep the models and road condition information updated, measurements are performed annually, and the databases and models used in these systems are designed to work with this annual approach. As is the case for HDM, these tools are built to help knowledgeable engineering staff manage very large and complex road networks. Furthermore, life cycles for surfaced road networks are most often evaluated on cycles of 15 to 25 years for rehabilitation and 2 to 5 years for maintenance. In contrast, the Canadian forest industry makes rehabilitation planning decisions annually, and the rest of the situation is also very different. Measurements, if they are performed, are mostly roughness measurements (collected daily by a system such as Opti-Grade), and the roughness values are not yet linked to any standard roughness index. Road managers in forestry are generally not engineers skilled at road management and evaluation; instead, they generally have significant field experience and knowledge of the road from a forest operations viewpoint. Finally, rehabilitation life cycles tend to fall within a 5- to 7-year window, and maintenance plans tend to be created weekly.

For these reasons, the complexities of PMS developed for surfaced roads and the skills required to use these systems lend themselves poorly to the forestry situation. Using them on 400- to 500-km-long forestry road networks would be overkill, and the difficult learning curve would make them difficult to implement; road managers would have neither the time nor the patience to master the skills required to operate a traditional PMS. However, certain features of these various systems would prove useful in a purpose-built forestry rehabilitation-planning tool. The concept of grouping the road network into families of segments to allow for future predictions is interesting and could easily be applied if daily road condition measurements are gathered. As well, the consideration of lifecycle costs and obtaining the maximum benefit from a rehabilitation budget could be considered in the development of a forestry system.

PMS for low-volume roads

Given that low-volume roads most closely resemble forest roads in Canada, particular attention was paid to this topic area in this literature search. Most of what was found focused on collecting road condition measurements for use with the World Bank's HDM model (discussed earlier in this thesis) and how to use the model. Other agencies that manage low-volume roads and that don't rely heavily on the World Bank for funding have tended towards using manual measurements and evaluations similar to those in the USACE system for unsurfaced roads. Alternatively, they focused on adapting these visual and manual measurements to work within a PMS for surfaced roads that the agency was already using for the bulk of their network.

Given the concerns over the complexity of HDM and traditional PMS plus the related implementation difficulties, the unwillingness of the forest industry to implement such time-consuming manual measurements suggests that the approaches presented for traditional low-volume roads are unlikely to be practical.

CHAPTER 2

OPTI-GRADE

With FERIC's introduction of Opti-Grade, the forest industry has an effective and efficient road roughness evaluation tool and an analytic companion tool for road maintenance management. Given its relative wide acceptance in the forest industry, its simplicity, its low cost and the large amount of data on road condition it provides, Opti-Grade is a logical base to a forest road rehabilitation management system.

A good first step to introducing a road rehabilitation management tool involves understanding Opti-Grade and the data it produces. This chapter describes the Opti-Grade system, as it has been designed, developed, and introduced during the author's work with FERIC, and the decision-support tool used to manage daily road management. This thesis does not address the design or the development of Opti-Grade. It does however examine the repeatability of the Opti-Grade data to confirm that it offers a reliable basis for a road rehabilitation management system.

2.1 Opti-Grade

To meet the information needs for routine daily management of road maintenance and to help reduce the cost of poor management decisions, FERIC introduced Opti-Grade as a tool to help managers implement the principles of pavement management. Opti-Grade can obtain objective low-cost road roughness measurements, and can manage this information so as to support decisions on where daily road maintenance must be performed. Opti-Grade combines two key components: the Opti-Grade hardware and the Opti-Grade software.

2.2 Opti-Grade hardware and data collection

The Opti-Grade hardware consists of a roughness sensor based on accelerometer technology, a controller, a global positioning system (GPS) receiver, and a datalogger. The equipment is mounted on a vehicle that uses the active road network regularly; in the forest industry, the ideal candidate is a haul truck. This approach collects measurements during regular operations without interfering with or interrupting normal work. Thus, data collection imposes no additional ongoing costs. Once installed, the sensor measures the vehicle's response to road roughness by detecting vibrations. These vibrations are sampled at a high rate by the controller and are used to calculate a road roughness value every 1 second for 5 seconds. Over the next 2 seconds, the controller then records the highest of the five calculated values along with the GPS location of that point. This means that the roughest 15 to 20% of every 50- to 175-m portion of road is known, depending on the vehicle's travel speed. This information is stored until it is downloaded for use by the Opti-Grade software.

Each line of data includes the latitude, longitude, date, time, direction of travel, and vehicle speed, along with the roughness value for the segment of road monitored since the last point (Table 1). The "Date" and "Time" columns indicate when the data point was recorded. "Latitude" and "Longitude" are indicated in degree, minutes and decimals of minutes (DDMM.mmm). "Elevation" is the distance above sea level in metres and "Speed" is the travel speed in kilometres per hour at the time of the data recording. "Azimuth" is the direction of travel in degrees at the time of the data recording, and "Roughness" is the highest 1-second roughness measurement since the last data point was recorded.

Table I

An example of Opti-Grade data, including roughness measurements

Date	Time (H:M:S)	Latitude	Longitude	Elevation (m)	Speed (km/h)	Azimuth	Roughness
04/18/2001	13:28:50	4521.425	7408.860	12.4	0	0	3
04/18/2001	13:28:56	4521.437	7408.832	13.4	37.5	59.7	37
04/18/2001	13:29:03	4521.454	7408.790	14.5	37.4	59.7	67
04/18/2001	13:29:10	4521.479	7408.730	16.0	39.3	60.7	54
04/18/2001	13:29:16	4521.496	7408.687	16.8	40.2	59.7	55
04/18/2001	13:29:23	4521.515	7408.641	17.5	41.1	60.1	60
04/18/2001	13:29:30	4521.538	7408.584	18.0	38.5	60.3	78
04/18/2001	13:29:37	4521.557	7408.540	18.3	41.2	60.4	62

2.3 Opti-Grade software and using the data

The Opti-Grade software reads and stores the data collected by the hardware for the road network being managed. This network is defined by a digitized base map that the user provides to the software. This base map lets Opti-Grade equate GPS data with known landmarks along the road. Any data collected outside the area of concern is eliminated. In the forest industry, portions of each trip commonly occur on public roads that are not managed by the forestry company; thus, information on their condition is not needed. Opti-Grade uses the stored information to produce grading schedules as well as other reports on travel speed and road roughness.

2.3.1 Opti-Grade grader schedules

To build a grading schedule, Opti-Grade locates the most recent data from the road. This up-to-date information is then evaluated based on three user-defined criteria to identify sections that require grading:

Threshold

All sections that are considered too rough are identified based on a user-defined threshold determined during calibration of the system by comparing the roughness measurements with the road manager's careful visual assessment. All identified sections then become candidates for grading. These candidates represent many 50- to 175-m-long sections spread throughout the road network and separated by as little as 50 m or as much as several kilometres. To ensure that the schedule produced by the software can be applied operationally, two additional criteria allow the software to base its recommendations on operational constraints.

Treatment separation

The first of these two constraints defines the minimum distance between two candidates in order for them to remain separate; this constraint recognizes the operational impracticality of leaving too-small sections between sections that are graded. The software compares the distance between candidate segments with this constraint, and if necessary, joins them into one longer section. The candidates to be graded now range in length from as little as 50 m to as long as several kilometres.

Treatment length

The final criterion defines the minimum acceptable length for a candidate section to be included in the schedule; this constraint recognizes that it is not economical to send a grader to work on sections that are too short (i.e. less than 750 m). Once this last user-defined criterion has been applied, the software produces a suggested grading schedule.

2.3.2 Opti-Grade reports

The Opti-Grade software provides additional performance reports that can be used to evaluate the road and its users. These reports include summaries for each section of the average roughness and average travel speed of the vehicle that carries the Opti-Grade hardware for any given day or period. These reports assist in evaluating the road because they let the road manager determine what roughness levels appear to affect the driver's habits or travel speed. This knowledge lets the road manager make informed decisions about where to set the threshold values to trigger the necessary grading activities.

The analysis process can also help road managers identify sections of the road that are causing traffic slowdowns unrelated to roughness, including problems related to road geometry or dust levels. Depending on the impact of these problem spots, road managers may want to intervene by improving the road geometry during future rehabilitation work or by targeting the use of costly dust suppressants in problem areas. The performance reports can also help managers ensure that travel regulations for the road are being respected; these include speed limits, reduced speed zones, and obligatory load-check stops. These reports can also be used to determine true travel speeds and trip times, thereby helping managers set fair and reasonable pay rates for drivers based on true travel times.

Based on these benefits, many Canadian forestry companies have begun implementing Opti-Grade in their operations to manage road maintenance and road users. While this limited use is a valuable step toward a comprehensive road management system, the data collected offers more value. If the data collected and stored by the Opti-Grade system is reliable, the right tools and methods of analysis can make the system a key component in a broader management system for unpaved roads.

2.4 Testing Opti-Grade's Data Quality

18 Opti-Grade systems have been in use by the forest industry for the past year. Although feedback based on this limited experience with the system has all been positive, no effort was conducted before the preparation of this thesis to establish the repeatability of the system. As any decision is only as correct as the information it relies on, it is critical that the Opti-Grade system's repeatability be established. To determine the quality of the data provided by Opti-Grade, a preliminary evaluation and a though evaluation were performed.

2.4.1 Repeatability of Opti-Grade data

Preliminary evaluation

A preliminary evaluation intended to confirm that the data were repeatable was performed. This preliminary evaluation was intended to determine whether the repeatability of the data appeared sufficient to justify further, more thorough evaluation. In this preliminary test, 55 files of three to seven runs each collected by an Opti-Grade system over a period of 4 months were evaluated. In the road network where these files were generated, a 60-m-long concrete-surfaced bridge was assumed to provide a constant roughness value throughout the data collection. Since the system's users were unaware of our plans to evaluate their data, and since they consistently used the data to plan and schedule their daily road maintenance activities, there was no reason to suspect user interference with the data.

Using the GPS locations for both ends of the bridge, all data points that occurred on the bridge within the 55 data files were isolated. In total, 485 data points were collected on the bridge. For these points, all roughness measurements were less than 35, versus values as high as 120 elsewhere on the road; moreover, 92% of the roughness values were below the company's established threshold for grading (a roughness value of 30). These data suggest that a correct decision not to grade the bridge would be made at least 92% of the time based on the current threshold. The average roughness value for the bridge was 24.6, with a coefficient of variation of 21%. This relatively good grouping of the data suggested that a more controlled look at Opti-Grade's data quality was warranted.

Thorough Evaluation

A controlled test was designed that would account for how the system works, how it is generally used in real applications, and how the data is used for making decisions. Since

Opti-Grade measurements are based on interactions between the road and the vehicle, each installation will provide unique measurements based on these interactions. Consequently, each system must be calibrated after installation. In the forest industry, each operation tends to use one system on a given road network, and because comparisons of road roughness between two or more systems are unnecessary, absolute calibration between systems is not a concern.

Because Opti-Grade records data on the condition of the road network every 7 seconds and only records the roughest 1-second measurement within that 7-second period, the data can't be used to pinpoint the exact location of a defect on the road. Instead, it identifies problem segments that need to be addressed and can help to make decisions on 0.5- or 1-km sections. For this reason, it was not considered necessary to determine an absolute roughness value for the test section using a standard measure such as IRI, and the test was performed on 1-km segments to see whether the system consistently predicted the general condition of that segment.

2.5 Test design

For the test, it was important to understand that the speed of data collection is not controlled in real use. As a result, various travel speeds would have to be tested to see whether they produced the same results for a given test section. To make the tests as realistic as possible, the speeds recorded in the 55 files used in the initial test were evaluated to identify the normal range. It was found that 80% of the data were collected at speeds between 35 and 80 km/h, with most of the remaining 20% of the speeds below 35 km/h and occurring outside the road network (i.e., on spur roads, and in mill and garage yards). Further investigation also showed that more than 50% of the speeds ranged between 60 and 80 km/h. Based on these data, it was decided to test the system at three speeds: 40, 60, and 70 km/h.

To perform the test, two 1-km-long test sections were selected (section A and section B) that would remain in consistent condition throughout the day-long tests, and represent the range of roughness expected on forest roads. These sections would be easily accessible and could be driven upon safely at the three test speeds. To obtain large enough data samples for statistical analysis while still working within a limited time and budget, a minimum of 10 sets of measurements would be collected from each of the two test sections at each speed (for a total of 30 measurements per section). In each test, the driver tried to follow the exact same path with each pass so as to reduce the possible roughness variation that different paths might introduce.

2.6 Data analysis

The data collection produced 32 sets of data for each of the two test sections; this included 11 passes at 40 km/hr, 10 at 60 km/hr, and 11 at 70 km/hr on each section, as illustrated in Table 2. The results of each pass were compared using the Student-Newman-Keuls (SNK) test as recommended by Zar (1974). The SNK test is a multiple-comparison procedure.

Table II

Test data that was collected on the two road sections

Test section	A	B	A	B	A	B
Speed (km/h)	40	40	60	60	70	70
# passes	11	11	10	10	11	11

Roughness variation at individual speeds

The test was first performed by considering the data for each speed level to be a single group so the repeatability of the system at a controlled speed could be confirmed. Table

3 shows the results for one section at 40 km/h. Complete results are presented in Appendix A. In the table:

- **a to b represents** the two passes being compared,
- **Mean b – mean a** equals the difference in the means for the two passes being compared,
- **SE** is the standard error for the samples used in the **qc** calculation
- **qc** is the variation value calculated for the comparison
- **Q 0.05,120,10 and Q 0.05,30,3** are published values that represent the theoretical variation for the difference between the two data sets being compared. If the **qc** value is less than the **Q** value (i.e., if Q–qc is positive), then the two means cannot be considered different at the 95% probability level ("equal"); if the value is negative or zero, the two means differ ("not equal").

In all six tests (two road sections at three speeds), no significant difference was found in average roughness measurements. This means that the Opti-Grade system provided highly repeatable measurements of road roughness.

Table III

Repeatability tests for test section 1 at 40 km/h

a to b	Mean b–mean a	SE	Qc	Q 0.05,120,10	Q–qc	Conclusion (means are)
1 to 2	8.71	3.00	2.90	4.56	1.66	equal
1 to 3	2.43	2.88	0.84	4.56	3.72	equal
1 to 4	4.33	2.94	1.47	4.56	3.09	equal
1 to 5	7.14	2.88	2.48	4.56	2.08	equal
1 to 6	3.45	2.84	1.22	4.56	3.34	equal
1 to 7	6.21	2.88	2.15	4.56	2.41	equal
1 to 8	5.79	2.94	1.97	4.56	2.59	equal
1 to 9	3.79	2.94	1.29	4.56	3.27	equal
1 to 10	0.02	2.94	0.01	4.56	4.55	equal
1 to 11	1.57	2.88	0.54	4.56	4.02	equal
2 to 3	6.29	3.00	2.09	4.56	2.47	equal
2 to 4	4.38	3.06	1.44	4.56	3.12	equal
2 to 5	1.57	3.00	0.52	4.56	4.04	equal
2 to 6	5.27	2.96	1.78	4.56	2.78	equal
2 to 7	2.50	3.00	0.83	4.56	3.73	equal
2 to 8	2.92	3.06	0.96	4.56	3.60	equal
2 to 9	4.92	3.06	1.61	4.56	2.95	equal
2 to 10	8.69	3.06	2.84	4.56	1.72	equal
2 to 11	7.14	3.00	2.38	4.56	2.18	equal
3 to 4	1.90	2.94	0.65	4.56	3.91	equal
3 to 5	4.71	2.88	1.63	4.56	2.93	equal
3 to 6	1.02	2.84	0.36	4.56	4.20	equal
3 to 7	3.79	2.88	1.31	4.56	3.25	equal
3 to 8	3.36	2.94	1.14	4.56	3.42	equal
3 to 9	1.36	2.94	0.46	4.56	4.10	equal
3 to 10	2.41	2.94	0.82	4.56	3.74	equal
3 to 11	0.86	2.88	0.30	4.56	4.26	equal
4 to 5	2.81	2.94	0.96	4.56	3.60	equal
4 to 6	0.88	2.89	0.30	4.56	4.26	equal
4 to 7	1.88	2.94	0.64	4.56	3.92	equal
4 to 8	1.46	2.99	0.49	4.56	4.07	equal
4 to 9	0.54	2.99	0.18	4.56	4.38	equal
4 to 10	4.31	2.99	1.44	4.56	3.12	equal
4 to 11	2.76	2.94	0.94	4.56	3.62	equal

5 to 6	3.70	2.84	1.30	4.56	3.26	equal
5 to 7	0.93	2.88	0.32	4.56	4.24	equal
5 to 8	1.35	2.94	0.46	4.56	4.10	equal
5 to 9	3.35	2.94	1.14	4.56	3.42	equal
5 to 10	7.12	2.94	2.42	4.56	2.14	equal
5 to 11	5.57	2.88	1.93	4.56	2.63	equal
6 to 7	2.77	2.84	0.98	4.56	3.58	equal
6 to 8	2.34	2.89	0.81	4.56	3.75	equal
6 to 9	0.34	2.89	0.12	4.56	4.44	equal
6 to 10	3.43	2.89	1.18	4.56	3.38	equal
6 to 11	1.88	2.84	0.66	4.56	3.90	equal
7 to 8	0.42	2.94	0.14	4.56	4.42	equal
7 to 9	2.42	2.94	0.82	4.56	3.74	equal
7 to 10	6.19	2.94	2.11	4.56	2.45	equal
7 to 11	4.64	2.88	1.61	4.56	2.95	equal
8 to 9	2.00	2.99	0.67	4.56	3.89	equal
8 to 10	5.77	2.99	1.93	4.56	2.63	equal
8 to 11	4.22	2.94	1.44	4.56	3.12	equal
9 to 10	3.77	2.99	1.26	4.56	3.30	equal
9 to 11	2.22	2.94	0.76	4.56	3.80	equal
10 to 11	1.55	2.94	0.53	4.56	4.03	equal

Roughness variation between speeds

The next goal was to determine whether the degree of repeatability of the roughness results changes for different travel speeds. To do so, the average roughness values for the two road sections at each speed were calculated and the results were treated as three averages that were then compared using the SNK test. The results for both road sections indicated that changing speed also changed the average roughness value for a patch of road (Tables 4 and 5) and that this change was significant ($P = 0.05$). The terms used in this table are the same as those used in Table 3, but with the addition of rows labeled "mean" to represent the mean roughness value for a given speed, "N" to represent the population size, and "varp" to represent the variation of the population.

Table IV

Repeatability of roughness measurements for road section 1 at three speeds

	Travel speed (km/h)					
	40	**60**	**70**			
Mean	51.82	83.98	102.04			
N	149	80	75			
Varp	120.85	196.65	215.96			
	s^2	165.90				
a to b	**Mean b–mean a**	**SE**	**Qc**	**Q 0.05,30,3**	**Q–qc**	**Conclusion (means are)**
1 to 2	32.16	1.26	25.47	3.49	-21.99	not equal
1 to 3	50.22	1.29	38.95	3.49	-35.46	not equal
2 to 3	18.07	1.46	12.34	3.49	-8.85	not equal

Table V

Repeatability of roughness measurements for road section 2 at three speeds

	Travel speed (km/h)					
	40	**60**	**70**			
Mean	51.34	75.66	97.74			
N	138	80	72			
Varp	150.79	248.57	281.22			
	s^2	212.34				
a to b	**Mean b–mean a**	**SE**	**Qc**	**Q 0.05,30,3**	**Q–qc**	**Conclusion (means are)**
1 to 2	24.32	1.45	16.80	3.49	-13.75	not equal
1 to 3	46.40	1.50	30.97	3.49	-27.93	not equal
2 to 3	22.07	1.67	13.19	3.49	-10.14	not equal

Impact of the observed inequality at different speeds on the use of Opti-Grade

Because Opti-Grade is used operationally in situations where the speed of the data-collection vehicle is not controlled, and because travel speed affected the roughness values collected, it is important to determine how large the difference is between the data collected at different speeds. Table 6 shows the results of this evaluation.

Table VI

Magnitude of the variation in roughness measurements at three speeds

	Speed (km/h)						
	Road section 1			Road section 2			All speeds
	40 km/h	60 km/h	70 km/h	40 km/h	60 km/h	70 km/h	
Test #							
1	55.71	81.43	103.33	51.42	74.14	96.29	
2	47.00	87.00	96.71	51.67	70.75	99.43	
3	53.29	81.75	106.43	46.08	71.00	107.80	
4	51.38	85.33	98.86	52.25	74.78	105.00	
5	48.57	80.78	111.00	53.31	68.63	91.14	
6	52.27	82.00	106.14	47.15	87.86	96.71	
7	49.50	81.56	100.71	47.08	68.11	93.67	
8	49.92	86.00	95.00	48.25	81.71	95.43	
9	51.92	85.89	112.00	54.17	75.13	105.67	
10	55.69	88.00	97.17	55.69	84.38	92.29	
11	54.14	—	—	57.00	—	94.67	
Mean	51.763	83.974	102.735	51.279	75.649	98.009	76.748
Standard Deviation	2.843	2.715	6.018	3.697	6.808	5.715	21.105
***Error**	3.4%	2.5%	5.3%	4.5%	7.1%	5.3%	19.4%

* Error = ((SD*2.23)/√(N-1))*100 (Zar, 1974)
SD = Standard deviation
N = population size

It was found that the amount of variation at a given speed was very low. Thus, if a user implemented Opti-Grade and invested the time to perform roughness measurements at a controlled speed, they could easily obtain an accuracy (Table 5) of ±4%. However, without controlling travel speeds, the error can increase to nearly 20%.

A typical forestry example would be a 300-km road network with measurements taken for about 150 operating days per year; here, the cost associated with taking the measurements at a controlled travel speed would not be justified by the expected benefits. With uncontrolled speeds, the cost of measurement is easily repaid by the benefits gained through maintenance management. Controlling travel speeds during measurements would require a dedicated vehicle, and in this example, these measurements would each require 12 hours at a travel speed of 50 km/h. A pickup truck and driver to perform the measurements could cost $50/h, for a cost increase of $300/km over a 150-day season. If the rehabilitation cost for a forest road averages $3000/km and a company rehabilitates 5 to 15% of a 300-km road network per year, the costs of unneeded rehabilitation with 20% and 5% accuracy levels would work out to between $23 and $68 per km. This is far less than the $300/km required to control the travel speed during measurements; thus, it would not make economic sense to make this increased investment.

Based on the results of these tests and evaluations of the Opti-Grade system and how it is used, the repeatability was considered acceptable given the system's cost and the levels of precision required in this use. The next chapter will present the key components and process to make use of the Opti-Grade data for rehabilitation management.

CHAPTER 3

REHABILITATION MANAGEMENT WITH OPTI-GRADE

Given that Opti-Grade has been shown to provide acceptable repeatability, the data it provides can serve as the basis for a pavement management system intended to guide road rehabilitation decisions. This chapter will determine a suitable method to model forest road performance based on Opti-Grade data, describe how the model will be used to make rehabilitation decisions, and present a hypothetical example of a model and its results.

3.1 Data provided by Opti-Grade and how it can be modeled and simulated for rehabilitation management

3.1.1 Context

The value of Opti-Grade data is that it provides users with a series of snapshots of the road condition over time that show how the road has performed. Figure 2 illustrates road condition for a 1-km section over 4 days.

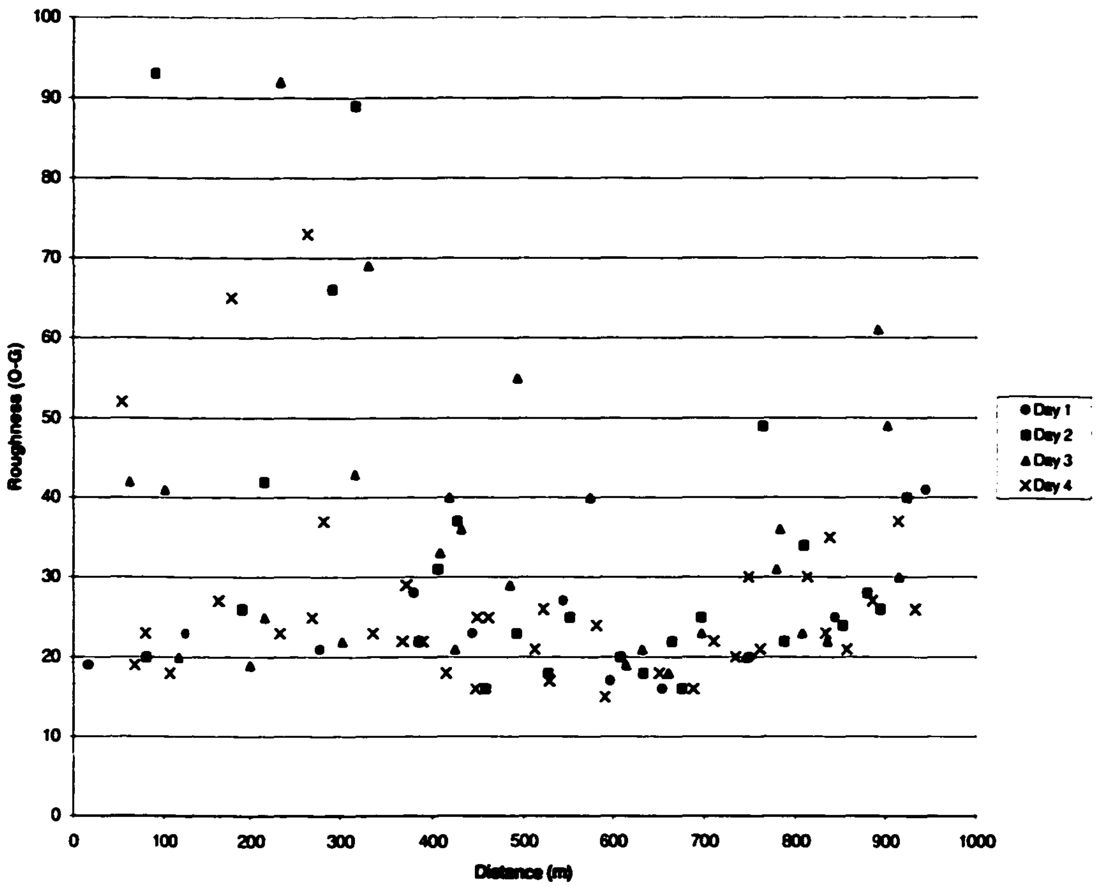

Figure 3 Graph of Opti-Grade data for a 1-km section of road over 4 days

As can be seen from this example, the roughness on a forest road can change quickly both in time and distance along the road. As a result, this type of data collected from up to 400 km of road for up to a 150-day period will show a wide range of variation. Because these fluctuations are common, the use of this data does not lend itself well to the development of traditional deterioration curves, which are used in many pavement management systems. Because deterioration curves were seen to be a less than ideal way to model the evolution of forest road roughness, other modeling methods were examined.

In selecting a method to model large amounts of data with the potential for significant fluctuations over short time periods, the nature of the condition being modeled and the expectations of the end user must be considered. Given a roughness measurement every 50 to 175 m along the road over a total length of 400 km, measured up to eight times per day for a period of up to 150 days, there is no lack of data on which to base a model. What has been seen, as demonstrated in Figure 3, is that the roughness values for a given section of road can vary significantly from one day to the next and between adjacent sections of road. Any model selected for use by the forest industry must be able to deal with these variations.

Next, the conditions being modeled tend to be quite random because the roughness of a forest road is very much related to the weather conditions on a given day. As a result, the performance of the road does not relate solely to the road structure and level and type of traffic it is exposed to, as you would expect to be the case for well-built surfaced roads, but also on the weather, which cannot be controlled. The model selected for forest roads needs to deal with this relatively random input to road condition.

Finally, the end user in the forest industry, in majority of the situations, is a non-technical person making technical decisions. This means that they are not familiar with traditional pavement management systems or the values and methods used to make pavement management decisions (e.g., structural number, IRI, deterioration curves). Since they are also very busy dealing with other issues within their forest operations, having to learn how to use this technical information to make road management decisions would not be well received. As a result, technical evaluation must be considered in this context and any proposed system must return simple results, using values the user is familiar with such as a cost in dollars per kilometre.

3.1.2 Selecting modeling and simulation methods

Considering the required properties identified for a forestry-specific rehabilitation management system, it was believed that using Markov matrices or chains (Cox and Miller, 1965) to model the road roughness performance and Monte Carlo–style simulation (Kleijnen, 1974) to arrive at different cost scenarios would satisfy the manager's needs well. Other possible modeling, simulation and optimization tools viewed in the literature were less of an effective fit to the needs. Markov, with its condition categories, was effective in smoothing and dealing with the inherent variability in forest road condition as measured with Opti-Grade. Further Markov provided a simple and effective modeling approach that did not require a standardized inputs like most pavement management models require.

Markov chains

Markov chains examine discrete times within a discrete state space (Cox and Miller, 1965). This approach assumes that given the probability of a change in state over a defined period of time, the system can be modeled in matrix form using Markov chains. The main issue with using Markov chains for modeling a situation is the large amount of data required to build an effective model. In the case of Opti-Grade data, a full season of maintenance management would collect large amounts of data over a period of time. Thus, the key obstacle to using Markov chains is not a concern for the Opti-Grade application. Further, because Markov chains use the probability of change in state over a defined period of time, they represent a very clean way to evaluate data that contains large fluctuations in a short time period compared with an approach such as performance curves.

Monte Carlo Simulation

Using Markov matrices to directly determine which sections are in good or poor condition would be relatively complicated and would return rank values that would have to be further analyzed before making rehabilitation decisions. For this reason, and to better include the random effect of weather on road performance, Monte Carlo simulation is used in combination with the Markov model to simulate the expected changes in state each day over an entire maintenance season. Once the changes in state have been determined, the road maintenance and user costs associated with each can be calculated to determine the total cost for the section for that 1-year period. By considering the simulated annual road maintenance and user costs for sections within a family with different ages will allow the calculation of the total cost associated with a section over longer periods of time (e.g., 5 years). Finally, by producing an estimated rehabilitation cost, different rehabilitation scenarios can be calculated (e.g., no rehabilitation, rehabilitation in year 1) to determine which scenario has the lowest overall cost and should be applied. Table 11 later in this chapter illustrates how these scenarios are presented. Details of this simulation process are covered later in this chapter in the section "simulation with the models".

3.2 The model for rehabilitation management

The objective of the model is to provide effective predictions of what the road costs will be in the future with and without rehabilitation. The costs associated with no rehabilitation (increased maintenance costs and decreased travel speeds) can then be compared with the cost of rehabilitating a section of road at different times in the future to determine whether rehabilitation would be a good investment. Because managers will use Opti-Grade daily to produce maintenance schedules, each maintenance season will generate a database of measurements on how road conditions evolved. With Opti-Grade, the road is already divided into identifiable segments on the base map, and these segments represent sections that can be economically treated as discrete for maintenance and rehabilitation purposes. These base map segments become easy units suitable for developing models; each segment of the base map (i.e., each decision-level segment) contributes data for the family or group it is linked to within the model. The basis for creating these family associations is discussed later in the chapter in the section "additional information for rehabilitation decisions". Users can then define three possible states for the road: level 1 = good condition, level 2 = marginal condition, and level 3 = poor condition. These states are defined based on the measured roughness. Working within three levels was chosen to best reflect how forest road managers look at their roads; as well, this system matches the three-level approach used in other simple pavement management systems such as the evaluation method presented by USACE for unsurfaced roads (Eaton et al., 1988). Having more than three categories would simply add a degree of resolution that would not clarify the situation for the user.

To build a model for each decision-level segment, these segments will be subdivided into ten equal subsections. These subsections will improve the model's resolution and ensure that data comparisons over time actually compare the same road segments. For these smaller subsections, all data points collected over the course of a season will be isolated. For every 24-hour period (the period for which maintenance decisions are normally made), the change in state will be determined. If two or more roughness values are available for a given period, the average value will be used to determine the state of the road for that 24-hour period. After all the data has been checked to determine whether a change in state occurred between days, the probability of each change of state can be determined and a transition matrix such as the one in Table 7 can be created for the subsection. The levels indicate the roughness condition, and P (X to Y) is the probability that the section with change from level X to level Y in a 24-hour period. Examples of this transition matrix based on hypothetical numbers are presented in Tables 12 through 20 later in this chapter.

Table VII

Example of a transition matrix built from Opti-Grade data

	Future state		
	Level 1 (Good)	Level 2 (Marginal)	Level 3 (Poor)
Current state			
Level 1 (Good)	P(1 to 1)	P(1 to 2)	P(1 to 3)
Level 2 (Marginal)	P(2 to 1)	P(2 to 2)	P(2 to 3)
Level 3 (Poor)	P(3 to 1)	P(3 to 2)	P(3 to 3)

Where: P (1 to 1) + P (1 to 2) + P (1 to 3) = 1
P (2 to 1) + P (2 to 2) + P (2 to 3) = 1
P (3 to 1) + P (3 to 2) + P (3 to 3) = 1

The results from each of the 10 subsections are then combined to produce a single matrix for their decision-level segment. Though the matrix for one subsection may be very different from the matrix for another section within a decision-level segment, economic and technological reasons prevent the forest industry from making rehabilitation decisions for such small sections of road. For this reason, the subsection models need to be combined to produce a single model for each decision-level segment. The matrices for decision-level segment of a similar age since the last rehabilitation occurred within a family are then combined to create a transition matrix for that entire age class within the family for simulation purposes.

Since Opti-Grade is currently used without feedback on where maintenance is actually performed relative to where it is required, models constructed from the Opti-Grade data can't be developed much further. As a result, the probability that grading occurs when it is required is blended in with the probability of road roughness change. Evaluations done with this model still reflect what actually occurs and thus provide effective predictions, but modeling the probability that grading occurs relative the current level of roughness on the road can further improve the model. As a result, if a maintenance feedback mechanism were added to Opti-Grade, the additional information could be used to separate the probability of grading occurring from the probability of roughness change, and the model could predict expected maintenance costs more accurately.

With recorded information on where grading actually occurred relative to the roughness of the sections that were graded, the probability of grading occurring can be modeled. In addition, whether the section had been graded would affect the probability of its transition to another condition (level). As a result, each decision-level segment could have a table that lists the probability of grading (Table 8) and a transition matrix (Table 9) that includes sections for whether or not grading occurred. In Table 8, P (G) X is the probability that grading will occur within a segment given the current condition (X). Table 9 uses the same terms as in Table 7.

Table VIII

Example of a grading probability table

	Probability of	
Condition	Grading	Not grading
Level 1 (Good)	P(G)1	1–P(G)1
Level 2 (Marginal)	P(G)2	1–P(G)2
Level 3 (Poor)	P(G)3	1–P(G)3

Table IX

Example of a transition matrix built from Opti-Grade data combined with feedback on whether grading was performed

		Future state					
		Level 1 (Good)		Level 2 (Marginal)		Level 3 (Poor)	
		Graded	Not graded	Graded	Not graded	Graded	Not graded
Current state	Level 1 (Good)	P(1 to 1)	P(1 to 1)	P(1 to 2)	P(1 to 2)	P(1 to 3)	P(1 to 3)
	Level 2 (Marginal)	P(2 to 1)	P(2 to 1)	P(2 to 2)	P(2 to 2)	P(2 to 3)	P(2 to 3)
	Level 3 (Poor)	P(3 to 1)	P(3 to 1)	P(3 to 2)	P(3 to 2)	P(3 to 3)	P(3 to 3)

Where: P (1 to 1) if graded + P (1 to 2) if graded + P (1 to 3) if graded = 1
P (1 to 1) not graded + P (1 to 2) not graded + P (1 to 3) not graded = 1
P (2 to 1) if graded + P (2 to 2) if graded + P (2 to 3) if graded = 1
P (2 to 1) not graded + P (2 to 2) not graded + P (2 to 3) not graded = 1
P (3 to 1) if graded + P (3 to 2) if graded + P (3 to 3) if graded = 1
P (3 to 1) not graded + P (3 to 2) not graded + P (3 to 3) not graded = 1

3.3 Additional information for rehabilitation decisions

To make useful decisions based on Opti-Grade data, other details of the road must be considered. First, the database for each road segment should indicate when the segment's last rehabilitation was performed to express its age since the last rehabilitation; this data will improve predictions of long-term trends in road degradation rates. In addition, better decisions can be made if the road network is broken into families or similar groups of segments. Although it is easier to consider the whole network as a single group or family, even a small 300-km network such as those commonly managed by the forest industry will have different groups of road segments, each with a different potential, that warrant different treatment.

3.3.1 Families

For the forest industry, this approach could be as simple as breaking the network into three families (straight, flat segments; curved segments; and hill segments) that will receive different maintenance and that will have different potentials that could be attained through good management of maintenance and rehabilitation. Other ways to subdivide the network could be based on road class, construction method, traffic level, or any combination of these criteria. The correct balance requires families whose members are similar enough to permit evaluation and comparison while maintaining families large enough to provide a wide range of data per family to facilitate decisions. For a 200- to 700-km-long network, a good target would be between two and five families.

In looking at the 18 Opti-Grade systems currently in use by FERIC members, the roughness data is collected almost exclusively on their class 1 roads (the main haul road network). As a result, creating families based on road class is not likely to be a good choice for a forest application. These main haul road networks are also almost always constructed using the same methods and exposed to very similar traffic over a given haul season, so these two criteria also fail to offer a good basis for creating families. A common criterion used in traditional pavement management systems, such as the type of sub-base or base thickness, could be effective, but almost no forest road manager has access to this type of information about their roads, and obtaining it would be very costly. While gathering this type of information for newly constructed roads would help develop a better family classification and thus improve the results produced by the rehabilitation model, the large number of roads that require management and that already exist would require another practical method of dividing the network into families. This suggests a division based on road geometry, since forest roads of about the same construction, exposed to similar traffic, perform quite differently on hills, curves, or straight segments; the result of using road geometry would be three or four well-defined families. These families would include the following breakdowns:

For three families on a network:

- Family 1: straight and flat (no radii <150 m and no slope >1.5%)
- Family 2: curves (radii <150 m and no slope >1.5%)
- Family 3: hills (slopes >1.5%)

For four families on a network:

- Family 1: straight and flat (no radii <150 m and no slope >1.5%)
- Family 2: curves on flat ground (radii <150 m and no slope >1.5%)
- Family 3: curves on hills (radii <150 m and slopes >1.5%)
- Family 4: straight hills (no radii <150 m and slopes >1.5%)

3.3.2 Costs for simulation

Road maintenance and rehabilitation costs

Next, information on operational costs will be required to let decisions about the economics of treatment be made effectively. The cost per km of grading for each family must be established so that a total cost can be calculated each time the Opti-Grade data indicates that grading has taken place and road roughness improved. To calculate rehabilitation costs, users must provide the average cost of each type of rehabilitation activity for each family of road segment. Some segments may have several possible interventions to consider; in this case, managers would enter the cost of the most probable intervention, the weighted average of the possible interventions, or a simple average of the possible interventions. This step becomes easy if only one type of rehabilitation is normally used, and this is often the case in the forest industry (which uses regravelling in most cases). It's important to include all the costs associated with rehabilitation in the treatment cost, including the cost of material, transportation, and labor.

User costs

To more precisely estimate the road costs associated with road maintenance and rehabilitation, the inclusion of user costs and how they are effected by road conditions is valuable. Unfortunately, the forest industry has limited information on the actual costs of trucking operations and no information on how these costs relate to road roughness. This has resulted primarily from the industry having contracted out almost all haul operations. If this information were available or if reasonable estimates could be obtained, the HDM models could provide good guidance on estimating user costs and road managers could include them in the costs. Each time a road segment was used in less than good condition, the grading cost might be zero, but user costs would increase. Knowing these costs would provide a truer value for the road cost and the cost of poor maintenance and rehabilitation decisions. Where no good information is available on these costs, trying to include this information in making decisions might just add confusion and complications or could lead to poor decisions based on incorrect estimates, and both would hinder implementation of such a system by the industry. More information must be collected on these costs by the forest industry.

Summary of additional information requirements

In summary, each decision-level segment will require the following information in addition to the Opti-Grade data to permit simulation:

- Family
  - Age (time since last rehabilitation)
  - Average maintenance (grading) cost per kilometre
  - Cost of rehabilitation per kilometre
  - User costs (if available)

How these are used in simulation is discussed in the next section.

3.4 Simulation with the models

Once the information described in the previous sections is available, the model can begin predicting the cost of maintenance for each decision-level segment for the coming season based on Opti-Grade data collected in previous seasons. Each age class within a family will be modeled by creating a transition matrix. This process will create a set of matrices for each family that includes expected transitions for each age of road based on the time since the last rehabilitation treatment. Knowing the time of that treatment for each decision-level segment within a family lets the user apply the appropriate decision matrix after simulation of the road costs.

To calculate costs, all segments being modeled would begin in good condition (level 1) at the start of each season being simulated, since managers traditionally grade roads before haul operations begin. From this starting point, the model would estimate the condition on the following day based on a transition matrix for age class. If the road begins in condition level 1, the probabilities of changing to levels 1, 2, or 3 the following day are known. Based on these known probabilities, the model can predict the segment's state on the following day through a Monte Carlo simulation that uses a random-number model based on the known probabilities. Given the possibility of a random value between 0 and 1, the outcomes can be divided into three groups based on the cumulative probabilities calculated from the known probabilities found in the transition matrices for the age group being simulated. A model of these transition matrices can be seen in Table 7. A model of a random-number prediction table is presented in Table 10 and is calculated based on the cumulative probabilities from the row of probabilities for level 1 in Table 7; examples based on a hypothetical transition matrix are presented in Tables 21 to 23.

Table X

Example of a random-number prediction table
based on Monte Carlo simulations

	Random number equals
Result	
Road stays at level 1 if	0 **to** P(1 to 1)
Road goes to level 2 if	P(1 to 1) **to** P(1 to 1) + P(1 to 2)
Road goes to level 3 if	P(1 to 1) + P(1 to 2) **to** P(1 to 1) + P(1 to 2) + P(1 to 3)

Based on the end-state of a segment after each step in the simulation, the model calculates costs. If the segment improves in quality, the model assumes that grading took place and adds the cost of this grading to the total maintenance and user costs. If the road condition is rougher than level 1 at the beginning of the simulation step, the model adds a user cost created by working on a rougher road. If the user has defined these increased user costs and wants to include them in the calculations, this cost increase is added to the total maintenance and user costs. Finally, the end-state for the segment after a given step in the simulation becomes the starting state for the next step.

This simulation loop repeats using the first transition matrix for the equivalent of one grading season. At the end of this first simulated season, the simulation then switches to the transition matrix for 1-year-older road segments and simulates the total maintenance and user costs for the next age group within the family. This process continues for all transition matrices available for a family. The result is the expected maintenance and user cost for a season for each age of road segment within a family. These costs are then used to build a decision matrix for each age group within a family. A sample decision matrix for each decision-level segment appears in Table 11. It presents six scenarios for each age group of road within the family; the first scenario considers the cost with no rehabilitation and the following five consider the costs including rehabilitation at different years over the 5 years of the simulation. In the year that rehabilitation is performed, the maintenance and user costs are those of a newly rehabilitated section (an age group less than 1), and in the following years, maintenance and user costs for age groups increase from that point. For years prior to rehabilitation, the maintenance and user costs for the current age are used for year 1 and increase from that point until rehabilitation. A 5-year period was chosen for the decision matrix, since this is the widely accepted maximum life of a rehabilitation within the forest industry based on discussions with Opti-Grade users. With this decision matrix, road managers can assess the best course of action for each decision-level segment over the next 5 years. In table 11 "M" represents the maintenance and user costs, if included, for a given year (discounted to the present value), "R" is the rehabilitation cost, discounted to the present value. Examples of decision matrices based on a sample simulation are presented in Tables 28 through 39.

Table XI

Example of a decision matrix produced by the model

	Rehabilitation in:					
	None	Year 1	Year 2	Year 3	Year 4	Year 5
Year						
1	M	R+M	M	M	M	M
2	M	M	R+M	M	M	M
3	M	M	M	R+M	M	M
4	M	M	M	M	R+M	M
5	M	M	M	M	M	R+M
Total cost	Total present value cost	Total present value cost	Total present value cost	Total present value cost	Total present value cost	Total present value cost

Where the database contains feedback information on where and when grading actually took place, an additional step would occur for each day of the simulation. Based on the historical data, each family would have a probability of being graded based on the time elapsed since the previous rehabilitation and based on the present state (as shown in Table 10). Before simulating the transition from one condition level to another for a segment, the model would determine whether grading takes place using a Monte Carlo approach, as was done to predict the future state. Once the model determines whether grading took place, it would then use the appropriate sub-model for prediction of future states to determine the condition of the decision-level segment on the following day. Since the model knows whether grading took place, it doesn't need to assume a maintenance cost, since this would be determined using the probability in the grading model. Apart from this additional step, the simulation and results using grader feedback information would be the same as it would be without this information.

3.5 Feedback loop and continual improvement of the models

The last step in the Opti-Grade rehabilitation system would be to obtain feedback on where rehabilitation was performed each year. This information would let the system improve its prediction ability with increased information. Segments that are rehabilitated would be reset to age 0 and would subsequently provide additional performance information that could be used to improve the transition matrices for each family. Further, with continued use of Opti-Grade, the roughness measurements collected can be used to update all the age class transition matrices within each family and continually improve the quality of the model. With this feedback step, the models and predictions made by the simulations would become better and more accurate with each season of use. Figure 4 summarizes the proposed process and shows how the feedback loop fits in the process.

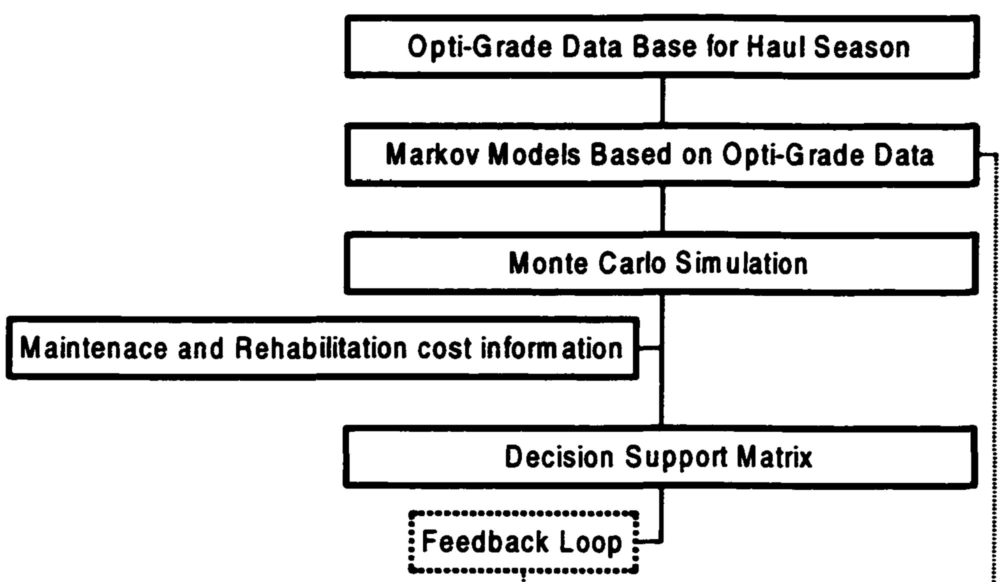

Figure 4 Diagram of the proposed rehabilitation management system

3.6 Example of simulation

The purpose of this example is to demonstrate the method discussed above. The transition matrices for the example model are based on hypothetical numbers, since it was not feasible within the time limits of this project to manually develop the models based on true data and the analysis software tool has not yet been programmed. The example will look at one family of roads.

3.6.1 The Model: Transition matrices

Within a given family, each age group would have a model developed based on the available Opti-Grade data. Tables 12 through 20 are the models used for this example. A model of these transition matrices and an explanation of how they are developed was covered earlier in this chapter and can be found with Table 7.

Table XII

Transition matrix model for a road that has been rehabilitated within the last year

		Future state		
		Level 1	Level 2	Level 3
Current State	Level 1	0.8	0.2	0
	Level 2	0.1	0.8	0.1
	Level 3	0.7	0	0.3

Table XIII

Transition matrix model for a road that was rehabilitated 1 to 2 years ago

		Future state		
		Level 1	Level 2	Level 3
Current State	Level 1	0.8	0.1	0.1
	Level 2	0.1	0.7	0.2
	Level 3	0.7	0.1	0.2

Table XIV

Transition matrix model for a road that was rehabilitated 2 to 3 years ago

		Future state		
		Level 1	Level 2	Level 3
Current State	Level 1	0.6	0.3	0.1
	Level 2	0.1	0.6	0.3
	Level 3	0.7	0.1	0.2

Table XV

Transition matrix model for a road that was rehabilitated 3 to 4 years ago

		Future state		
		Level 1	Level 2	Level 3
Current State	Level 1	0.6	0.2	0.2
	Level 2	0.2	0.4	0.4
	Level 3	0.8	0.1	0.1

Table XVI

Transition matrix model for a road that was rehabilitated 4 to 5 years ago

		Future state		
		Level 1	Level 2	Level 3
Current State	Level 1	0.5	0.3	0.2
	Level 2	0.2	0.2	0.6
	Level 3	0.8	0.1	0.1

Table XVII

Transition matrix model for a road that was rehabilitated 5 to 6 years ago

		Future state		
		Level 1	Level 2	Level 3
Current State	Level 1	0.4	0.3	0.3
	Level 2	0.2	0.1	0.7
	Level 3	0.8	0.1	0.1

Table XVIII

Transition matrix model for a road that was rehabilitated 6 to 7 years ago

		Future state		
		Level 1	Level 2	Level 3
Current State	Level 1	0.3	0.2	0.5
	Level 2	0.0	0.2	0.8
	Level 3	0.8	0.1	0.1

Table XIX

Transition matrix model for a road that was rehabilitated 7 to 8 years ago

		Future state		
		Level 1	Level 2	Level 3
Current State	Level 1	0.2	0.2	0.6
	Level 2	0.0	0.1	0.9
	Level 3	0.8	0.1	0.1

Table XX

Transition matrix model for a road that was rehabilitated 8 to 9 years ago

		Future state		
		Level 1	Level 2	Level 3
Current State	Level 1	0.1	0.1	0.8
	Level 2	0.0	0.1	0.9
	Level 3	0.8	0.1	0.1

3.6.2 Random number prediction tables

Each transition matrix model is transferred to a set of random number prediction tables for Monte Carlo simulation, as was presented in Table 10 along with an explanation of their development. Tables 21 to table 23 are the random number prediction tables for the transition matrix presented in Table 12 for a road segment that has been rehabilitated within the last year.

Table XXI

Random number prediction table for a road rehabilitated
within the last year if its current state is level 1

	Random number equals
Result	
Road stays at level 1 if	0 to 0.8
Road goes to level 2 if	0.81 to 1.0
Road goes to level 3 if	NA

Table XXII

Random number prediction table for a road rehabilitated
within the last year if its current state is level 2

	Random number equals
Result	
Road goes to level 1 if	0 to 0.1
Road stays at level 2 if	0.11 to 0.8
Road goes to level 3 if	0.81 to 1.0

Table XXIII

Random number prediction table for a road rehabilitated within the last year if its current state is level 3

	Random number equals
Result	
Road goes to level 1 if	0 to 0.7
Road goes to level 2 if	NA
Road stays at level 3 if	0.71 to 1.0

Similar sets of random number prediction tables would be required for each of the transition matrix models.

3.6.3 Simulation

Using the prediction tables, a road maintenance season is simulated with Monte Carlo simulation. Table 24 is the result of a 150-day simulation for a road segment that has been rehabilitated within the last year based on the random number prediction tables presented in Tables 21 through 23. The simulation used grading costs of $65/km and no increase in user costs due to poor road condition. A grading cost was applied whenever the end level was better (lower roughness) than the start level. Table 25 provides similar simulation results for the same road age over the same 150-day period, but with the application of increased user costs due to increased road roughness. In this case, grading costs were applied in the same way as for the previous simulation. For the user costs, there were no increased user costs if the start level was 1, versus an increased user cost of $10 per kilometre per day if the start level was 2 and $30 per kilometre per day if the start level was 3. Since no good values could be obtained for user costs on forest roads as a function of road roughness, these values are estimates. In the development of this example, the sensitivity of the decision results to cost was tested with different ranges of increased user costs. It was found that as long as the cost for level 2 was less than the cost for level 3, the resulting decision was not affected by the magnitude of the number. As better values become available for these user costs, this relationship should be further evaluated.

Table XXIV

Results of a 150-day simulation for a road that was rehabilitated within the last year at a grading cost of $65/km and with no increased user cost as a function of deteriorating road condition

Day	Start level	Random number	End level	Costs
1	1	0.30	1	$0
2	1	0.15	1	$0
3	1	0.87	2	$0
4	2	0.24	2	$0
5	2	0.54	2	$0
6	2	0.48	2	$0
7	2	0.36	2	$0
8	2	0.45	2	$0
9	2	0.54	2	$0
10	2	0.98	3	$0
11	3	0.04	1	$65
12	1	0.52	1	$0
13	1	0.85	2	$0
14	2	0.82	2	$0
15	2	0.43	2	$0
16	2	0.56	2	$0
17	2	0.27	2	$0
18	2	0.49	2	$0
19	2	0.12	2	$0
20	2	0.95	3	$0
21	3	0.70	3	$0
22	3	0.60	1	$65
23	1	0.42	1	$0
24	1	0.84	2	$0
25	2	0.61	2	$0

26	2	0.77	2	$0
27	2	0.62	2	$0
28	2	0.02	1	$65
29	1	0.02	1	$0
30	1	0.95	2	$0
31	2	0.43	2	$0
32	2	0.57	2	$0
33	2	0.02	1	$65
34	1	0.66	1	$0
35	1	0.95	2	$0
36	2	0.55	2	$0
37	2	0.06	1	$65
38	1	0.85	2	$0
39	2	0.62	2	$0
40	2	0.46	2	$0
41	2	0.16	2	$0
42	2	0.30	2	$0
43	2	0.60	2	$0
44	2	0.24	2	$0
45	2	0.74	2	$0
46	2	0.45	2	$0
47	2	0.11	2	$0
48	2	0.29	2	$0
49	2	0.48	2	$0
50	2	0.08	1	$65
51	1	0.96	2	$0
52	2	0.91	3	$0
53	3	0.04	1	$65
54	1	0.57	1	$0
55	1	0.21	1	$0
56	1	0.95	2	$0
57	2	0.45	2	$0
58	2	0.95	3	$0
59	3	0.69	1	$65
60	1	0.01	1	$0
61	1	0.37	1	$0
62	1	0.26	1	$0
63	1	0.74	1	$0
64	1	0.30	1	$0
65	1	0.65	1	$0
66	1	0.62	1	$0
67	1	0.42	1	$0
68	1	0.30	1	$0

69	1	0.85	2	$0
70	2	0.38	2	$0
71	2	0.27	2	$0
72	2	0.18	2	$0
73	2	0.19	2	$0
74	2	0.63	2	$0
75	2	0.40	2	$0
76	2	0.52	2	$0
77	2	0.39	2	$0
78	2	0.85	2	$0
79	2	0.20	2	$0
80	2	0.50	2	$0
81	2	0.64	2	$0
82	2	0.39	2	$0
83	2	0.38	2	$0
84	2	0.81	2	$0
85	2	0.98	3	$0
86	3	0.93	3	$0
87	3	0.53	1	$65
88	1	0.35	1	$0
89	1	0.02	1	$0
90	1	0.30	1	$0
91	1	0.76	1	$0
92	1	0.34	1	$0
93	1	0.87	2	$0
94	2	0.87	2	$0
95	2	0.01	1	$65
96	1	0.86	2	$0
97	2	0.25	2	$0
98	2	0.35	2	$0
99	2	0.41	2	$0
100	2	0.71	2	$0
101	2	0.13	2	$0
102	2	0.92	3	$0
103	3	0.26	1	$65
104	1	0.18	1	$0
105	1	0.16	1	$0
106	1	0.99	2	$0
107	2	0.66	2	$0
108	2	0.90	2	$0
109	2	0.27	2	$0
110	2	0.76	2	$0
111	2	0.14	2	$0

112	2	0.90	2	$0
113	2	0.05	1	$65
114	1	0.26	1	$0
115	1	0.58	1	$0
116	1	0.58	1	$0
117	1	0.79	1	$0
118	1	0.61	1	$0
119	1	0.57	1	$0
120	1	0.74	1	$0
121	1	0.78	1	$0
122	1	0.82	2	$0
123	2	0.55	2	$0
124	2	0.80	2	$0
125	2	0.82	2	$0
126	2	0.61	2	$0
127	2	0.49	2	$0
128	2	0.34	2	$0
129	2	0.92	3	$0
130	3	0.34	1	$65
131	1	0.99	2	$0
132	2	0.02	1	$65
133	1	0.48	1	$0
134	1	0.48	1	$0
135	1	0.52	1	$0
136	1	0.27	1	$0
137	1	0.67	1	$0
138	1	0.46	1	$0
139	1	0.23	1	$0
140	1	0.94	2	$0
141	2	0.92	3	$0
142	3	0.54	1	$65
143	1	0.46	1	$0
144	1	0.73	1	$0
145	1	0.47	1	$0
146	1	0.68	1	$0
147	1	0.62	1	$0
148	1	0.82	2	$0
149	2	0.92	3	$0
150	3	0.94	3	$0
Total	—	—	—	$975

Table XXV

Results of a 150-day simulation for a road that was rehabilitated
within the last year at a grading cost of $65/km,
with increased user costs of $10 per kilometre per day for level 2 road condition
and $30 per kilometre per day for level 3 condition

Day	Start level	Random number	End level	Costs
1	1	0.30	1	$0
2	1	0.15	1	$0
3	1	0.87	2	$0
4	2	0.24	2	$10
5	2	0.54	2	$10
6	2	0.48	2	$10
7	2	0.36	2	$10
8	2	0.45	2	$10
9	2	0.54	2	$10
10	2	0.98	3	$10
11	3	0.04	1	$95
12	1	0.52	1	$0
13	1	0.85	2	$0
14	2	0.82	2	$10
15	2	0.43	2	$10
16	2	0.56	2	$10
17	2	0.27	2	$10
18	2	0.49	2	$10
19	2	0.12	2	$10
20	2	0.95	3	$10
21	3	0.70	3	$30
22	3	0.60	1	$95
23	1	0.42	1	$0
24	1	0.84	2	$0
25	2	0.61	2	$10
26	2	0.77	2	$10
27	2	0.62	2	$10
28	2	0.02	1	$75
29	1	0.02	1	$0
30	1	0.95	2	$0
31	2	0.43	2	$10
32	2	0.57	2	$10
33	2	0.02	1	$75

34	1	0.66	1	$0
35	1	0.95	2	$0
36	2	0.55	2	$10
37	2	0.06	1	$75
38	1	0.85	2	$0
39	2	0.62	2	$10
40	2	0.46	2	$10
41	2	0.16	2	$10
42	2	0.30	2	$10
43	2	0.60	2	$10
44	2	0.24	2	$10
45	2	0.74	2	$10
46	2	0.45	2	$10
47	2	0.11	2	$10
48	2	0.29	2	$10
49	2	0.48	2	$10
50	2	0.08	1	$75
51	1	0.96	2	$0
52	2	0.91	3	$10
53	3	0.04	1	$95
54	1	0.57	1	$0
55	1	0.21	1	$0
56	1	0.95	2	$0
57	2	0.45	2	$10
58	2	0.95	3	$10
59	3	0.69	1	$95
60	1	0.01	1	$0
61	1	0.37	1	$0
62	1	0.26	1	$0
63	1	0.74	1	$0
64	1	0.30	1	$0
65	1	0.65	1	$0
66	1	0.62	1	$0
67	1	0.42	1	$0
68	1	0.30	1	$0
69	1	0.85	2	$0
70	2	0.38	2	$10
71	2	0.27	2	$10
72	2	0.18	2	$10
73	2	0.19	2	$10
74	2	0.63	2	$10
75	2	0.40	2	$10
76	2	0.52	2	$10

77	2	0.39	2	$10
78	2	0.85	2	$10
79	2	0.20	2	$10
80	2	0.50	2	$10
81	2	0.64	2	$10
82	2	0.39	2	$10
83	2	0.38	2	$10
84	2	0.81	2	$10
85	2	0.98	3	$10
86	3	0.93	3	$30
87	3	0.53	1	$95
88	1	0.35	1	$0
89	1	0.02	1	$0
90	1	0.30	1	$0
91	1	0.76	1	$0
92	1	0.34	1	$0
93	1	0.87	2	$0
94	2	0.87	2	$10
95	2	0.01	1	$75
96	1	0.86	2	$0
97	2	0.25	2	$10
98	2	0.35	2	$10
99	2	0.41	2	$10
100	2	0.71	2	$10
101	2	0.13	2	$10
102	2	0.92	3	$10
103	3	0.26	1	$95
104	1	0.18	1	$0
105	1	0.16	1	$0
106	1	0.99	2	$0
107	2	0.66	2	$10
108	2	0.90	2	$10
109	2	0.27	2	$10
110	2	0.76	2	$10
111	2	0.14	2	$10
112	2	0.90	2	$10
113	2	0.05	1	$75
114	1	0.26	1	$0
115	1	0.58	1	$0
116	1	0.58	1	$0
117	1	0.79	1	$0
118	1	0.61	1	$0
119	1	0.57	1	$0

120	1	0.74	1	$0
121	1	0.78	1	$0
122	1	0.82	2	$0
123	2	0.55	2	$10
124	2	0.80	2	$10
125	2	0.82	2	$10
126	2	0.61	2	$10
127	2	0.49	2	$10
128	2	0.34	2	$10
129	2	0.92	3	$10
130	3	0.34	1	$95
131	1	0.99	2	$0
132	2	0.02	1	$75
133	1	0.48	1	$0
134	1	0.48	1	$0
135	1	0.52	1	$0
136	1	0.27	1	$0
137	1	0.67	1	$0
138	1	0.46	1	$0
139	1	0.23	1	$0
140	1	0.94	2	$0
141	2	0.92	3	$10
142	3	0.54	1	$95
143	1	0.46	1	$0
144	1	0.73	1	$0
145	1	0.47	1	$0
146	1	0.68	1	$0
147	1	0.62	1	$0
148	1	0.82	2	$0
149	2	0.92	3	$10
150	3	0.94	3	$30
Total	—	—	—	$2095

Similar simulation results would be performed for each age class within a family either using or not using user costs, depending on the analysis the road manager wants to perform and the data they have available. The total costs from each simulation are then grouped to build decision matrices for each age class.

3.6.4 Results and extrapolations to produce decision matrices

Information may not be available to simulate costs for all the age classes required to complete a decision matrix. The values for some age classes beyond the range of current data can be estimated through extrapolation. To do this extrapolation, the total cost was analyzed as a function of age (years since rehabilitation). More extensive data analysis was not required since the need to include multiple variables is reduced through the grouping of data into families. Table 26 shows the simulated costs for this example using no effect on user costs with increasing roughness, while Table 27 presents the same values but with increased user costs of $10 and $30 per kilometre per day (respectively) for roughness levels 2 and 3. Figures 3 and 4 show the extrapolations used to fill in the decision matrices where data was not available to simulate the cost for a required age class. In both cases, there was a strong linear relationship, therefore the extrapolation can be reasonably used to estimate values for ages classes that do not have data available and other more extensive multivariate analysis is not warranted.

Table XXVI

Simulation results, showing annual road maintenance costs as they relate to time since last rehabilitation

Time since last rehabilitation (years)	Annual maintenance cost
0 to 1	$ 975
1 to 2	$1365
2 to 3	$1950
3 to 4	$2080
4 to 5	$2730
5 to 6	$3055
6 to 7	$3380
7 to 8	$3900
8 to 9	$4095

Table XXVII

Simulation results, showing annual road maintenance plus user costs as they relate to time since last rehabilitation

Time since last rehabilitation (years)	Annual maintenance cost
0 to 1	$2095
1 to 2	$2265
2 to 3	$3220
3 to 4	$3210
4 to 5	$4270
5 to 6	$4605
6 to 7	$5470
7 to 8	$6150
8 to 9	$6365

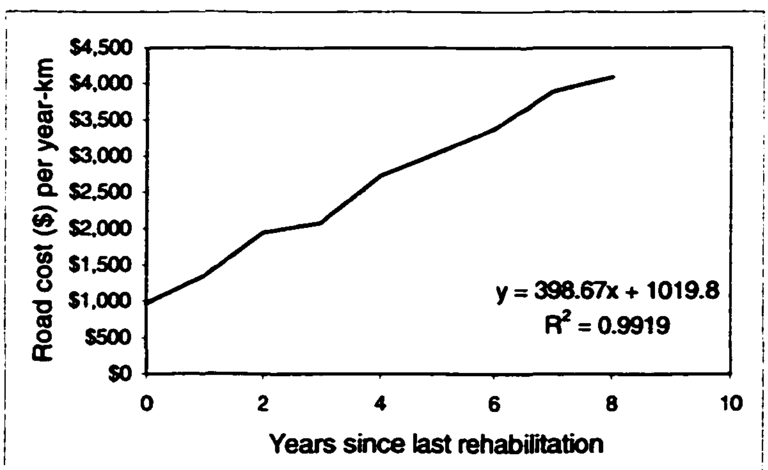

Figure 5 Graph of annual road maintenance costs versus time since last rehabilitation

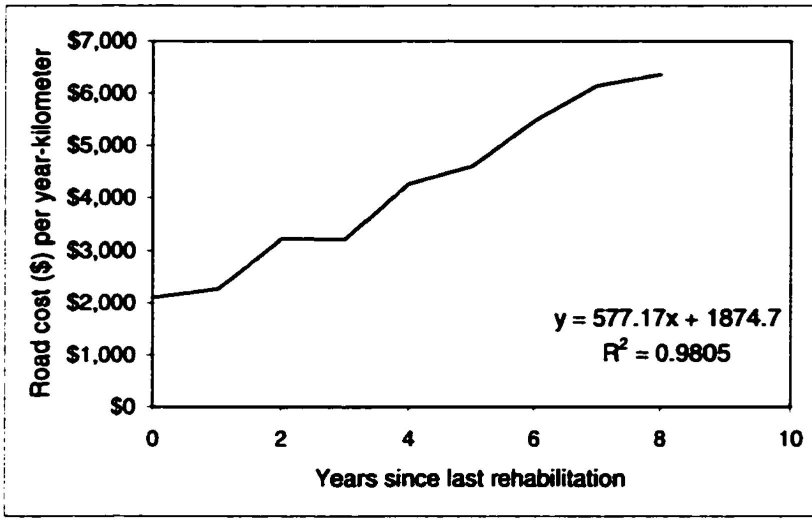

Figure 6 Graph of annual road maintenance and user costs versus time since last rehabilitation

3.6.5 Decision Matrices

In using the proposed system, the user would launch software that would perform all the work to this point in the example; essentially, the process would be transparent to the user. All the user would supply would be the Opti-Grade databases and the information identified earlier in this chapter in the section "additional information for rehabilitation decisions". The software would then return the decision matrices.

Using the total cost results from the simulations, six different 5-year scenarios are created for each age class of road within the family. The result allows the road manager to easily identify the best time in the next 5 years to perform road rehabilitation on a given age group from an economic point of view; "no rehabilitation" is also an option. Tables 28 to 33 are decision matrices based on the example models and simulation, and consider only road maintenance costs ($65/km, Table 26) and rehabilitation costs ($3000/km). Tables 34 to 39 present decision matrices for the same road age groups with the same maintenance and rehabilitation costs, but also include the user costs in Table 27. In all cases, the costs have been calculated to a discounted present value using a 10%

discount rate. All decision matrices are based on the model and explanation presented in Table 11.

Table XXVIII

Decision matrix for a road segments rehabilitated in the last year, considering only maintenance and rehabilitation costs

		Rehabilitation in:					
		None	Year 1	Year 2	Year 3	Year 4	Year 5
Present value of cost in:	Year 1	$975	$3,975	$975	$975	$975	$975
	Year 2	$1,241	$1,241	$3,614	$1,241	$1,241	$1,241
	Year 3	$1,612	$1,612	$1,128	$3,285	$1,612	$1,612
	Year 4	$1,563	$1,563	$1,465	$1,026	$2,986	$1,563
	Year 5	$1,865	$1,865	$1,421	$1,332	$932	$2,715
	Total	$7,255	$10,255	$8,602	$7,858	$7,746	$8,105

Table XXIX

Decision matrix for a road segments rehabilitated 1 to 2 years ago, considering only maintenance and rehabilitation costs

		Rehabilitation in:					
		None	Year 1	Year 2	Year 3	Year 4	Year 5
Present value of cost in:	Year 1	$1,365	$3,975	$1,365	$1,365	$1,365	$1,365
	Year 2	$1,773	$1,241	$3,614	$1,773	$1,773	$1,773
	Year 3	$1,719	$1,612	$1,128	$3,285	$1,719	$1,719
	Year 4	$2,051	$1,563	$1,465	$1,026	$2,986	$2,051
	Year 5	$2,087	$1,865	$1,421	$1,332	$932	$2,715
	Total	$8,994	$10,255	$8,992	$8,780	$8,776	$9,623

Table XXX

Decision matrix for a road segments rehabilitated 2 to 3 years ago, considering only maintenance and rehabilitation costs

		Rehabilitation in:					
		None	Year 1	Year 2	Year 3	Year 4	Year 5
Present value of cost in:	Year 1	$1,950	$3,975	$1,950	$1,950	$1,950	$1,950
	Year 2	$1,891	$1,241	$3,614	$1,891	$1,891	$1,891
	Year 3	$2,256	$1,612	$1,128	$3,285	$2,256	$2,256
	Year 4	$2,295	$1,563	$1,465	$1,026	$2,986	$2,295
	Year 5	$2,309	$1,865	$1,421	$1,332	$932	$2,715
	Total	$10,701	$10,255	$9,577	$9,483	$10,016	$11,107

Table XXXI

Decision matrix for a road segments rehabilitated 3 to 4 years ago, considering only maintenance and rehabilitation costs

		Rehabilitation in:					
		None	Year 1	Year 2	Year 3	Year 4	Year 5
Present value of cost in:	Year 1	$2,080	$3,975	$2,080	$2,080	$2,080	$2,080
	Year 2	$2,482	$1,241	$3,614	$2,482	$2,482	$2,482
	Year 3	$2,525	$1,612	$1,128	$3,285	$2,525	$2,525
	Year 4	$2,539	$1,563	$1,465	$1,026	$2,986	$2,539
	Year 5	$2,664	$1,865	$1,421	$1,332	$932	$2,715
	Total	$12,290	$10,255	$9,707	$10,204	$11,005	$12,341

Table XXXII

Decision matrix for a road segments rehabilitated 4 to 5 years ago, considering only maintenance and rehabilitation costs

		Rehabilitation in:					
		None	Year 1	Year 2	Year 3	Year 4	Year 5
Present value of cost in:	Year 1	$2,730	$3,975	$2,730	$2,730	$2,730	$2,730
	Year 2	$2,777	$1,241	$3,614	$2,777	$2,777	$2,777
	Year 3	$2,793	$1,612	$1,128	$3,285	$2,793	$2,793
	Year 4	$2,930	$1,563	$1,465	$1,026	$2,986	$2,930
	Year 5	$2,797	$1,865	$1,421	$1,332	$932	$2,715
	Total	$14,028	$10,255	$10,357	$11,150	$12,219	$13,946

Table XXXIII

Decision matrix for a road segments rehabilitated 5 to 6 years ago, considering only maintenance and rehabilitation costs

		Rehabilitation in:					
		None	Year 1	Year 2	Year 3	Year 4	Year 5
Present value of cost in:	Year 1	$3,055	$3,975	$3,055	$3,055	$3,055	$3,055
	Year 2	$3,073	$1,241	$3,614	$3,073	$3,073	$3,073
	Year 3	$3,223	$1,612	$1,128	$3,285	$3,223	$3,223
	Year 4	$3,077	$1,563	$1,465	$1,026	$2,986	$3,077
	Year 5	$4,828	$1,865	$1,421	$1,332	$932	$2,715
	Total	$17,256	$10,255	$10,682	$11,770	$13,270	$15,142

Table XXXIV

Decision matrix for a road segments rehabilitated in the last year, considering only maintenance costs, user costs, and rehabilitation costs

		Rehabilitation in:					
		None	Year 1	Year 2	Year 3	Year 4	Year 5
Present value of cost in:	Year 1	$2,095	$5,095	$2,095	$2,095	$2,095	$2,095
	Year 2	$2,059	$2,059	$4,632	$2,059	$2,059	$2,059
	Year 3	$2,661	$2,661	$1,872	$4,211	$2,661	$2,661
	Year 4	$2,412	$2,412	$2,419	$1,702	$3,828	$2,412
	Year 5	$2,916	$2,916	$2,192	$2,199	$1,547	$3,480
	Total	$12,143	$15,143	$13,210	$12,266	$12,190	$12,707

Table XXXV

Decision matrix for a road segments rehabilitated 1 to 2 years ago, considering only maintenance costs, user costs, and rehabilitation costs

		Rehabilitation in:					
		None	Year 1	Year 2	Year 3	Year 4	Year 5
Present value of cost in:	Year 1	$2,265	$5,095	$2,265	$2,265	$2,265	$2,265
	Year 2	$2,927	$2,059	$4,632	$2,927	$2,927	$2,927
	Year 3	$2,653	$2,661	$1,872	$4,211	$2,653	$2,653
	Year 4	$3,208	$2,412	$2,419	$1,702	$3,828	$3,208
	Year 5	$3,145	$2,916	$2,192	$2,199	$1,547	$3,480
	Total	$14,199	$15,143	$13,380	$13,304	$13,220	$14,533

Table XXXVI

Decision matrix for a road segments rehabilitated 2 to 3 years ago, considering only maintenance costs, user costs, and rehabilitation costs

		Rehabilitation in:					
		None	Year 1	Year 2	Year 3	Year 4	Year 5
Present value of cost in:	Year 1	$3,220	$5,095	$3,220	$3,220	$3,220	$3,220
	Year 2	$2,918	$2,059	$4,632	$2,918	$2,918	$2,918
	Year 3	$3,529	$2,661	$1,872	$4,211	$3,529	$3,529
	Year 4	$3,460	$2,412	$2,419	$1,702	$3,828	$3,460
	Year 5	$3,736	$2,916	$2,192	$2,199	$1,547	$3,480
	Total	$16,863	$15,143	$14,335	$14,250	$15,042	$16,607

Table XXXVII

Decision matrix for a road segments rehabilitated 3 to 4 years ago, considering only maintenance costs, user costs, and rehabilitation costs

		Rehabilitation in:					
		None	Year 1	Year 2	Year 3	Year 4	Year 5
Present value of cost in:	Year 1	$3,210	$5,095	$3,210	$3,210	$3,210	$3,210
	Year 2	$3,882	$2,059	$4,632	$3,882	$3,882	$3,882
	Year 3	$3,806	$2,661	$1,872	$4,211	$3,806	$3,806
	Year 4	$4,110	$2,412	$2,419	$1,702	$3,828	$4,110
	Year 5	$4,201	$2,916	$2,192	$2,199	$1,547	$3,480
	Total	$19,208	$15,143	$14,325	$15,204	$16,273	$18,487

Table XXXVIII

Decision matrix for a road segments rehabilitated 4 to 5 years ago, considering only maintenance costs, user costs, and rehabilitation costs

		Rehabilitation in:					
		None	Year 1	Year 2	Year 3	Year 4	Year 5
Present value of cost in:	Year 1	$4,270	$5,095	$4,270	$4,270	$4,270	$4,270
	Year 2	$4,186	$2,059	$4,632	$4,186	$4,186	$4,186
	Year 3	$4,521	$2,661	$1,872	$4,211	$4,521	$4,521
	Year 4	$4,621	$2,412	$2,419	$1,702	$3,828	$4,621
	Year 5	$4,347	$2,916	$2,192	$2,199	$1,547	$3,480
	Total	$21,945	$15,143	$15,385	$16,568	$18,352	$21,078

Table XXXIX

Decision matrix for a road segments rehabilitated 5 to 6 years ago, considering only maintenance costs, user costs, and rehabilitation costs

		Rehabilitation in:					
		None	Year 1	Year 2	Year 3	Year 4	Year 5
Present value of cost in:	Year 1	$4,605	$5,095	$4,605	$4,605	$4,605	$4,605
	Year 2	$4,973	$2,059	$4,632	$4,973	$4,973	$4,973
	Year 3	$5,083	$2,661	$1,872	$4,211	$5,083	$5,083
	Year 4	$4,782	$2,412	$2,419	$1,702	$3,828	$4,782
	Year 5	$4,828	$2,916	$2,192	$2,199	$1,547	$3,480
	Total	$24,271	$15,143	$15,720	$17,690	$20,035	$22,922

3.6.6 Decisions based on decision matrices

If these decision matrices are examined, the total cost row for each age group of road would be evaluated and the scenario with the lowest net cost over a 5-year period would be selected. Since the forest industry does not view their roads as assets, the residual values of a road in better condition at the end of the 5-year period are not considered. Table 40 shows what decisions should be made based on the decision matrices presented in Tables 28 through 39.

Table XXXX

Resulting decisions based on the decision matrices

	Rehabilitate the road in year	
Age group	Not considering user costs	Considering user costs
0 to 1	none	none
1 to 2	4	4
2 to 3	3	3
3 to 4	2	2
4 to 5	1	1
5 to 6	1	1

In this example, the same decision is reached whether or not user costs are considered. As was stated earlier, better information must be obtained on these user costs so that the model can better evaluate their effects.

CHAPTER 4

RECOMMENDATIONS

The proposed management system for forest road rehabilitation is simply a model to aid in an economic evaluation of when to trigger rehabilitation over a 5-year period. It does not address which specific type of rehabilitation should be performed, as the rehabilitation of forest roads is usually limited to regravelling. Although decisions on where and when to intervene are based on economics, rehabilitation budgets may still be used suboptimally if the best treatment isn't chosen. Thus, the management system should be teamed with a guide to help managers select the most appropriate rehabilitation interventions. In this case, the proposed system could identify the most likely candidates for rehabilitation. Managers could then evaluate these road segments more closely to diagnose the problem and present the best rehabilitation solution. The recommended solution could then be implemented and the economic results tracked using Opti-Grade. The implementation of different interventions within a given family of road segments would eventually reveal the most economical or effective interventions. The result would be a simple, fast, and powerful diagnostic tool that could direct treatments to problem sections using the proposed economic models.

In developing this system, it was found that there was little applicable information on how user costs are affected by road condition in the forest industry. Although the forest industry generally agrees that as roughness increases, costs increase for road users in terms of fuel use, travel time, and maintenance, nobody can quantify this cost. With a tool like Opti-Grade available to closely track road conditions, the forest industry now has a tool that will let them begin tracking these costs by obtaining true user costs to accompany the road condition data. This information would let the industry better manage their transportation costs as a whole, since they may find it cheaper to maintain a road network at a lower level and pay truckers slightly more to cover their increased haul costs; alternatively, it may make more sense to improve the road quality and pay truckers slightly less. This broader view of the transportation system will undoubtedly lead to lower transportation costs.

Because Opti-Grade has been designed solely for use by the Canadian forest industry, equating its measurements with established international standards isn't necessary. However, doing so would still offer some attractive advantages. For example, since Opti-Grade operates on similar principles to other tools used to measure values such as IRI (e.g., a Mays trailer), it's reasonable to expect that Opti-Grade measurements could be converted into IRI values. Doing so would let the forest industry compare road conditions and costs between different operations. Moreover, the ability to measure IRI values with Opti-Grade would improve its credibility to and usability by other road managers around the world.

CONCLUSION

The forest industry represents a significant and unique road management situation. With low-frequency traffic, high vehicle weights, and a relatively low-cost network of unsurfaced roads, road management poses significant challenges to managers who may not have the resources to make good economic decisions. Opti-Grade's introduction to the forest industry represents a significant step forward in road management; it greatly improves the available information on road conditions, and specifically on roughness levels. By providing this information daily, Opti-Grade lets managers examine road roughness data and develop daily maintenance schedules based on user-defined criteria that define the sections of the road that most require attention on any given day. Though this provides obvious benefits, it does not adequately address the issue of managing rehabilitation.

The proposed management system takes advantage of the vast database of information on road roughness that can be generated by using Opti-Grade to build reliable statistical models that predict how a road will perform. These performance predictions let managers predict maintenance costs and possibly user costs under various rehabilitation scenarios. Given these costs, road managers can make economically informed decisions about when and where rehabilitation should be performed. With further research, the use of Opti-Grade, and proposed further development of the system, managers will be better able to diagnose problems and determine the best solutions. Combining Opti-Grade with the proposed rehabilitation management system and a proposed diagnostic tool for recommending the most appropriate form of intervention will provide the Canadian forest industry with a low-cost, effective road management tool.

APPENDIX A

REPEATABILITY TESTS FOR OPTI-GRADE

Repeatability tests for test section 2 at 40 km/h (a = pass used as basis for comparison, b = pass being compared with pass a, qc = variation, Q 0.05, 120,10 = theoretical value)

a to b	Mean b–mean a	SE	qc	Q 0.05,120,10	Q–qc	Conclusion (means are)
1 to 2	0.25	7.33	0.03	4.56	4.53	equal
1 to 3	5.34	7.18	0.74	4.56	3.82	equal
1 to 4	0.83	7.33	0.11	4.56	4.45	equal
1 to 5	1.89	7.18	0.26	4.56	4.30	equal
1 to 6	4.26	7.18	0.59	4.56	3.97	equal
1 to 7	4.33	7.33	0.59	4.56	3.97	equal
1 to 8	3.17	7.33	0.43	4.56	4.13	equal
1 to 9	2.75	7.33	0.38	4.56	4.18	equal
1 to 10	4.28	7.18	0.60	4.56	3.96	equal
1 to 11	5.58	7.06	0.79	4.56	3.77	equal
2 to 3	5.59	7.18	0.78	4.56	3.78	equal
2 to 4	0.58	7.33	0.08	4.56	4.48	equal
2 to 5	1.64	7.18	0.23	4.56	4.33	equal
2 to 6	4.51	7.18	0.63	4.56	3.93	equal
2 to 7	4.58	7.33	0.63	4.56	3.93	equal
2 to 8	3.42	7.33	0.47	4.56	4.09	equal
2 to 9	2.50	7.33	0.34	4.56	4.22	equal
2 to 10	4.03	7.18	0.56	4.56	4.00	equal
2 to 11	5.33	7.06	0.76	4.56	3.80	equal
3 to 4	6.17	7.18	0.86	4.56	3.70	equal
3 to 5	7.23	7.04	1.03	4.56	3.53	equal
3 to 6	1.08	7.04	0.15	4.56	4.41	equal
3 to 7	1.01	7.18	0.14	4.56	4.42	equal
3 to 8	2.17	7.18	0.30	4.56	4.26	equal
3 to 9	8.09	7.18	1.13	4.56	3.43	equal
3 to 10	9.62	7.04	1.37	4.56	3.19	equal
3 to 11	10.92	6.91	1.58	4.56	2.98	equal
4 to 5	1.06	7.18	0.15	4.56	4.41	equal
4 to 6	5.10	7.18	0.71	4.56	3.85	equal
4 to 7	5.17	7.33	0.71	4.56	3.85	equal
4 to 8	4.00	7.33	0.55	4.56	4.01	equal
4 to 9	1.92	7.33	0.26	4.56	4.30	equal
4 to 10	3.44	7.18	0.48	4.56	4.08	equal
4 to 11	4.75	7.06	0.67	4.56	3.89	equal
5 to 6	6.15	7.04	0.87	4.56	3.69	equal
5 to 7	6.22	7.18	0.87	4.56	3.69	equal
5 to 8	5.06	7.18	0.70	4.56	3.86	equal

5 to 9	0.86	7.18	0.12	4.56	4.44	equal
5 to 10	2.38	7.04	0.34	4.56	4.22	equal
5 to 11	3.69	6.91	0.53	4.56	4.03	equal
6 to 7	0.07	7.18	0.01	4.56	4.55	equal
6 to 8	1.10	7.18	0.15	4.56	4.41	equal
6 to 9	7.01	7.18	0.98	4.56	3.58	equal
6 to 10	8.54	7.04	1.21	4.56	3.35	equal
6 to 11	9.85	6.91	1.42	4.56	3.14	equal
7 to 8	1.17	7.33	0.16	4.56	4.40	equal
7 to 9	7.08	7.33	0.97	4.56	3.59	equal
7 to 10	8.61	7.18	1.20	4.56	3.36	equal
7 to 11	9.92	7.06	1.40	4.56	3.16	equal
8 to 9	5.92	7.33	0.81	4.56	3.75	equal
8 to 10	7.44	7.18	1.04	4.56	3.52	equal
8 to 11	8.75	7.06	1.24	4.56	3.32	equal
9 to 10	1.53	7.18	0.21	4.56	4.35	equal
9 to 11	2.83	7.06	0.40	4.56	4.16	equal
10 to 11	1.31	6.91	0.19	4.56	4.37	equal

Repeatability tests for test section 1 at 60 km/h (a = pass used as basis for comparison, b = pass being compared with pass a, qc = variation, Q 0.05, 120,10 = theoretical value)

a to b	Mean b–mean a	SE	qc	Q 0.05,120,10	Q–qc	Conclusion (means are)
1 to 2	5.57	5.39	1.03	4.56	3.53	equal
1 to 3	0.32	5.39	0.06	4.56	4.50	equal
1 to 4	3.90	5.25	0.74	4.56	3.82	equal
1 to 5	0.65	5.25	0.12	4.56	4.44	equal
1 to 6	0.57	5.80	0.10	4.56	4.46	equal
1 to 7	0.13	5.25	0.02	4.56	4.54	equal
1 to 8	4.57	5.39	0.85	4.56	3.71	equal
1 to 9	4.46	5.25	0.85	4.56	3.71	equal
1 to 10	6.57	5.57	1.18	4.56	3.38	equal
2 to 3	5.25	5.21	1.01	4.56	3.55	equal
2 to 4	1.67	5.06	0.33	4.56	4.23	equal
2 to 5	6.22	5.06	1.23	4.56	3.33	equal
2 to 6	5.00	5.63	0.89	4.56	3.67	equal
2 to 7	5.44	5.06	1.07	4.56	3.49	equal
2 to 8	1.00	5.21	0.19	4.56	4.37	equal
2 to 9	1.11	5.06	0.22	4.56	4.34	equal
2 to 10	1.00	5.39	0.19	4.56	4.37	equal
3 to 4	3.58	5.06	0.71	4.56	3.85	equal
3 to 5	0.97	5.06	0.19	4.56	4.37	equal
3 to 6	0.25	5.63	0.04	4.56	4.52	equal
3 to 7	0.19	5.06	0.04	4.56	4.52	equal
3 to 8	4.25	5.21	0.82	4.56	3.74	equal
3 to 9	4.14	5.06	0.82	4.56	3.74	equal
3 to 10	6.25	5.39	1.16	4.56	3.40	equal
4 to 5	4.56	4.91	0.93	4.56	3.63	equal
4 to 6	3.33	5.49	0.61	4.56	3.95	equal
4 to 7	3.78	4.91	0.77	4.56	3.79	equal
4 to 8	0.67	5.06	0.13	4.56	4.43	equal
4 to 9	0.56	4.91	0.11	4.56	4.45	equal
4 to 10	2.67	5.25	0.51	4.56	4.05	equal
5 to 6	1.22	5.49	0.22	4.56	4.34	equal
5 to 7	0.78	4.91	0.16	4.56	4.40	equal
5 to 8	5.22	5.06	1.03	4.56	3.53	equal
5 to 9	5.11	4.91	1.04	4.56	3.52	equal
5 to 10	7.22	5.25	1.37	4.56	3.19	equal
6 to 7	0.44	5.49	0.08	4.56	4.48	equal
6 to 8	4.00	5.63	0.71	4.56	3.85	equal

6 to 9	3.89	5.49	0.71	4.56	3.85	equal
6 to 10	6.00	5.80	1.03	4.56	3.53	equal
7 to 8	4.44	5.06	0.88	4.56	3.68	equal
7 to 9	4.33	4.91	0.88	4.56	3.68	equal
7 to 10	6.44	5.25	1.23	4.56	3.33	equal
8 to 9	0.11	5.06	0.02	4.56	4.54	equal
8 to 10	2.00	5.39	0.37	4.56	4.19	equal
9 to 10	2.11	5.25	0.40	4.56	4.16	equal

Repeatability tests for test section 2 at 60 km/h (a = pass used as basis for comparison, b = pass being compared with pass a, qc = variation, Q 0.05, 120,10 = theoretical value)

a to b	Mean b– mean a	SE	qc	Q 0.05,120,10	Q–qc	Conclusion (means are)
1 to 2	3.39	5.46	0.62	4.56	3.94	equal
1 to 3	3.14	5.46	0.58	4.56	3.98	equal
1 to 4	0.63	5.30	0.12	4.56	4.44	equal
1 to 5	5.52	5.46	1.01	4.56	3.55	equal
1 to 6	13.71	5.65	2.43	4.56	2.13	equal
1 to 7	6.03	5.30	1.14	4.56	3.42	equal
1 to 8	7.57	5.65	1.34	4.56	3.22	equal
1 to 9	0.98	5.46	0.18	4.56	4.38	equal
1 to 10	10.23	5.46	1.88	4.56	2.68	equal
2 to 3	0.25	5.46	0.05	4.56	4.51	equal
2 to 4	4.03	5.30	0.76	4.56	3.80	equal
2 to 5	2.13	5.46	0.39	4.56	4.17	equal
2 to 6	17.11	5.65	3.03	4.56	1.53	equal
2 to 7	2.64	5.30	0.50	4.56	4.06	equal
2 to 8	10.96	5.65	1.94	4.56	2.62	equal
2 to 9	4.38	5.46	0.80	4.56	3.76	equal
2 to 10	13.63	5.46	2.50	4.56	2.06	equal
3 to 4	3.78	5.30	0.71	4.56	3.85	equal
3 to 5	2.38	5.46	0.44	4.56	4.12	equal
3 to 6	16.86	5.65	2.99	4.56	1.57	equal
3 to 7	2.89	5.30	0.54	4.56	4.02	equal
3 to 8	10.71	5.65	1.90	4.56	2.66	equal
3 to 9	4.13	5.46	0.76	4.56	3.80	equal
3 to 10	13.38	5.46	2.45	4.56	2.11	equal
4 to 5	6.15	5.30	1.16	4.56	3.40	equal
4 to 6	13.08	5.50	2.38	4.56	2.18	equal
4 to 7	6.67	5.14	1.30	4.56	3.26	equal
4 to 8	6.94	5.50	1.26	4.56	3.30	equal
4 to 9	0.35	5.30	0.07	4.56	4.49	equal
4 to 10	9.60	5.30	1.81	4.56	2.75	equal
5 to 6	19.23	5.65	3.41	4.56	1.15	equal
5 to 7	0.51	5.30	0.10	4.56	4.46	equal
5 to 8	13.09	5.65	2.32	4.56	2.24	equal
5 to 9	6.50	5.46	1.19	4.56	3.37	equal
5 to 10	15.75	5.46	2.89	4.56	1.67	equal
6 to 7	19.75	5.50	3.59	4.56	0.97	equal
6 to 8	6.14	5.83	1.05	4.56	3.51	equal

6 to 9	12.73	5.65	2.25	4.56	2.31	equal
6 to 10	3.48	5.65	0.62	4.56	3.94	equal
7 to 8	13.60	5.50	2.47	4.56	2.09	equal
7 to 9	7.01	5.30	1.32	4.56	3.24	equal
7 to 10	16.26	5.30	3.07	4.56	1.49	equal
8 to 9	6.59	5.65	1.17	4.56	3.39	equal
8 to 10	2.66	5.65	0.47	4.56	4.09	equal
9 to 10	9.25	5.46	1.70	4.56	2.86	equal

Repeatability tests for test section 1 at 70 km/h (a = pass used as basis for comparison, b = pass being compared with pass a, qc = variation, Q 0.05, 120,10 = theoretical value)

a to b	Mean b–mean a	SE	qc	Q 0.05,120,10	Q–qc	Conclusion (means are)
1 to 2	6.62	6.06	1.09	4.56	3.47	equal
1 to 3	3.10	6.06	0.51	4.56	4.05	equal
1 to 4	4.48	6.06	0.74	4.56	3.82	equal
1 to 5	7.67	6.06	1.27	4.56	3.29	equal
1 to 6	2.81	6.06	0.46	4.56	4.10	equal
1 to 7	2.62	6.06	0.43	4.56	4.13	equal
1 to 8	8.33	6.06	1.38	4.56	3.18	equal
1 to 9	8.67	6.06	1.43	4.56	3.13	equal
1 to 10	6.17	6.29	0.98	4.56	3.58	equal
1 to 11	8.76	6.06	1.45	4.56	3.11	equal
2 to 3	9.71	5.82	1.67	4.56	2.89	equal
2 to 4	2.14	5.82	0.37	4.56	4.19	equal
2 to 5	14.29	5.82	2.45	4.56	2.11	equal
2 to 6	9.43	5.82	1.62	4.56	2.94	equal
2 to 7	4.00	5.82	0.69	4.56	3.87	equal
2 to 8	1.71	5.82	0.29	4.56	4.27	equal
2 to 9	15.29	5.82	2.63	4.56	1.93	equal
2 to 10	0.45	6.06	0.07	4.56	4.49	equal
2 to 11	2.14	5.82	0.37	4.56	4.19	equal
3 to 4	7.57	5.82	1.30	4.56	3.26	equal
3 to 5	4.57	5.82	0.79	4.56	3.77	equal
3 to 6	0.29	5.82	0.05	4.56	4.51	equal
3 to 7	5.71	5.82	0.98	4.56	3.58	equal
3 to 8	11.43	5.82	1.96	4.56	2.60	equal
3 to 9	5.57	5.82	0.96	4.56	3.60	equal
3 to 10	9.26	6.06	1.53	4.56	3.03	equal
3 to 11	11.86	5.82	2.04	4.56	2.52	equal
4 to 5	12.14	5.82	2.09	4.56	2.47	equal
4 to 6	7.29	5.82	1.25	4.56	3.31	equal
4 to 7	1.86	5.82	0.32	4.56	4.24	equal
4 to 8	3.86	5.82	0.66	4.56	3.90	equal
4 to 9	13.14	5.82	2.26	4.56	2.30	equal
4 to 10	1.69	6.06	0.28	4.56	4.28	equal
4 to 11	4.29	5.82	0.74	4.56	3.82	equal
5 to 6	4.86	5.82	0.83	4.56	3.73	equal
5 to 7	10.29	5.82	1.77	4.56	2.79	equal
5 to 8	16.00	5.82	2.75	4.56	1.81	equal

5 to 9	1.00	5.82	0.17	4.56	4.39	equal
5 to 10	13.83	6.06	2.28	4.56	2.28	equal
5 to 11	16.43	5.82	2.82	4.56	1.74	equal
6 to 7	5.43	5.82	0.93	4.56	3.63	equal
6 to 8	11.14	5.82	1.91	4.56	2.65	equal
6 to 9	5.86	5.82	1.01	4.56	3.55	equal
6 to 10	8.98	6.06	1.48	4.56	3.08	equal
6 to 11	11.57	5.82	1.99	4.56	2.57	equal
7 to 8	5.71	5.82	0.98	4.56	3.58	equal
7 to 9	11.29	5.82	1.94	4.56	2.62	equal
7 to 10	3.55	6.06	0.59	4.56	3.97	equal
7 to 11	6.14	5.82	1.06	4.56	3.50	equal
8 to 9	17.00	5.82	2.92	4.56	1.64	equal
8 to 10	2.17	6.06	0.36	4.56	4.20	equal
8 to 11	0.43	5.82	0.07	4.56	4.49	equal
9 to 10	14.83	6.06	2.45	4.56	2.11	equal
9 to 11	17.43	5.82	2.99	4.56	1.57	equal
10 to 11	2.60	6.06	0.43	4.56	4.13	equal

Repeatability tests for test section 2 at 70 km/h (a = pass used as basis for comparison, b = pass being compared with pass a, qc = variation, Q 0.05, 120,10 = theoretical value)

a to b	Mean b–mean a	SE	qc	Q 0.05,120,10	Q–qc	Conclusion (means are)
1 to 2	3.14	6.95	0.45	4.56	4.11	equal
1 to 3	11.51	7.61	1.51	4.56	3.05	equal
1 to 4	8.71	6.95	1.25	4.56	3.31	equal
1 to 5	5.14	6.95	0.74	4.56	3.82	equal
1 to 6	0.43	6.95	0.06	4.56	4.50	equal
1 to 7	2.62	7.23	0.36	4.56	4.20	equal
1 to 8	0.86	6.95	0.12	4.56	4.44	equal
1 to 9	9.38	7.23	1.30	4.56	3.26	equal
1 to 10	4.00	6.95	0.58	4.56	3.98	equal
1 to 11	1.62	7.23	0.22	4.56	4.34	equal
2 to 3	8.37	7.61	1.10	4.56	3.46	equal
2 to 4	5.57	6.95	0.80	4.56	3.76	equal
2 to 5	8.29	6.95	1.19	4.56	3.37	equal
2 to 6	2.71	6.95	0.39	4.56	4.17	equal
2 to 7	5.76	7.23	0.80	4.56	3.76	equal
2 to 8	4.00	6.95	0.58	4.56	3.98	equal
2 to 9	6.24	7.23	0.86	4.56	3.70	equal
2 to 10	7.14	6.95	1.03	4.56	3.53	equal
2 to 11	4.76	7.23	0.66	4.56	3.90	equal
3 to 4	2.80	7.61	0.37	4.56	4.19	equal
3 to 5	16.66	7.61	2.19	4.56	2.37	equal
3 to 6	11.09	7.61	1.46	4.56	3.10	equal
3 to 7	14.13	7.87	1.80	4.56	2.76	equal
3 to 8	12.37	7.61	1.63	4.56	2.93	equal
3 to 9	2.13	7.87	0.27	4.56	4.29	equal
3 to 10	15.51	7.61	2.04	4.56	2.52	equal
3 to 11	13.13	7.87	1.67	4.56	2.89	equal
4 to 5	13.86	6.95	1.99	4.56	2.57	equal
4 to 6	8.29	6.95	1.19	4.56	3.37	equal
4 to 7	11.33	7.23	1.57	4.56	2.99	equal
4 to 8	9.57	6.95	1.38	4.56	3.18	equal
4 to 9	0.67	7.23	0.09	4.56	4.47	equal
4 to 10	12.71	6.95	1.83	4.56	2.73	equal
4 to 11	10.33	7.23	1.43	4.56	3.13	equal
5 to 6	5.57	6.95	0.80	4.56	3.76	equal
5 to 7	2.52	7.23	0.35	4.56	4.21	equal
5 to 8	4.29	6.95	0.62	4.56	3.94	equal

5 to 9	14.52	7.23	2.01	4.56	2.55	equal
5 to 10	1.14	6.95	0.16	4.56	4.40	equal
5 to 11	3.52	7.23	0.49	4.56	4.07	equal
6 to 7	3.05	7.23	0.42	4.56	4.14	equal
6 to 8	1.29	6.95	0.19	4.56	4.37	equal
6 to 9	8.95	7.23	1.24	4.56	3.32	equal
6 to 10	4.43	6.95	0.64	4.56	3.92	equal
6 to 11	2.05	7.23	0.28	4.56	4.28	equal
7 to 8	1.76	7.23	0.24	4.56	4.32	equal
7 to 9	12.00	7.50	1.60	4.56	2.96	equal
7 to 10	1.38	7.23	0.19	4.56	4.37	equal
7 to 11	1.00	7.50	0.13	4.56	4.43	equal
8 to 9	10.24	7.23	1.42	4.56	3.14	equal
8 to 10	3.14	6.95	0.45	4.56	4.11	equal
8 to 11	0.76	7.23	0.11	4.56	4.45	equal
9 to 10	13.38	7.23	1.85	4.56	2.71	equal
9 to 11	11.00	7.50	1.47	4.56	3.09	equal
10 to 11	2.38	7.23	0.33	4.56	4.23	equal

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