Decision Support Modules in the MTO Second Generation Pavement Management System

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Paper prepared for presentation at the
Technology Advancements in the Design and Construction of Intelligent Pavements
Session of the 2002 Annual Conference of the
Transportation Association of Canada
September 15-18, 2002
Winnipeg, Manitoba
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ABSTRACT

Managing Ontario’s highway network is a complex task, due to the size of the province, different climatic zones, highway classes and pavement types. The development of the 2nd generation Pavement Management System (PMS/2) for the Ministry of Transportation of Ontario (MTO) was aimed at enhancing the Ministry’s pavement management process in the areas of the data management and network level analysis, the latter was based on the development of the Decision Support Subsystem (DSS).

In the process of developing and implementing the existing mainframe based PMS, the Ministry has acquired a large amount of experiences in terms of data acquisition, pavement performance index modeling, pavement rehabilitation and engineering decision support models, etc. This paper provides highlights of how these experiences were encompassed in developing the second generation PMS. The paper will also present the main modules in the system in order to facilitate description of the challenges and the approach used in the development of the decision support elements, and how these elements are implemented in PMS/2.

Key Words: Pavement Management Systems, network level decision support, pavement performance study, decision trees.

BACKGROUND

The Ministry of Transportation of Ontario (MTO) is in charge of building and maintaining the provincial transportation system that includes a network of approximately 18 thousand km of highways. This mandate requires monitoring the physical condition of pavements on these highways and addressing both the near term (1-5 years) and the long term (5-10 years) management objectives within certain funding limits.

The existing Pavement Management System (PMS) used at the Ministry was developed in 1985 and was implemented successfully concerning the requirements at the time. The major components of the system included a mainframe based database maintained by the pavement management section at the headquarter and a rehabilitation selection and priority ranking process applied at the Regional level offices. The selection of proposed rehabilitation treatments and the condition based priority rankings were carried out by the Program Management Branch in MTO and were followed by the development of the annual capital funding programs. The process was supported by a number of other existing systems, procedures, guidelines and manuals established by the Ministry.

After some 13 years’ application in the province, a number of weaknesses of the existing PMS were observed by the practitioners, which included the database structure deficiencies and
inadequate network level analysis functions. In 1998 MTO decided to develop a second generation PMS in order to facilitate data management tasks and to enhance the analytical components that are related to determining the network level funding needs and project priorities. The project was named the 2nd Generation Pavement Management System, and referred to as PMS/2 in this paper.

Stantec Consulting Ltd. was awarded the contract for the project development. The tasks specified by the contract include (a) reviewing the Ministry’s existing pavement management process, (b) designing and developing the new pavement management process, (c) integrating the new PMS with the Ministry’s corporate information management system, and (d) participate in the implementation of the new system. A project plan was developed to customize Stantec’s Highway Pavement Management Application (HPMA) software package based on these requirements. The project development was guided by the PMS Steering Committee that represents the stakeholders in the Ministry.

REVIEWING THE EXISTING PAVEMENT MANAGEMENT SYSTEM AND PRACTICE

The first phase of the project was to review the existing pavement management system and practices in the Ministry. This review was to ensure understanding of the Ministry’s business needs and the pavement management processes that involve different user groups. The review also provided the basis of improvement recommendations for developing the new system, as described later in the paper.

The existing PMS has the following components: pavement data inventory, pavement condition analysis, maintenance and rehabilitation treatment selection, budgeting and work programming. The MTO pavement management activities are carried out primarily at two levels: the head office level (the Pavement Management Unit in Toronto) and the regional level (Geotechnical offices in the five regional branches).

Pavement Data Inventory

Since the establishment of the first generation PMS, the network pavement condition has been continuously monitored by MTO. The pavement management database maintains the historical pavement condition data from the mid ‘80s to the current year. Pavement condition is measured in terms of roughness, rutting, surface distresses, friction and deflection. The roughness survey is contracted to consulting firms at the head office level, and rutting measurements are carried out by the Ministry staff using the Automatic Road ANalyzer (ARAN). Surface distress assessment is done at the regional level by specially trained Pavement Design and Evaluation Officers (PDEOs). Friction and deflection tests are not performed on a routine basis, and are not stored in the pavement management database.

Prior to 1996, pavement roughness was measured in two-year cycles using an accelerometer-based response type roughness measuring equipment, the Portable Universal Roughness Device (PURD). The output of the PURD was in terms of root mean square vertical acceleration (RMSVA), which was summarized for each pavement section. Due to concerns about data quality and the network analysis needs, the Ministry decided to switch to the approach of annual measurements of International Roughness Index (IRI) using profile type equipment in 1996 (1).

Surface distresses are assessed using a windshield-based method for each pavement management section. The detailed distresses are surveyed in term of distress type, severity level and extent.
level. Severity and extent ratings for each distress type are made for each pavement section as a whole. The Ministry has developed standard pavement condition rating manuals for each type of pavement (2, 3, and 4).

Due to the subjective nature of the distress survey procedure, the Ministry holds a biennial workshop to "calibrate" the field evaluators in order to keep the ratings consistent over time and across the province. In addition, the Regions develop their own quality control processes such as spot inspection (5).

Another important part of condition data is the pavement rutting data. Severe pavement rutting causes safety problems to the travelling public and makes snow removal difficult. MTO collects the rutting condition data using two methods: (a) as part of the manual distress survey, (b) measured mechanically in the annual ARAN rutting survey. The Regions may use either types of rutting data in their rehabilitation project treatment selections.

Pavement Condition Analysis

The condition of pavement in Ontario is summarized as a group of indices for certain analysis units known as pavement management sections. Over the period of implementing the first generation PMS, the Ministry developed a Riding Comfort Index (RCI), a Distress Manifestation Index (DMI) and a composite Pavement Condition Index (PCI) to evaluate pavement performance based on the measured pavement condition. These indices are described below.

Riding Comfort Index (RCI)

In the current data collection procedure, the riding quality of a pavement section is captured by an objective measurement of roughness (IRI), which through a group of correlation equations, links with the Riding Comfort Index (RCI) in a scale of 0-10, where 10 represents the highest riding quality. The relationships between IRI and RCI were developed in a recent MTO study (1). The transfer functions were formulated according to pavement types, as summarized in Table 1.

<table>
<thead>
<tr>
<th>Pavement Type</th>
<th>Transfer function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt Concrete</td>
<td>( RCI = 8.52 - 7.49 \times \log_{10} (IRI) )</td>
</tr>
<tr>
<td>Exposed Concrete</td>
<td>( RCI = 9.27 - 6.22 \times \log_{10} (IRI) )</td>
</tr>
<tr>
<td>Composite</td>
<td>( RCI = 8.48 - 3.81 \times \log_{10} (IRI) )</td>
</tr>
<tr>
<td>Surface Treatment</td>
<td>( RCI = 15.7 e^{-0.307 (IRI)} )</td>
</tr>
</tbody>
</table>

A subjective Riding Condition Rating, called RCR, is also evaluated by PDEOs in the Regions. Both RCI and RCR have the range of 0 -10, with the score 10 representing a new or very smooth pavement. RCR is obtained subjectively by driving over the pavement section. It is used when RCI is not available, may not be delivered in time, or the quality of RCI value is in doubt. Therefore, RCR is both a supplement and a reality check on RCI.

Distress Manifestation Index (DMI)
DMI is calculated from detailed distresses that are collected for individual pavement management sections. The calculation is based on the distress type, the evaluated severity and extent levels and a set of predetermined weighting factors. Following is the DMI function:

\[
DMI = \sum_{i=1}^{n} W_i (s_i + d_i),
\]

where:
- \(i\) = distress type
- \(n\) = number of distresses
- \(W_i\) = weighting factor of the \(i\)th distress (0.5 - 3.0)
- \(s_i\) = severity of the \(i\)th distress on a 5-point scale (0.5 - 4.0)
- \(d_i\) = density of the \(i\)th distress on a 5-point scale (0.5 - 4.0)

It should be noted that the above DMI procedure was developed only for the pavements with asphalt concrete (AC), the development of DMI for other pavement types was included in the PMS/2 project, as subsequently described.

**Pavement Condition Index (PCI)**

The PCI of a pavement management section is calculated based on RCI and DMI, and is used as an overall performance indicator for the section. The PCI scale is 0-100, with scores 95-100 representing new pavement conditions. The following formula shows the PCI as a function of RCI and DMI:

\[
PCI = 100 \times (0.1 RCI) \times \frac{205 - DMI}{205} \times c
\]

where: \(c\) is a constant, for which 1.077 was used prior to development of PMS/2.

A subjective pavement condition rating (PCR) is also carried out in the field. Since PCR has the same range as PCI (0-100), it has been used by the Regions as a supplement to and a check on the PCI. As PCI is available only for AC pavements, PCR has been used in lieu of PCI for pavement management decisions on PCC, composite and surface treatment pavements.

**Maintenance and Rehabilitation Treatment Selection**

Selection of appropriate maintenance and rehabilitation strategies is a key step in the pavement management process. It requires the knowledge of the pavement condition and experience in knowing what treatments are most effective in correcting deficiencies.

The current method requires the selection of 3 types of alternative maintenance and rehabilitation strategies: the Preferred, Holding and Deferred strategies. These strategies may include one or more treatment alternatives. A preferred strategy is considered the most cost-effective solution to the pavement problem, which could range from a major maintenance treatment, to a rehabilitation treatment or reconstruction. The following factors are considered when selecting treatment alternatives for preferred strategies:
Present pavement condition in terms of the riding quality and predominant distresses.

Projected deterioration of the pavement condition, specifically the estimated change of PCI for the next 3 years.

Threshold PCI levels of the functional classes as given by the Ministry's guideline (6).

Maintenance and rehabilitation policies and guidelines.

Availability of materials and construction resources, and

Knowledge of local conditions in terms of traffic, pavement structure and past performance.

When the preferred strategy is a rehabilitation treatment, two fall-back strategies are also prepared: the Holding and Deferred strategies. These strategies are prepared for the cases in which the preferred strategy can not be implemented at the needs year due to funding limitations, or if there are other reasons that the project must be postponed, such as co-ordination with other needs or projects.

The holding strategy is applied if the delay is within 3 years. It normally consists of a major maintenance treatment followed by a rehabilitation treatment as in the original preferred strategy.

Deferred strategies are used when the anticipated delay is more than 3 years. It is assumed that no maintenance or rehabilitation activities will take place during the period other than those of the routine maintenance. This may result in a different treatment at a later time. Such a delayed treatment is usually more expensive than the original preferred treatment, since it must address the additional problems caused by the delay.

The preferred/holding/deferred strategies are initially selected by personnel conducting distress surveys according to a guideline for selecting treatments and preparing the strategies developed by the Ministry. The results are reviewed and verified by senior regional Geotechnical staff. The information is recorded on a standard report called the Pavement Action Plan Fact Sheets. The preferred/holding/deferred strategies are developed for a 5-year period, and the strategies are updated each time the sections are evaluated.

The current process of rehabilitation treatment selection is primarily experience based. The resulting treatment selection represents the preference of the individual(s) who make the decision. A weakness of this approach is the lack of a systematic evaluation of the alternate treatment strategies based on the cost-effectiveness analysis.

**Budgeting and Work Programming**

The process of budgeting and work programming is initiated at the regional level, compiled at the Program Management Branch and returned to the Regions for work programming. Although it varies from Region to Region, the common steps followed at the regional level include:

- Identify the needs projects based on the performance data on the Action Plan Fact Sheets and on inputs received from the Districts.

- The regional Program Development Officer (or the Scheduling Officer in some Regions) compiles the needs lists of pavement, structure and safety projects into a yearly budget requirement list and sends it to the Program Management Branch in the Head Office.
Program Management Branch will evaluate the regional budget requirement against the available resources and feedback in the format of the regional funding envelopes.

- Development of the prioritized project listings for the preservation management fund and for the capital fund, respectively.
- Combine the individual priority lists into a regional priority list for the 1-5 year period. This step is important, since it is used to make sure that there are no conflicts between the rehabilitation projects in different funding groups and between pavement and non-pavement construction projects.
- Generate a feasible work program that includes yearly listing of the construction projects for the next 5 years. The major factors considered in the task are the priority ranking, geographical location, deliverability and the yearly funding constraints.

A problem faced by decision makers is the lack of a systematic tool to generate work program based on evaluating cost-effectiveness at the network level. In addition, when the funding levels change during the programming period, it is a challenge for the Regions to produce alternate work programs in responding to such changes. In connection to this, senior management needs to understand the impact of funding level changes in a timely fashion. The existing system lacks tools to perform such analysis.

**RECOMMENDED IMPROVEMENTS TO THE DECISION SUPPORT MODULES**

Based on the findings from reviewing the existing PMS and from the interviews with various user groups at the both head office and the regional levels, an enhancement recommendation report was developed, which covered such areas as data collection, data analysis, and additional system functions that were missing in the first generation PMS. The new decision support components and modules recommended for the second generation PMS include:

- Updated pavement condition evaluation indices.
- Standard pavement maintenance and rehabilitation treatment list.
- Pavement performance prediction models
- Maintenance and rehabilitation alternative decision trees.
- Project prioritization module based on optimization analysis.
- Engineering feedback module.

A main task in the second phase of the project was to customize these components and modules to suit the needs of MTO. In addition to the knowledge gained in the first phase the consulting firm teamed up with the Ministry experts to work on the major issues relating to the decision support modules. The following sections describe how these components were developed.

**Enhanced Database for PMS/2**

One of the key features of PMS/2 is the structure of its relational database. The foundation of the database is formed by a number of detailed highway data tables. The detailed highway tables provide highway data, segmented as appropriate for the individual data type. The historical pavement condition data, the as-built pavement structural data and other attribute data exist at this detailed level. For the purposes of querying and analysis, the detailed data are extracted as data
views on a common sectioning basis. The system allows the provision of using predefined section limits, section limits defined based on the sectioning criteria specified by the user (a routine known as the dynamic sectioning), or a mix of the two.

Customizing the HPMA database to meet the Ministry’s requirements in data management and integration with the MTO corporate Integrated Highway Information System (IHIS). This task required a two-way interface to retrieve the data from IHIS for use in the PMS analysis and to feed the analysis results back to IHIS.

While IHIS will provide the majority of the data needed by the new PMS software in terms of highway attributes and summarized pavement section performance data, there are certain areas that have been identified as requiring additional detailed data. These areas include the following:

- Roughness and rut measurement (multiple measurements within a pavement section, stored on a historical basis)
- Distress (field evaluation within a pavement section, stored on a historical basis)
- Deflection (multiple measurements within a pavement section, stored on a historical basis)
- Construction History (project based activity and layer information)

After reviewing the options with the MTO steering committee, a decision was made to use the detailed highway database as a common platform for organizing the field data and the data transition between the PMS and IHIS. As shown in Figure 1, the detailed highway database receives the pavement condition data from the field and the highway attribute data from IHIS. The detailed condition and attribute data is then made available for PMS sectional data views. PMS will receive the pavement section definition information from IHIS and feed back the results of the analysis on the network needs, rehabilitation treatment and optimization to IHIS (in terms of the deficient sections and the proposed deficiency correction strategies).

Figure 1  PMS/2 Integration with IHIS
Modifying Pavement Performance Indices

The pavement condition data exist in two formats: (1) detailed data from measurement or field evaluation, such as IRI, rutting, and pavement distresses; and (2) pavement performance indices that are calculated from the detailed data. The pavement performance indices include two component indices RCI and DMI for describing the riding quality and surface distress status, respectively, and the overall pavement condition index PCI.

Based on decisions made during the first phase of the project, the following tasks were carried out to modify these indices:

- The DMI is calculated based on aggregation of the individual distress severity and extent levels with pre-assigned weighting factors. After careful reviews with the Ministry's project working group, the existing weighting factors for the AC pavement type were adjusted. For example, surface deformation receives higher weights than the centerline cracking. The new weighting factors are considered able to better reflect the significance of the distresses.

- Similar development of the distress weighting factors was carried out to other pavement types, including the Portland cement concrete (PC) pavement, composite (CO) pavement and surface treatment (ST) pavement. The resulting DMI's lead to the development of new pavement condition indices (PCI) for the associated pavement types.

- The DMI calculated using weighting factors can not be used in PMS/2 directly, since the index is in a reversed scale when compared with RCI and PCI -- the higher the DMI score, the worse the pavement condition. In addition, the total DMI score can get higher than 100, making it difficult to present along with other indices in the summary and graphic reports. As a result, the index was modified to the 0-10 scale, with 10 represents the new condition, same as the RCI scale.

These developments were accomplished with panel discussions, working group meetings and trial analysis. Since the working group involved both the head office and regional engineers, the results were well received.

Establishing Standard Rehabilitation Treatment List

In PMS/2 the condition of pavement sections are summarized in terms of the current or most recent performance indices. To evaluate future pavement conditions PMS/2 needs to have the capability of predicting the change of performance index values against the pavement age. For the purposes of the developing these performance prediction models and for developing the network level work programs, a standard rehabilitation treatment list has to be established.

The working panel was involved in reviewing the treatment activities commonly used by MTO in the past pavement rehabilitation programs. In the history different rehabilitation treatments were used by the Regions. Some treatment alternatives were similar in nature, but the way these treatments were used and referred to varied in different regions and at different times. These treatments were standardized and summarized for different pavement types. The result is shown in Table 2. In addition, expert opinions were solicited with regard to the typical treatment life and the after-treatment performance indices. This information provides valuable inputs for developing the performance prediction models.
Table 2  Summary of Rehabilitation Treatments for Different Pavement Types

<table>
<thead>
<tr>
<th>Rehabilitation Treatment</th>
<th>Life Span</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flexible Pavements</strong></td>
<td></td>
</tr>
<tr>
<td>1 Lift HM Overlay</td>
<td>5 – 9</td>
</tr>
<tr>
<td>Mill and 1 Lift HM Overlay</td>
<td>7 – 10</td>
</tr>
<tr>
<td>2 Lift HM Overlay</td>
<td>8 – 12</td>
</tr>
<tr>
<td>Mill and 2 Lift HM Overlay</td>
<td>10 – 15</td>
</tr>
<tr>
<td>Mill and 3 Lift HM Overlay</td>
<td>10 – 15</td>
</tr>
<tr>
<td>Reclamation, 1 Lift HM Overlay</td>
<td>7 – 10</td>
</tr>
<tr>
<td>Reclamation, 2 Lift HM Overlay</td>
<td>10 – 15</td>
</tr>
<tr>
<td>Reclamation, 3 Lift HM Overlay</td>
<td>12 – 15</td>
</tr>
<tr>
<td>Reclamation, Double Surface Treatment</td>
<td>4 – 7</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>12 – 18</td>
</tr>
<tr>
<td>Micro-Surfacing</td>
<td>5 – 9</td>
</tr>
<tr>
<td>Hot-in-Place Recycling</td>
<td>9 – 12</td>
</tr>
<tr>
<td>Cold-in-Place Recycling</td>
<td>10 – 15</td>
</tr>
<tr>
<td>White Topping</td>
<td>10 – 12</td>
</tr>
<tr>
<td>Foamed Asphalt</td>
<td>5 – 9</td>
</tr>
<tr>
<td><strong>Exposed Concrete Pavements</strong></td>
<td></td>
</tr>
<tr>
<td>Concrete Rehab, Diamond Grinding</td>
<td>8 – 12</td>
</tr>
<tr>
<td>Concrete Rehab, 2 Lift HM Overlay</td>
<td>12 – 14</td>
</tr>
<tr>
<td>Reconstruction with Concrete</td>
<td>25 – 30</td>
</tr>
<tr>
<td>Concrete Rehab</td>
<td>15 – 20</td>
</tr>
<tr>
<td>Rubblizing, 2 Lift HM Overlay</td>
<td>12 – 15</td>
</tr>
<tr>
<td>Unbonded Concrete Overlay</td>
<td>25 – 30</td>
</tr>
<tr>
<td><strong>Composite Pavements</strong></td>
<td></td>
</tr>
<tr>
<td>Mill and 1 Lift HM Overlay</td>
<td>7 – 10</td>
</tr>
<tr>
<td>Mill to Concrete, 2 Lift HM Overlay</td>
<td>12 – 15</td>
</tr>
<tr>
<td>Mill to Concrete, Concrete Rehab, 2 Lift HM Overlay</td>
<td>14 – 18</td>
</tr>
<tr>
<td>Reconstruction</td>
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<td>Cold-in-Place Recycling</td>
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</tr>
<tr>
<td>Mill, Rubblize, 3 Lift HM Overlay</td>
<td>14 – 18</td>
</tr>
</tbody>
</table>
Developing Pavement Performance Prediction Models

Pavement performance prediction models are used for predicting future needs and used in analyzing the cost effectiveness of rehabilitation treatment activities. As mentioned in the recommendations for developing the new system, performance models are developed to predict future RCI and DMI. The future values of the overall pavement condition index PCI is calculated based on the predicted RCI and DMI. RCI and DMI prediction models share the same sigmoidal form, with different model coefficients. The mathematical model is:

\[ P = P_o - e^{(a - b \times c^t)} \]

Where  
\( P = \) performance index, RCI or DMI  
\( P_o = \) P at age 0  
\( t = \log_e(1/\text{Age}) \)  
\( a, b, c = \) model coefficients

Depending on the model coefficients, the shape of the performance curve can be close to a straight line, convex, concave or s-shaped with various degrees of curvature, which provides the flexibility to fit into different pavement performance deterioration trends. The model coefficients are determined in two different ways, in order to provide the user with the options of using the default prediction models or the site-specific models in the analysis.

Default Performance Prediction Models

The future performance of a pavement is associated with the rehabilitation treatment it receives. As a result, the prediction models need to be linked with the rehabilitation activity. The default performance prediction models have been developed using the expert opinions from the working panel. The models are developed for 54 performance classes that are defined by 3 traffic levels, 3 structural thickness classes, 3 subgrade types and 2 environment types. The models are then calibrated based on the historical pavement condition data in the PMS database. For those performance classes with insufficient historical data, engineering judgement is used based on the expert opinions and the models of the neighboring classes. Figure 2 shows an example of RCI and DMI prediction models of one performance class.

These models can be adjusted from time to time using the Engineering Feedback subsystem that provides a means of updating the model coefficients through analysis of the historical database which will continue to grow with the addition of new pavement condition data each year.
Site-specific Models

After the database in the new system is populated, site-specific models can be developed for predicting RCI and DMI of individual pavement sections using the historical pavement performance data. The model coefficients are determined automatically using the least squares (regression) method. As additional performance data becomes available (from the pavement condition surveys), it is used together with any existing data to calculate new coefficients for the specific section. For this reason, the model is also termed to be self-adaptive. This modeling approach is expected to produce the most accurate results.

To ensure the reasonableness of the models, expected minimum and maximum life expectancy are used at lower and upper limits. These limits are determined for each performance class. For example, if it is defined that one-lift overlays will last at least 5 years, but not longer than 9 years, then if an adjusted site specific performance prediction model violates this condition, it will be rejected and the default model for the one-lift overlay will be used. Setting the life limits is also useful in identifying erroneous or questionable data points in the collected data (7).

Treatment Selection Using Decision Trees

Developing the standard decision trees for maintenance and rehabilitation is a key step to ensure the program generated by the system truly reflects the engineering decision process of treatment selection. The decision trees use a series of logical tests to capture the decision making process in
selecting appropriate maintenance and rehabilitation treatments based on the status of key parameters including pavement roughness, rutting and individual distresses.

Separate decision trees need to be built to address the deficiencies of each pavement type and each functional class. The raw information was acquired by asking the engineering team to identify the feasible maintenance and rehabilitation treatments under various pavement condition and traffic situations. This knowledge was grouped into condition testing blocks, which were then interconnected into a tree-structure. The feasible rehabilitation treatment alternatives are identified at end of the branch. Figure 3 shows the decision tree built for flexible pavements in the function class of “Freeway”.

The decision trees in the PMS/2 are user-editable (by users with appropriate password authority) and can be modified to reflect changes in practice. In addition, multiple decision trees can be developed and used with PMS/2, which provides the flexibility of exploring alternative maintenance and rehabilitation policies as reflected in different sets of trees. In practice, there are cases that the normal decision process must be overridden, e.g. specific safety projects and the special paving projects that serve the mining and logging industry. A tool for defining these types of projects is provided in PMS/2, with which a project can be selected with a fixed implementation year, a fixed treatment and at a fixed project cost. Staged project plans can also be defined using this tool. In such cases the decision tree analysis is by-passed for the selected project.

Figure 3  Example of Decision Tree Used for Treatment Selection
Prioritization and Work Programming Through Optimization Analysis

The network optimization analysis module in PMS/2 is used for budgeting, programming and planning analyses. Based on the requirements, the following two types of analysis can be carried out: short-term budgeting and programming (1-5 years) and long-term planning (1-10 years).

In the short term the objective of prioritization and work programming analysis is to prepare the 1-5 year construction program. The analysis is likely to be performed at the Regional level, and different budget scenarios may be evaluated. The selection of treatment alternatives is be performed using the marginal cost-effectiveness (MCE) method, in which the marginal cost-effectiveness of a treatment strategy is calculated as:

\[ MCE_{is} = \frac{E_i - E_s}{C_i - C_s} \]

where:
- MCE_{is} = marginal cost-effectiveness of strategy i given the selected strategy s,
- E_i = effectiveness of strategy i,
- C_i = cost of strategy i,
- E_s = effectiveness of strategy s,
- C_s = cost of strategy s.

The analysis will initially select treatments with maximum cost-effectiveness for each pavement section that is in need. Alternative feasible treatments are then evaluated in order to maximize the MCE within the budget constraints. This process is carried out for each year within the analysis period to refine the proposed priority program. Different budget levels may result in different priorities. Therefore, this analysis will need to be performed iteratively. If a Region defines separate budget categories for separate groups of PMS sections (road classes – functional, jurisdictional, funding source, etc.), then each budget stream can be analyzed to produce optimal work programs within a category.

Network Policy Analysis and Budgeting

In the long term, the objective of network level analysis for planning is to estimate the required pavement preservation investments in the 1-10 year horizon. A second objective is to evaluate the impact of different budget streams on future network performance. These two types of analysis can be carried out using the effectiveness maximization method and the cost minimization method.

The cost minimization method is suitable for the first objective, in which the network performance level is used as the primary constraint. The user is required to specify the desired network condition in terms of the average index values, the maximum percent of network below the trigger value or both. During the process of optimization analysis, the program will select projects from the network for rehabilitation until the performance goals are met. By repeating the analysis for each year in the analysis period, the program will return the required funding stream for the specified network condition. The maximum planning horizon is 20 years.

The effectiveness maximization method can be used for the second objective. The yearly budget over the analysis period is used as the primary constraint, and the network performance
constraints are removed. The optimization program will select projects from the network for rehabilitation until the yearly budgets are used up. By repeating the analysis for each year in the analysis period, the program will return the calculated network condition in terms of the average index values and the percent of the network below the trigger value. Although the analysis is more likely to be done for the entire network at the head office, it can be performed for any portion of the network such as a highway class or a geographical region.

Both types of analysis can be used in "what-if" analyses, in which the budget scenario can be varied so that the response and/or sensitivity of the network performance and trend can be evaluated. Similarly, the network performance constraints can be varied to evaluate the impact of these changes on the required budget.

**Engineering Feedback Module**

The Engineering Feedback Analysis is used to update the coefficients of the default performance index models and to analyze treatment effectiveness. The Engineering Feedback module provides the pavement management engineer with a special tool for the ongoing maintenance of PMS/2.

As the PMS database grows in size and sophistication, the historical performance data can be used to evaluate the existing default models. If significant differences exist between the model and the historical data of a pavement class, the coefficients of the model can be updated using the results from the regression analysis in the Feedback module. The same technique can be used to evaluate whether the expected life for various rehabilitation treatments has been achieved. This is called the treatment effectiveness analysis.

A large quantity of data of the same type of projects is required to determine the treatment life expectancy in this analysis. The results can be used by the Ministry to adjust the treatment selection rules when necessary. For researchers, this module can be valuable in evaluating experimental treatments.

**SUMMARY**

The province of Ontario covers a large area, and the highways in the network vary from heavily trafficked freeways to sparsely traveled rural roads, making the management of the provincial highway network a complex task. The development of the 2nd generation PMS for MTO was aimed to provide a tool for the Ministry to better plan the maintenance and rehabilitation activities, more efficiently spend the limited funding and understand the impact of changing the funding levels for both the short term and longer term horizons.

These tasks are handled by the decision support components and modules, including the standardized pavement maintenance and rehabilitation treatment list, the pavement performance prediction models, maintenance and rehabilitation alternative decision trees, project prioritization based on optimization module and the engineering feedback module. This paper reviewed the process of developing these elements based on the Ministry's experiences and expertise, and how these components and modules are implemented in the newly developed PMS/2. It is noted that, due to the dynamic nature of pavement management, the developments with the decision support system modules need to be renewed with the accumulation of data and experience.
ACKNOWLEDGEMENT

The financial support of the study was provided by the Ministry of Transportation of Ontario. Opinions presented in the paper reflect the views of the authors, not necessarily those of the Ministry.

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