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[1]A Proposed Framework for Optimized Road Maintenance

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Abstract

Highway agencies are faced with managing the deterioration of road infrastructure assets. This paper presents a road maintenance framework that can be used to assist highway agencies optimize road maintenance expenditures based on the integration of state of the art road engineering science and the sound principles of road asset management. This type of integrated approach will enable highway agencies better meet the specific needs of the agency and the users of the road infrastructure.

1.0 Background

The road infrastructure is a depreciating asset with its remaining service life (i.e. value) written off over time as it deteriorates. However, the value of the road infrastructure may increase if maintenance and rehabilitation is performed to improve the level of service and/or extend the service life of the road. It is the responsibility of highway agencies to determine optimal road maintenance strategies that will provide the maximum value in terms of reduced life cycle maintenance costs and/or improved service to the road users.

Recent years of shrinking highway budgets has made it increasingly difficult for highway agencies to manage the road infrastructure in an optimized manner. Therefore, a management framework that can accurately quantify costs and benefits associated with alternative road maintenance and rehabilitation strategies and identify to whom the costs and benefits accrue, is an essential tool for modern highway agencies.

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2.0 Define Agency Maintenance Goals and Objectives

The first step to optimize road infrastructure investments is defining clear goals and objectives for maintaining the road infrastructure. Well defined agency goals and objectives provide two things: 1) direction for road maintenance efforts and, 2) the means for which to measure the success or failure of maintenance expenditures. Recent years of shrinking highway budgets has resulted in agency objectives that focus on minimized short term agency costs. Although minimizing short term costs reflect well in deficit reduction efforts, they often result in stop gap maintenance which ultimately increases future maintenance expenditures. Because the road infrastructure is a long term asset, road maintenance goals and objectives should consider the life cycle of the road, thereby minimizing the bias of short term benefits associated with stop gap maintenance strategies.

3.0 Road Performance Models

In order to optimize the design and preservation of roads, road asset management must include road performance models that explicitly account for road type, road condition, traffic, environment, climate, and alternative maintenance treatments. The term "model" refers to a set of information or mathematical relationships that represent some physical aspect of the real world. In the context of road performance, models provide a measure of effectiveness of different maintenance treatments in terms of future road condition.

Road performance prediction models require: 1) definition of critical road performance measures, 2) identification of the variables that determine road performance and, 3) determination of the functional relationships between the critical variables and road performance. There are essentially two approaches that can be employed to predict road performance: an empirical-phenomenological modeling approach, or a mechanistic modeling approach (1).

3.1 Empirical-Phenomenological Road Performance Modeling

In the past, road engineers have relied primarily on empirical-phenomenological road performance models. Figure 1 illustrates the general empirical-phenomenological road performance modeling framework.

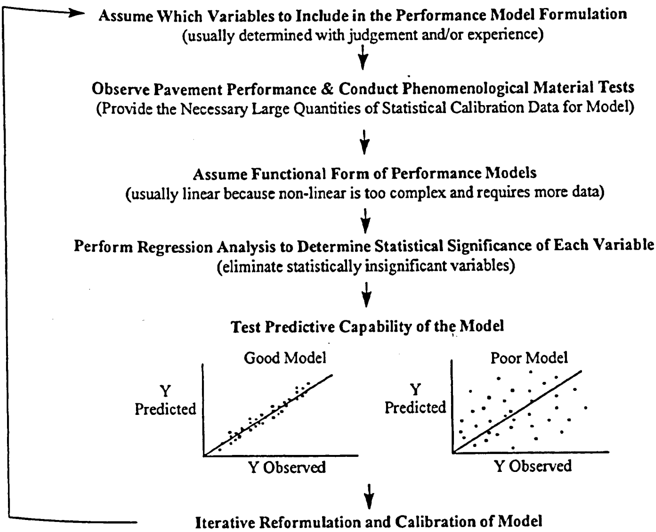

Fig 1 Empirical-Phenomenological Road Performance Modeling

As can be seen in Figure 1, empirical road performance models are heavily reliant on judgment and/or past experience for model formulation and identification of performance variables. As a result, empirical road performance models are limited in their applications and dependability because empirical models offer no sound scientific basis from which the functional form and variables of the performance prediction relationships may be determined (2,3).

3.2 Mechanistic Road Performance Modeling

Road performance is directly related to the mechanical response of the road structure (4). As a result, recent road performance modeling efforts have focused on employing mechanics and materials science to identify the important performance variables and formulate the constitutive behavior of roads based on the natural thermomechanical laws of science. The benefits associated with mechanistic road performance modeling include the following:

- fundamental principles of thermomechanics are universal and facilitate a multidisciplinary approach to modeling complex road behavior;
- thermomechanical laws provide a stable platform for continuous

improvements over time without discarding previous modeling efforts;

- mechanistic road performance modeling provides a direct mapping to road distress predictions based on thermomechanical behavior therefore reducing expensive model calibration and validation;
- thermomechanical material testing is independent of the test apparatus, test procedure, or test condition, and replace phenomenological "test-dependent" material characterization methods that are not sufficient to predict road performance (5) and standardizes all road material testing for research, design, quality control/quality assurance, and forensic analysis purposes;
- mechanistic based road performance models employ the same modeling framework for all road types, under any traffic or environmental conditions.

A general framework for mechanistic based road performance modeling is illustrated in Figure 2.

Define Critical Measures of the Road Performance
(fatigue cracking, rutting, thermal cracking, asphalt mix disintegration, etc.)

↓

Formulate Road Response Model Based on Applied Thermomechanics
$\sigma_{ij} = \sigma_{ij}$ {traffic, environment, site conditions, material properties}
$\varepsilon_{ij} = \varepsilon_{ij}$ {σ_{ij}, material properties}

↓

Formulate Road Performance Models Based on Applied Thermomechanics
distresses = distresses {σ_{ij} ε_{ij}, material properties}

↓

Characterize Thermomechanical Constitutive Behavior of Road Materials
(thermomechanics, fracture mechanics, micromechanics, viscoelasticity)

↓

Predict Road Response & Performance

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Compare Road Performance Predictions with Observed Performance

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Integrate Mechanistic Performance Prediction Methodology Into Agency Operations and Asset Management Systems
(PMS, MMS, design, quality control, quality assurance, research, forensics, etc)

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Optimize Road Infrastructure Investments

Fig 2 Mechanistic Road Performance Modeling Framework

As can be seen in Figure 2, mechanistic road performance modeling incorporates fundamental thermomechanical material characterization, a mechanistic road response model, and a distress prediction model based on the primary response of the road structure. As a result, mechanistic based road performance modeling requires a thorough understanding of engineering thermomechanics as applied to material constitutive characterization. Once adopted, mechanics can form the foundation for all agency operations, including: 1) end-product, performance and ultimately warranty based specifications, 2) quality control/quality assurance testing, 3) road materials selection and allocation, 4) road material job specifications, 5) mix design and structural design, and 6) research and forensic investigations (6). Therefore, mechanics is the foundation highway agencies can employ to optimize agency operations and the taxpayer's investment in the road infrastructure.

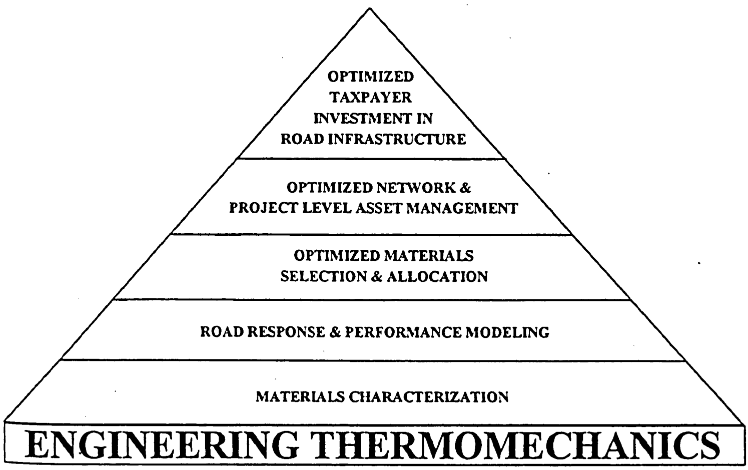

Fig 3 Thermomechanics Foundation for Road Asset Management

3.3 Probabilistic Road Performance Models

Road performance and the variables that affect road performance are inherently stochastic. Probabilistic modeling frameworks offer the advantage of accounting for the inherent variability of individual performance variables. Figure 4 illustrates a deterministic and probabilistic road distress predictions.

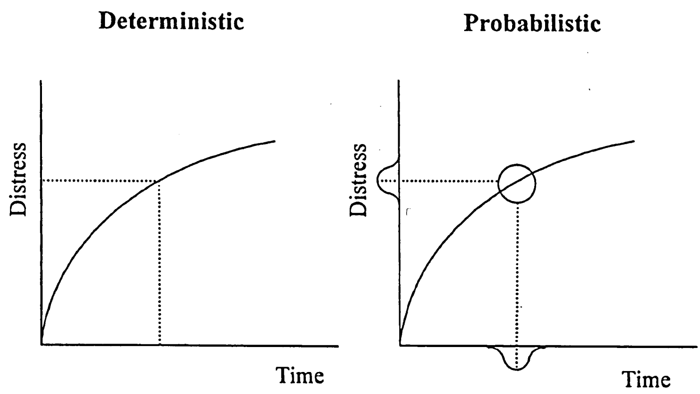

Fig 4 Deterministic vs. Probabilistic Performance Predictions

As can be seen in Figure 4, a deterministic performance models yields one value of performance for a given single value input. A probabilistic model employs distributions of input which is more representative of what is actually known. Therefore probabilistic models yield a distribution of possible performance outcomes. By formulating the inherent variability of the parameters that influence road performance, maintenance managers can quantify the impact variability will have on the road performance predictions. This assists in concentrating data collection efforts on the parameters with high variability in an attempt to reduce random and systematic errors of the performance predictions.

4.0 Road Asset Information

To optimize road infrastructure maintenance, highway agencies must have reliable up-to-date information regarding the inventory and condition of road infrastructure assets in order to establish needs based maintenance budgets. Because road condition information is time sensitive and expensive to collect, road condition data can be detrimental unless it is collected at the right place, at the right time, and used effectively within a road maintenance optimization framework. Too much data can "bog down" the maintenance optimization process and obscure the important and relevant issues of maintaining the road infrastructure. Therefore, more road condition data does not necessarily mean improved maintenance decisions. Therefore, road asset data collection should only be performed if the information corresponds to the current thresholds of maintenance decisions as dictated by the needs of the road asset management decision process.

Quality road infrastructure information should contain the following:

- be well defined and only collected if the maintenance management framework can employ the data in the decision process;
- be collected in stages to the level of detail and accuracy required by the management decision process;
- be fully auditable;
- be efficiently collected and compiled into a format that can directly support management decisions;
- be cost justified (i.e. maintenance savings that result from changed decisions as a result of the data collected should be greater than the cost of collecting and compiling the data);
- be collected at the correct time taking into account seasonal variations in the road infrastructure, lead time required to collect, process and analyze the data.

Road maintenance managers must implement effective data collection that meets the needs of the maintenance management decision framework. This requires maintenance managers to be aware of the costs, accuracies, and limitations of alternative data collection sources and technologies.

Data Management Systems

Given that road infrastructure condition data needed for scheduling road maintenance is relatively volatile, up to date information must be provided to the asset management decision framework to prevent maintenance strategies that are based on outdated information. Therefore efficient data management systems are commonly employed by highway agencies to assist in efficient road infrastructure asset management decisions. Geographic Information Systems (GIS's) are commonly used to store, compile, and analyze the vast amounts of spatial and non-spatial information typically required by highway agencies. The ability to efficiently update, summarize, and present road infrastructure data makes the GIS an extremely powerful analysis and communications custodial tool for information regarding the highway infrastructure.

Agency Construction and Maintenance Records
Highway agencies often have readily available historic information regarding the original construction and maintenance of road segments (i.e. as built drawings, materials testing, etc.). Maintenance records can provide valuable "first hand expert" information that can be readily used in the maintenance decision process with several benefits:

- road maintenance personnel understand road maintenance activities and are in direct contact with the road network;
- training of road maintenance personnel to identify road distresses would be relatively easy because of their expertise and background;
- experienced road maintenance personnel can provide explanations of road deterioration mechanisms occurring in specific locations;
- involving road maintenance personnel directly in the maintenance planning and management framework promotes a Total Quality Management orientated approach to optimized road maintenance.

To utilize road maintenance crews for road condition assessments, maintenance crews must have an efficient method for recording and downloading data without interfering with routine maintenance duties. Hand held electronic data loggers and GPS location referencing devices (7) can spatially reference and directly download information efficiently into a central GIS database.

Road User Complaints and Accident Records
Because most roads are publicly funded roads, the level of service being provided by the road infrastructure should be considered in the maintenance planning framework. Therefore, road user complaints and accident reports can be a valuable source of feedback regarding the public's perception of the level of service being provided by the agency.

Road Condition Surveys
Road condition surveys are performed to determine the approximate condition and rate of deterioration of the road infrastructure. Network level condition surveys are usually performed at regular intervals (i.e. every 1 to 3 years) depending on the age of the road, and the maintenance operations pending, to provide a cursory differentiation between road segments that require maintenance and the probable type of maintenance required. Previous research (8) determined the percentage of the road surface to be surveyed at the network level as a function of the intended use for the data.

- 3% to determine the general overall condition of the network;

- 10% to determine the general condition within one category of a particular asset;
- 30% for maintenance planning purposes.

Project level data collection is usually only performed on the road segments that: 1) have been identified in the network level survey and post maintenance analysis as being in need of maintenance in the very near term (either preventative or corrective maintenance) and 2) if the optimal maintenance to be performed on individual road segment is debatable and additional information is required to support the maintenance decision. Project level data collection often involves detailed walking inspections of the road and surrounding conditions (i.e. distress surveys, drainage, etc.) and may also employ structural assessment with ground penetrating radar, deflection measurements, or coring to obtain additional road structural information to support road maintenance planning decisions.

Recent advances in semi-automated data collection systems and technologies offer the road maintenance managers with the advantage of collecting road information at high speeds with semi-automated data compiling and downloading to a GIS system. Semi-automated data collection vehicles typically employ non-contact measurement devices such as lasers and ultrasonic sensors to simultaneously collect a wide range of pavement measurements including: transverse profile, rut depths, longitudinal roughness, surface texture, concrete pavement faulting, crack identification, etc. Video and film logging of the right of way and pavement surfaces has been widely used to provide pavement and road side appurtenance condition. Video logs may be integrated directly into storage systems for direct retrieval from the data base and as digital storage capacities are improved, entire video logs may be able to be stored directly into a GIS data base. Complimentary post processing systems are also being refined to provide on screen surveying for inventory data collection or automated distress identification and evaluation directly from the video logs. To accurately reference semi-automated data collection, spatial referencing is usually collected with the condition data. Global positioning systems (GPS) employ the theory of triangulation off high altitude orbiting satellites to provide absolute coordinate locations in global 2-D or 3-D space. Typical GPS accuracies from standard global positioning are typically ±30 to 100m lat.-long and ±50 to 200m elevation with respect to the absolute surface grid of the earth. If a fixed base station is used to differentially correct the GPS readings, positioning accuracy can reach sub meter. To compliment GPS, aircraft grade orientation systems employing aircraft grade accelerometers and gyroscopes may also be employed for improved road measurement and road surveying accuracy.

Structural Integrity

The structural integrity of the road structure is a critical input to road performance modeling. Road structural information can be obtained from coring, ground penetrating radar and deflection measurements. Ground penetrating radar may be used to provide high speed pre-surveillance for deflection measurements and coring by identifying potential weak spots in the road structure that require investigation.

Traffic Data Collection

In the past, traffic data has been collected in terms of equivalent standard axle loads (ESAL's). However, the ESAL is based on overall serviceability index. Mechanistic road performance models that predict the propagation of specific distresses require accurate traffic data collection in terms of specific vehicle types and axle weights because different distresses influence various levels of traffic, therefore, each distress has its own mechanistic based equivalency. The type of equipment used to collect traffic information will depend on the type of road, type of traffic, and the intended use for the data. The four most common weigh in motion technologies and their respective weighing accuracies may be summarized as follows (9):

- piezoelectric sensors: ±15%
- capacitance sensors: ±15%
- bending strain WIM scales: ±10%
- load cell WIM scales: ±5%

Climate and Environmental Data Collection

Climatic and environmental conditions can significantly effect the load carrying capacity and distress propagation of road structures. Because many maintenance treatments are performed to repair or mitigate against environmental damage, climate monitoring is essential to accurately predict the performance of road structures.

5.0 Maintenance Prioritization and Optimization

Road maintenance may be categorized into three distinct groups:

- preventative maintenance: maintenance performed to slow the rate of deterioration before it occurs;

- repair and rehabilitation: maintenance that corrects road deterioration after it has occurred;
- reconstruction: replaces a severely deteriorated road with a new road.

Prioritization of road maintenance refers to the identification and ranking of viable maintenance projects identified at the facility/network level. Prioritization is often used as an initial cut at identifying viable maintenance projects across the network. Road maintenance optimization refers to the decision processes used to identify optimal life cycle maintenance treatment strategies across a selected number of viable projects. The objective of road maintenance optimization analysis is to identify the optimal combination of the following:

- candidate road segments to receive maintenance treatments;
- maintenance treatments to be performed;
- timing of maintenance treatments.

Several optimization techniques have been employed in the road industry (10), linear and nonlinear programming, integer programming, survivor curves, and the Markovian and semi-Markovian optimization techniques. Of these optimization techniques, the Markovian and semi-Markovian optimization methods explicitly recognize the probabilistic nature of road infrastructure deterioration. The Markovian optimization framework establishes a road condition transition matrix to predict the future condition of the road at set intervals (usually 1 year). The Markovian transition matrix assigns a probability to road condition transitions that may occur from time period to time period. As a result, road structures may have several possible condition states, several possible condition transition paths, and several corresponding transition probabilities as a function of climate, traffic, maintenance treatments, etc.

The semi-Markov optimization approach employs the same probabilistic transition theory as the Markovian approach, however, the holding time between condition states is the dependent variable, and the transition probability is applied to the condition holding time (11). If the sequence of consecutive condition states over the life cycle of a road can be predicted, the semi-Markov formulation method only requires one node (expected transition time and time probability distribution per transition). The semi-Markov optimization methodology offers several advantages over the Markovian framework including: reduced computational dimensionally of any life cycle maintenance analysis; logical and convenient formulation framework for planning road maintenance;

definable condition states with time as the dependent variable which better correlates with road maintenance activities; and maintenance activity trigger points can be directly integrated into the analysis framework based on the maintenance manager's logic for planning road maintenance.

6.0 Life Cycle Cost Analysis

Once the optimal maintenance strategies have been identified, road agency and user costs and benefits associated with each maintenance strategy should be calculated and compared in terms of equivalent uniform annual costs and benefits at a given discount rate over different analysis time frames. There is an increasing need for road user costs and benefits to be incorporated into road asset management due to the increase in partnering relationships between highway agencies and the transportation sector. The intent of these partnering relationships is to facilitate increased transportation efficiency through larger and heavier truck configurations while still protecting the road infrastructure. As a result, road user cost models must be employed so as to accurately quantify the costs and benefits of such partnering agreements and to determine to whom the costs and benefits will accrue.

7.0 Feedback and Model Calibration

Once the road maintenance optimization analysis has identified and implemented the optimal maintenance strategy, the specific maintenance treatments and their respective performance should be monitored as part of the routine data collection process and entered into the historic road maintenance data base on a segment by segment basis. The performance information obtained from each road segment can be used to calibrate and update the road performance models and the maintenance condition transition matrices, thereby improving future road maintenance decisions.

8.0 Summary and Conclusions

In Canada, it is estimated that almost half of the pavements are below a minimal level of acceptable service, requiring approximately $11 billion to bring the road infrastructure up to an acceptable standard (12). To do this, highway agencies must adopt modern scientific methods and management techniques for the design, preservation, and management of roads. The procedures outlined herein outline an integrated approach of fundamental road engineering science and sound road management principles that will assist highway agencies optimize road design and preservation strategies to better meet future road infrastructure performance objectives.

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