Municipal Pavement Performance Prediction based on Pavement Condition Data

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ABSTRACT

A May 20, 2004 Special Report prepared by TD Economics announced "After a quarter century of under-investment, Canada's system of public infrastructure is in need of major repair and upgrade". The report suggests that the infrastructure gap, i.e. the backlog of deferred maintenance, rehabilitation, and replacement of public assets, could be as high as $125 billion or 6-10 times annual investment flows. Transportation facilities account for some 60 percent of the public infrastructure.

These funding shortfalls are considerable and a significant increase in funding is not likely. Pavement maintenance and rehabilitation needs studies frequently indicate that current funding levels are not sufficient to maintain the road system at an optimal level of service. In consideration, municipalities are now focusing on maintaining the overall value of their roadway assets and are striving to make better-informed decisions on how they allocate funding to minimize the deterioration of their assets.

One method municipalities have been using to priorize and justify expenditures is regular road surface condition ratings that are summarized using an index value such as, pavement condition index (PCI), distress manifestation index (DMI), or similar. In the absence of other overriding factors such as, level of service improvements (widening, etc) or underground utility maintenance/rehabilitation, road surface condition ratings can be successfully used to program short term road needs. In conjunction with construction history information, the road surface condition ratings can be used to generate pavement performance prediction models for each pavement surface and construction type. Although pavement prediction models generated in this manner are purely empirical, the technology is relatively simple and allows for longer term forecasting of reconstruction and rehabilitation needs.

This paper provides an overview of the pavement management process and presents a relatively simple methodology for developing pavement prediction models using existing inventory and condition data available to most municipalities.

PAVEMENT MANAGEMENT PROCESS

Municipal and other owners of pavement networks are faced with two basic questions: 1) how much money is needed for the upkeep of the network, and 2) how to ensure that money goes where it is most needed. Every roadway agency that has a pavement preservation budget has also has a process that is used to establish it. This may be a simplified process where the budget is based mainly on last year's budget, or may involve a process where the budget is based on customer-accepted pavement serviceability levels. The quality of the budgeting process has a major impact on the condition of the pavement network and on the cost of maintaining it.

The process starts with establishing standards and service levels for pavement condition, along with specific trigger values for maintenance and rehabilitation actions. A generic representation of trigger values, levels of service expressed as pavement condition versus age is shown in Figure 1.

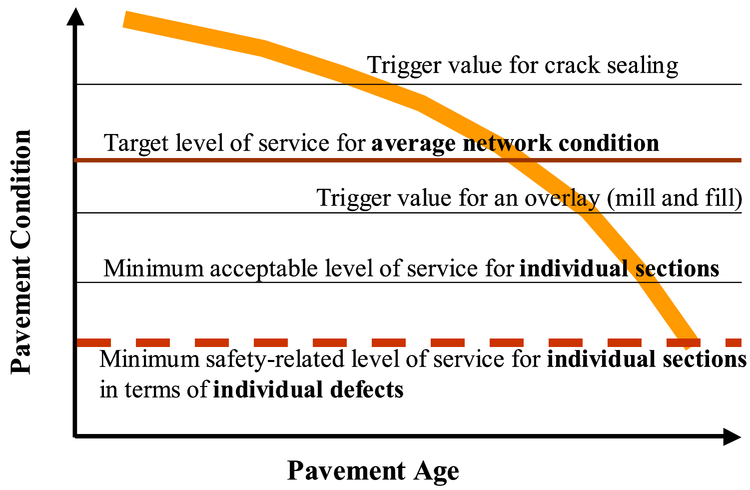

Figure 1 Types of Service Levels and Trigger Values [1]

The identification of pavement preservation needs is not a creation of a wish list, but rather the documentation of maintenance and rehabilitation needs based on mandated standards and levels of service. First priorities are projects related to minimum safety standards. These are followed by projects related to minimum condition levels (based on approved service levels), next come projects that will provide the best return on investments (such as sections requiring preventive maintenance), and finally projects that are initiated to achieve a target level of service. The projects that do not make it into the budget represent a backlog of pavement preservation needs.

The process has general applicability for both small and large municipalities, and can easily be adapted to include other infrastructure assets such as culverts and bridges, sidewalks, park and recreational facilities, and buildings. The process provides a rational methodology for managers and technical personnel responsible for the identification of pavement preservation needs and budgets. It can also provide objective information on pavement preservation needs to senior decision makers and the public. It can be used to quantify the link between the budget and the level of service provided to the public, and to support funding requests for pavement preservation.

DATA REQUIREMENTS

In order to effectively manage an agency's roadway infrastructure, it is necessary to have an understanding of the basic properties of that infrastructure, its historical, current and future performance, etc. The first step in developing an inventory is to define the road network and then divide the network into a number of smaller, and more manageable, uniform sections or links. For example, sections should have relatively uniform pavement structures and traffic volumes, and would therefore be considered to have similar performance characteristics. The sections may be one city block long or several kilometres long. As a minimum, the pavement inventory should include the following:

- Sectioning into "uniform" section identifiers including section name, limits, length and width;
- Roadway functional class (e.g. local residential, collector, arterial, etc.);
- Construction type (e.g. rigid (concrete, ultra thin whitetopping, etc.), flexible (hot mix asphalt, surface treatment, etc.)
- Construction history (when was it originally constructed?);
- Maintenance and rehabilitation history (was the section overlaid, patched or crack sealed?)
- Current condition (may also include past condition from previous pavement management inspections);

Sectioning is completed to divide the network into elements that are easy to manage, typically make good maintenance and construction "packages", have similar ages, traffic, etc. Typically, sections are given an element number, roadway name, from and to. Information on the element length and width are needed to develop appropriate costing and to provide a weighted condition index by pavement area.

Roadway functional class is basically a surrogate for subdivision of roadway sections based on traffic and pavement structure. Typically, higher volume roadways have thicker pavement structures and may have a higher priority level for maintenance and rehabilitation repairs. For most municipal networks, it is not necessary to subdivide performance data analysis by functional class because the performance of local roadways and collector arterial roadways may in fact be similar. Local roadways typically have relatively thin pavement structures but are only subjected to relatively light traffic whereas higher volume roadways have thicker pavement structures because they are subjected to more frequent, heavier traffic. The overall performance life of these two types of pavements is likely similar.

The method of construction (ie, surface type) and rehabilitation timing are interrelated and are considered important inventory attributes. The pavement surface distresses and failure mechanisms are different for rigid vs flexible pavements, and typically, rigid pavements are considered to have longer service lives than flexible pavements. It is also important to know if the last major work on a section was construction/reconstruction or maintenance/rehabilitation. Newly constructed/reconstructed pavements typically last longer than recently rehabilitated pavements (ie, overlays). This is important for the performance prediction models.

Finally, it is necessary to know the current condition of the pavement. Without knowing the current condition of the pavement, it is difficult to predict its future condition and maintenance and rehabilitation needs. Condition information can be a simple as rating on a scale of say 0 (poor) to 100 (excellent) or can include other pavement condition attributes such as deflection (structural capacity), smoothness, rut depth, etc.

CONDITION EVALUATION

Pavement condition evaluation serves two purposes: to identify maintenance and rehabilitation needs, and to monitor the health of the pavement network.

To identify maintenance and rehabilitation needs, particularly preventive maintenance needs, the condition evaluation must be timely (usually annual or biennial) and should be sufficiently detailed. The requirements for the condition evaluation for preventive maintenance purposes are presented in the National Guide for Sustainable Municipal Infrastructure best practice *Timely Preventive Maintenance for Municipal Roads* [2]. Briefly, condition evaluation requires the identification of individual pavement defects, such as transverse cracks, and the evaluation of their severity and extent. If the condition evaluation meets the preventive maintenance requirements, it will also meet the rehabilitation requirements.

Monitoring of the health of the pavement network must be objective and repeatable to produce reliable trends. It typically involves an assessment of pavement distresses and ride quality (roughness). Some agencies classify pavements into three or five categories (from very good to very poor); others use composite performance indicators. For example, the City of Edmonton, Alberta uses a pavement quality index that combines the influence of roughness, distresses, and structural adequacy. Monitoring of the network condition should be done about every second year for high traffic volume facilities and about every second or third year for local roads and streets.

There are numerous methodologies for evaluating the condition of pavements ranging from; windshield surveys that identify distresses and estimate the distress coverage by surface area percentage, to detailed ASTM PCI surveys [3] that identify distress and actually measure distress quantities. Both methodologies have their merits. Windshield surveys are quicker to perform and provide an overall condition of the pavement, but require a subsequent detailed survey for estimating purposes. Detailed PCI type surveys take longer to perform due to the requirement of linear/areal distress measurement, but at the same time, provide usable quantities for maintenance planning.

The surface distress and roughness evaluation procedure for municipalities described in this paper is based on the Ministry of Transportation, Ontario guidelines for the condition rating of flexible pavements for municipalities (SP-022) [4]. This rating methodology was selected to be compatible with, and to make full use of, the municipalities existing condition rating database. The survey can largely be performed as a windshield survey. The definition of distress severity and extent are shown in Table 1.

Table 1. Pavement Distress Severity and Extent

Severity	Extent (percent of surface area)
Very Slight	0 – 10 – Occasional
Slight	10 to 20 – Intermittent
Moderate	20 to 50 - Frequent
Severe	50 – 80 – Extensive
Very Severe	> 80 – Throughout

In addition, the ride quality of the pavement is categorized according the rating guidelines given in Table 2.

Table 2. Ride Condition Rating Guide

Ride Comfort Rating	Guidelines
8 – 10 Excellent	Very smooth
6 – 8 Good	Smooth with a few bumps or depressions
4 – 6 Fair	Comfortable with intermittent bumps or depressions
2 – 4 Poor	Uncomfortable with frequent bumps or depressions
0 – 2 Very Poor	Uncomfortable with constant bumps or depressions

A typical municipal roadway network can be divided into 4 primary surface types as indicated in Table 3.

Table 3. Pavement Surface Types

Surface	Guidelines
HCB	High Class Bituminous - Asphalt concrete surface (flexible pavement)
LCB	Low Class Bituminous – Surface treatment (flexible pavement)
CON	Concrete – PCC (rigid pavement)
A/C	Asphalt over Concrete – (rigid pavement)

The information in Tables 1-3 has been captured in a computerized pavement condition evaluation form as shown in Figure 2. This system allows for electronic data entry in the field that can subsequently be batch loaded into the PMS database.

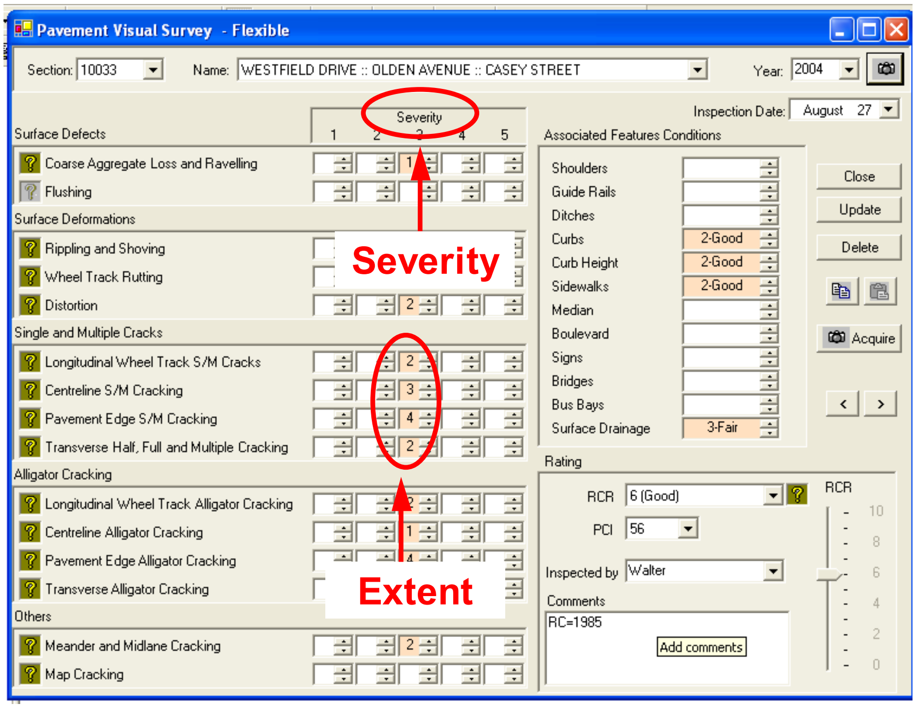

Figure 2. Computerized Pavement Condition Rating Form

The surface condition rating procedure differs depending on the pavement surface type, rigid vs flexible. The condition rating form is linked to the construction history database so that the appropriate form is automatically provided to the rating team. The rating team completes a "windshield" type survey by driving over each roadway section and entering the observed distresses by type, extent and severity. In order to assist in providing consistency of condition rating, the distress rating form has been linked to typical pavement distresses (Figure 3) and ride comfort rating (Figure 4). The distresses and ride comfort rating are used to calculate the pavement condition index (PCI) of the pavement on a rating scale of 0 (poor) to 100 (excellent).

A representative digital photograph can be taken for each section of roadway to provide an additional historical record of the pavement condition. The photographs are linked to the PMS system so that users can display the photograph when reviewing the PMS data. An example photograph of a pavement section in 2004 is shown in Figure 5.

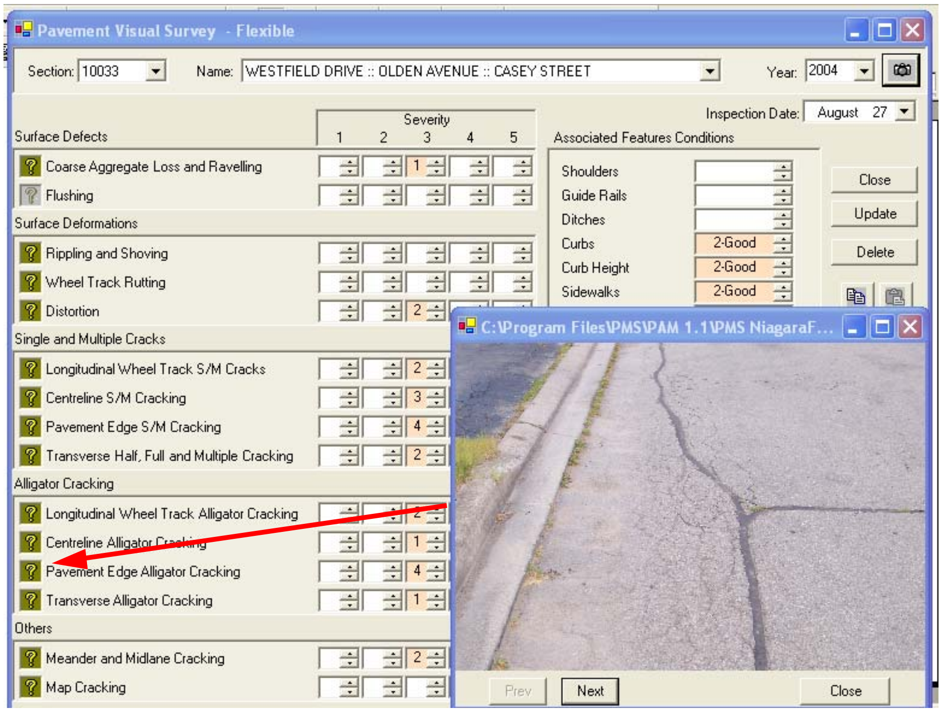

Figure 3. Example Pavement Condition for Moderate to Severe Pavement Edge Cracking.

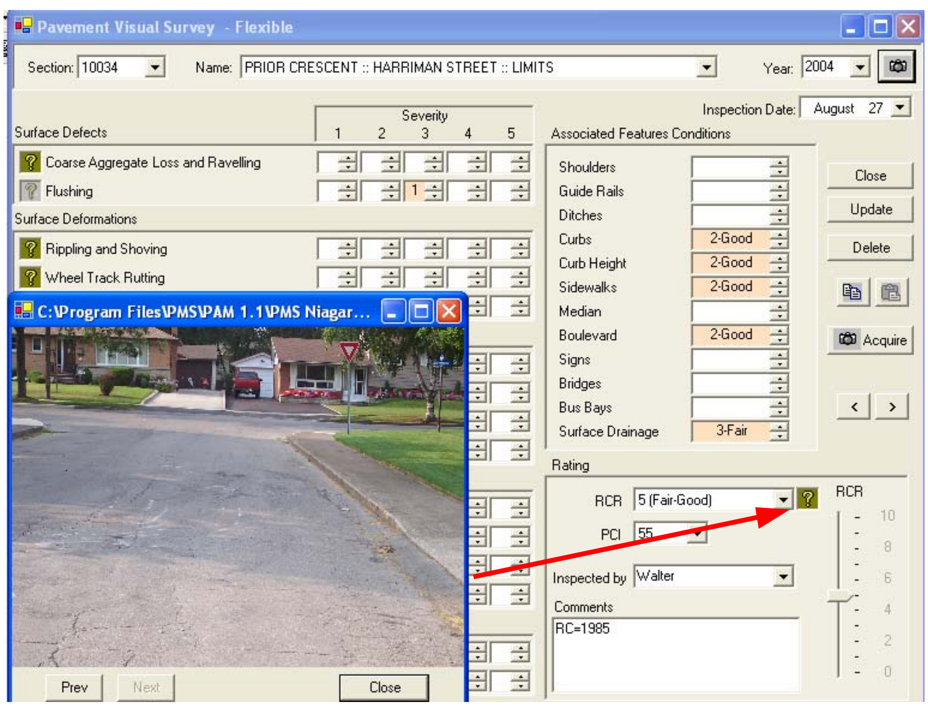

Figure 4. Example of a Pavement with Fair to Good Ride.

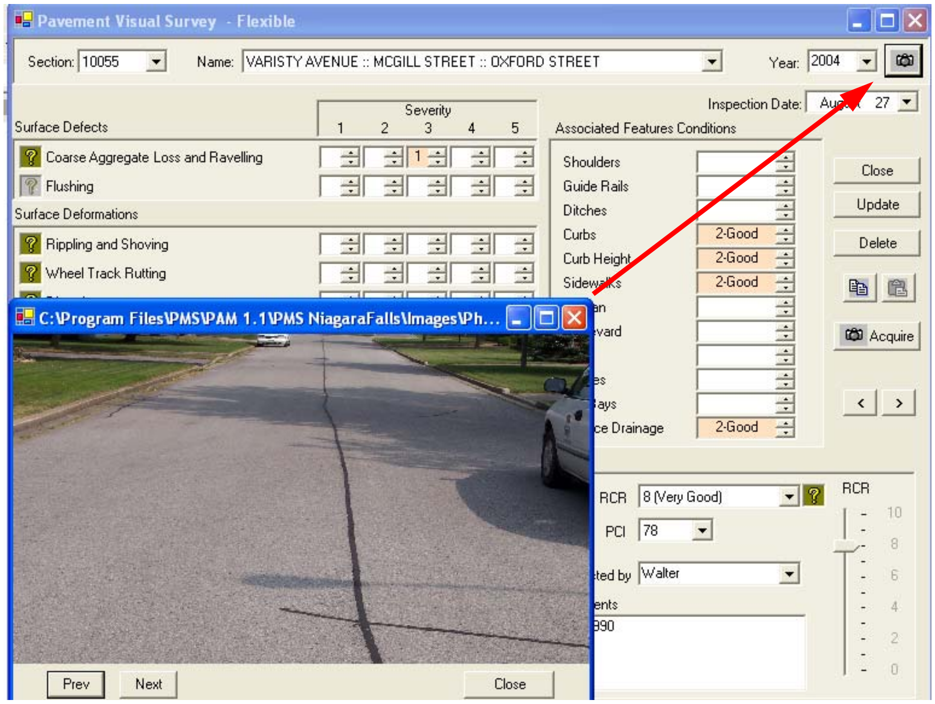

Figure 5. Example Pavement Condition for Section 10055, Varsity Avenue

Once the condition data is collected for each section of roadway, the status of the pavement network can be reviewed using simple analyses and graphics such as that shown in Figures 6 and 7.

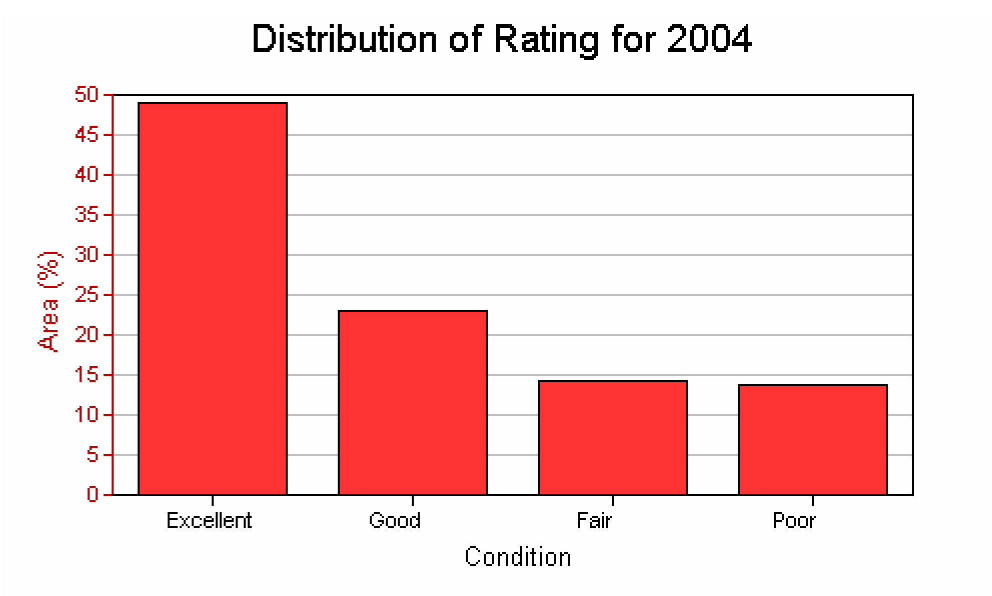

Figure 6. Distribution of PCI for All Pavement Sections in 2004.

In Figure 6, the distribution of pavement sections by PCI for the entire network is shown. A municipal PMS system typically allows summaries of pavement condition data to be provided in both graphical and tabular format. In Figure 7, the cumulative distribution of section PCI for pavement sections rated in 2004 is shown. Graphs like this are useful in determining if the distribution of pavement condition in various categories is relatively consistent and sustainable based on rehabilitation and reconstruction budgets.

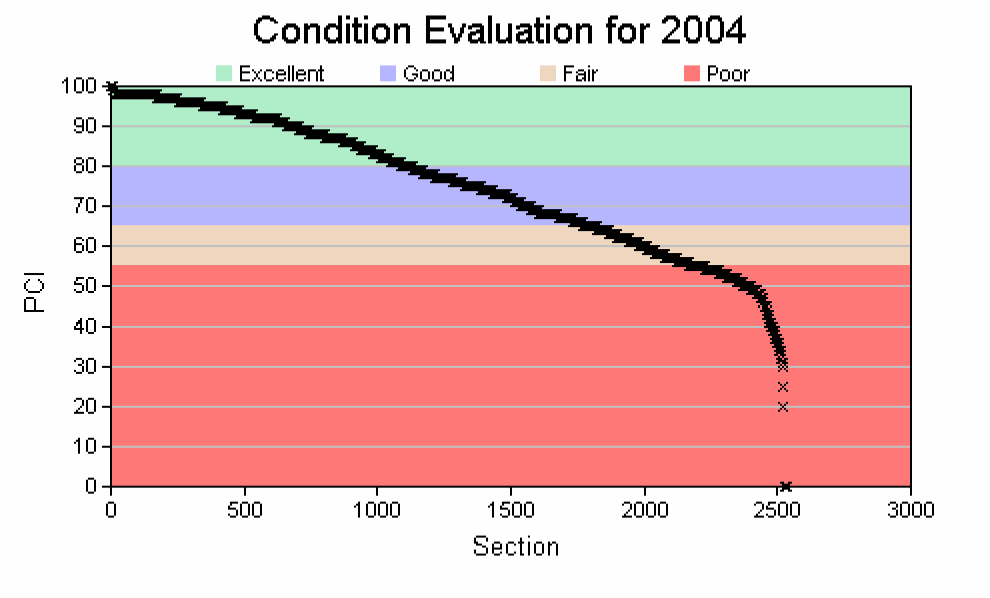

Figure 7. Distribution of PCI for All Pavement Sections in 2004.

PAVEMENT PERFORMANCE PREDICTION

Performance prediction is a critical requirement for the identification of future pavement preservation needs. Pavement performance depends on many local factors and is not easily transferable from municipality to municipality.

Figure 8 shows the importance of pavement performance prediction. The present condition rating of the two pavements shown in Figure 8 is the same. However, pavement B has a higher rate of deterioration than pavement A. Thus, pavement B will reach the minimum acceptable service level sooner, and will require a pavement preservation treatment earlier. The predicted rate of pavement deterioration can also be used as one of the factors to prioritize and select candidate sections for treatment.

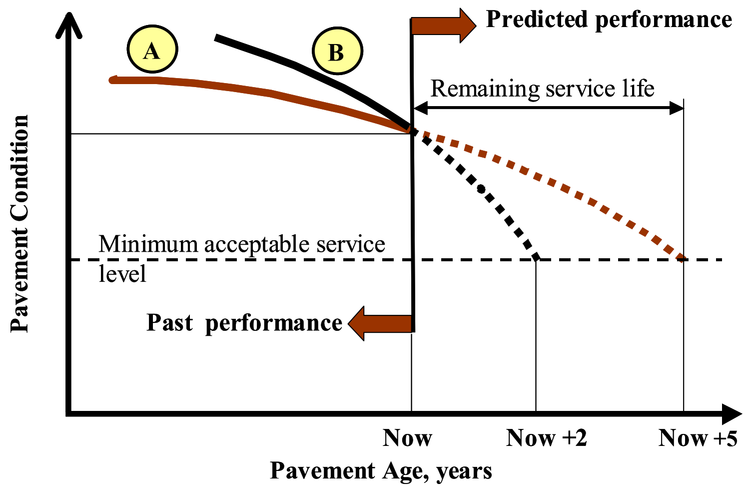

Figure 8. Basic Concepts of Pavement Performance Prediction

Long-term predictions (for five or more years) involve how long the existing pavements will last before they require a treatment (as shown in Figure 8), as well as how the individual sections will be rehabilitated during the intervening years, and how these rehabilitation treatments will perform.

Ideally, pavement condition information collected during a series of years from the same pavement section is used to predict the future condition of the pavement. This helps to ensure the accuracy of the prediction by using the past performance of the individual section. Unfortunately, this can only be used in a “mature” pavement management system (PMS) that has been in place and used for many years. This is typically not practical for agencies that have just started collecting PMS data. For newer applications, agencies must rely on groups of similar roadways that have been constructed at various intervals for which at least one year of condition data has been collected.

Using the pavement section inventory information, sections of like roadways are grouped together and “normalized” to their initial construction year (Year 0). A major event such as a rehabilitation will start a new Year 0 in the inventory database. By plotting the pavement performance versus year (Figure 9), one can get an idea of the anticipated performance of a particular group of similar roadways. However, for many agencies, this exercise identifies/magnifies inconsistencies in the historical database.

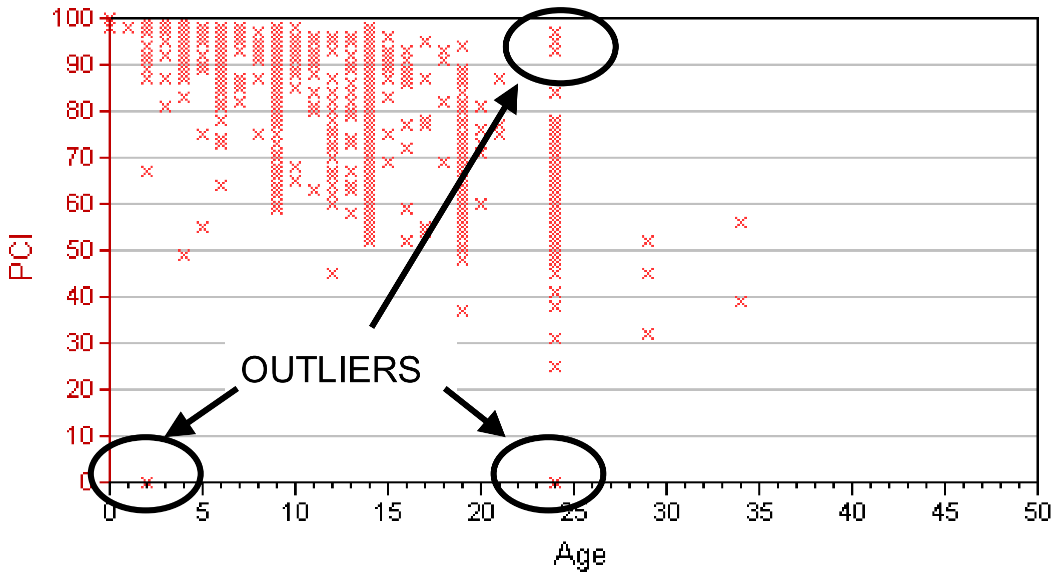

Figure 9. Pavement Condition (PCI) versus Age Since Last Construction (Years)

This type of plot is very useful in identifying data outliers. For example, the plot indicates that there is a two year old and 24 year old section of roadway in the database that has a PCI of zero. This is not likely the case but rather there are sections in the database for which the condition rating has not been completed. The graphic also shows a series of sections that are 25 years and have PCIs of over 90. While this may be the case, it is unlikely. From Figure 9, it can also be seen that there seems to be a concentration of data for years 9, 14, 19 and 24. In reviewing the pavement construction history database, it was found that this particular agency did not have very good construction history records and pavement sections were "assigned" to a particular year when other more specific information was not available. Regardless, it is necessary for an agency to review the construction history information to ensure that it is reasonable, otherwise some significant errors in the performance prediction modeling can be expected.

Prediction modeling is typically completed using either a best fit curve or by using survival analyses. For the best fit analysis, the results of all current and previous pavement condition surveys and construction history is used to generate pavement performance prediction models for each pavement surface and construction type. For this particular agency's roadways, the prediction models for the HCB and LCB pavements are shown in Figures 10 and 11.

While the general trends are fairly reasonable, it can be seen from the figures that there are still some outliers that should be carefully checked, particularly those with data falling close to the horizontal or vertical axis. The construction history information should continue to be verified to improve the performance prediction models.

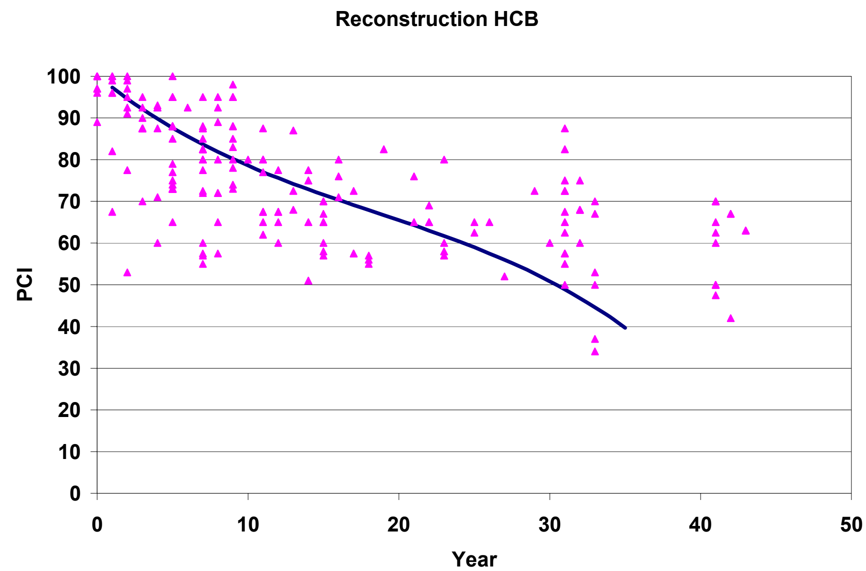

Figure 10. Condition Summary and Prediction Model for HCB Reconstructed Pavements

Based on the pavement construction history and condition information plotted in Figure 11, it can be seen that a rehabilitated HCB pavement could expected to last 17 years until it reached a terminal serviceability level PCI of 60 based on a best fit curve of the historical data. The spread of the data ranges from 4 to 28 years for a terminal PCI of 60. The best fit curve through the data (black line) is relatively good for the first 20 years of data but becomes unreasonable after that time and hence a modified curve is applied using engineering judgment.

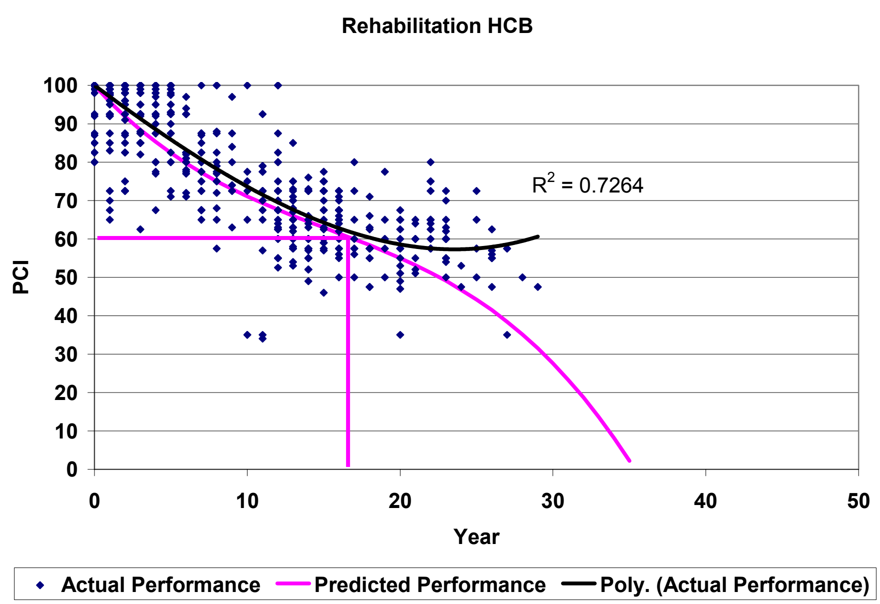

Figure 11. Condition Summary and Prediction Model for HCB Rehabilitated Pavements

The other popular method for developing and appropriate prediction model is the through the use of a survival analysis. For the survival analysis, the user selects the terminal serviceability level of the pavement and like pavement sections are grouped and statistically analyzed to determine the probability that they will reach a particular age and condition index. A probability level of 50 percent is typically selected. An example of a survival analysis is shown in Figure 12. For the example in Figure 12, there is a 50 percent probability that a rehabilitated HCB pavement will reach a terminal serviceability level PCI of 60 in 16.5 years. While there is a significant scatter in the historical data, both methods correlate reasonably well.

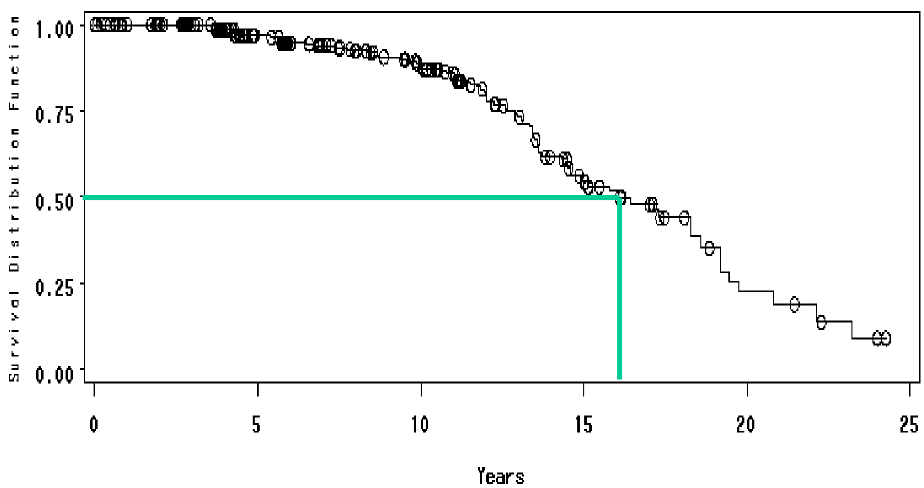

Figure 12. Example Survival Analysis Plot for Reconstruction HCB.

PAVEMENT MAINTENANCE AND REHABILITATION NEEDS FORECASTING

Once the performance models are developed, it is possible to predict the future condition of each pavement section and to develop pavement maintenance and rehabilitation needs. An example of a needs analysis is shown in Figure 13. In this example, pavement reconstruction (RC) and resurfacing (RS) needs are shown for a five year period. The example shows that there is an immediate need (backlog) of over $ 20 million after which an annual budget of about $ 5 million would be sufficient to maintain the network.

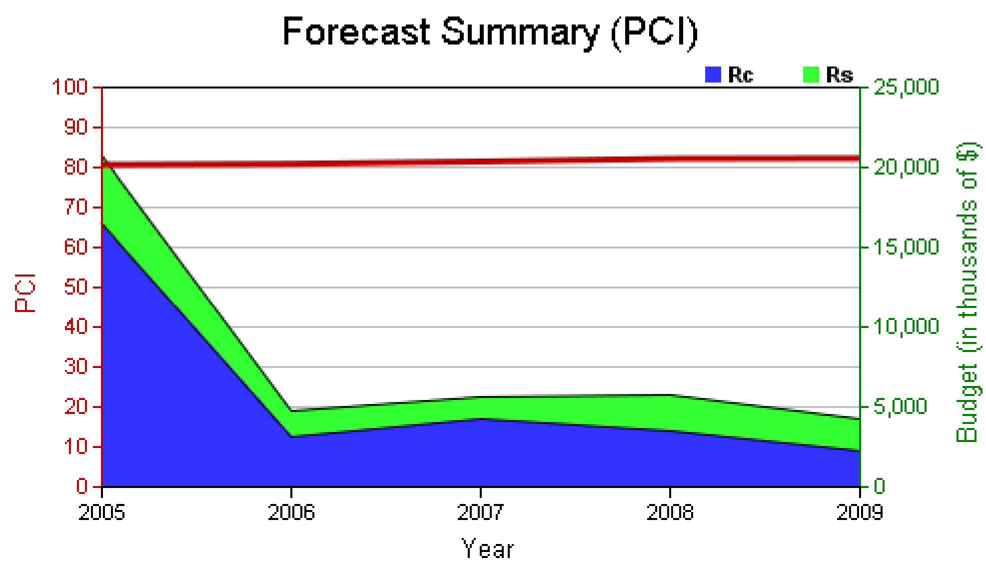

Figure 13. Example Pavement Maintenance and Rehabilitation Forecast Summary.

NETWORK VALUE

While the use of the pavement condition index can provide an agency with a good understanding of the condition and future needs of the roadway infrastructure, it should not be the only method used.

The concept of network value for pavements is based on the accounting principle of depreciation coupled with the engineering principal of survival analysis. During pavement rehabilitation and management, pavements are evaluated based on their functional and structural condition. The functional condition of the pavement is evaluated in terms of the ability of the pavement to provide a safe, durable platform for vehicular travel. The structural condition of the pavement is the ability of the pavement to protect the subgrade and for the individual layers to withstand the day-to-day loading imposed on it by vehicular traffic.

In order to evaluate the structural and functional condition of a pavement, engineers measure the condition of a pavement's ability to carry out its function by assessing:

- Condition of the pavement surface as determined by the type and extent of various pavement surfaced distresses;
- Ride condition of the pavement as determined by pavement smoothness measurements; and
- Structural condition of the pavement through load/deflection testing.

The condition of a pavement surface is assessed by determining the type and severity of various distresses and then deducting the impact of these distresses on the score of a 'perfect' pavement. As one would expect, a newly constructed pavement without distress would receive a 'score' of 100. For the purposes of this example, the 'value' of 1 square metre of a newly constructed pavement will have a value of $ 50. The expected overall service life of the pavement in this example is expected to be 50 years.

Pavements deteriorate with age and traffic. Typically, a pavement would be permitted to deteriorate to a condition of 60 on a scale of 100 over a period of 25 years and then would be considered for rehabilitation. Using the network value concept, this pavement would be considered to have a value of $ 25 (half its initial value). At the end of this service life, this 'example' pavement would be considered for a mill and overlay. Once the overlay is placed, the surface condition of the pavement would be considered to be excellent and the surface condition index of this pavement would be increased from 60 to 100.

A user of the pavement would perceive the pavement to be the same as new. However, the 'value' of the pavement is not the same as if the pavement were newly constructed. Therefore the value of the in-situ pavement is only increased by a percentage of how long the mill and overlay rehabilitation would last. The extent of the increase in value to the original pavement structure is depended on how on the effectiveness of the rehabilitation treatment (mill and overlay). For the purposes of this example, the mill and overlay is considered to cost $ 15 per square metre. Therefore it is considered to have increased the underlying value of the pavement from $ 25 per square metre to $ 40 per square metre. If the rehabilitation treatment is effective for a service life of 10 years, its effectiveness would decrease over its service life. The rate of reduction of value would be a function of the rate of deterioration of the pavement. Subsequent treatments would be considered in a similar fashion with the pavement deteriorating and reducing in value with time. The 'effectiveness' of each treatment would be a function of its initial value and the length of time that it would last. If a treatment is relatively expensive, but does not last for a long period of time, the 'effectiveness' of this treatment would be reflected in a significant reduction in the network value of the pavement. The pavement deteriorates with time until it eventually reaches its 'residual' value or 'salvage' value.

Using the network value concept, the underlying value of the pavement or amortized value of the pavement can be calculated at any point during its service life. It addition, the return on investment of any rehabilitation treatment can be expressed as a percentage of the increase in network value that it provides.

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