Performance Prediction Development Using Three Indexes for North Dakota Pavement Management System

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The development aspects of three pavement performance indicators are presented. The prediction curves were developed for North Dakota using the most innovative methods available. The methodology adapted for use in the North Dakota pavement management system (NDPMS) is unique because three performance indicators are used in the system and the performance techniques were also used in seven city and county NDPMS installations. The three performance indicators developed were an overall distress index, a structural index, and a roughness index. NDPMS incorporates the three indexes in the performance prediction module of the analytical software that was developed. Pavement prediction curves were developed for each index. The final curves provide a reasonable method of predicting pavement performance in North Dakota. The development process provided many technological challenges that were channeled into the curve designs.

Performance prediction models are the most essential part of a pavement management system. They are essential to the management of pavements at the network and the project levels, both technically and economically.

Methods for predicting pavement performance should not be selected arbitrarily: they are too important. Mistakes or random selection of methodology for performance prediction can be costly to the highway system. Besides raising cost-allocation questions, poorly designed models make optimal pavement design and selection of optimal rehabilitation strategies and timing of projects impossible. But well-done performance models will secure for their users economy, technical efficiency, and equity. Developing performance prediction curves for North Dakota involved exploring the available methods for predicting pavement performance and selecting or developing the most appropriate one. The performance modeling techniques used for the state system were also used to customize performance models for each of the seven cities and counties in North Dakota that also implemented the pavement management system.

Many factors can influence the performance of pavements and their ability to serve the transportation facility satisfactorily. These include truck traffic, climate, pavement structure, and type of pavement. Another important part of the performance prediction development was the determination of the factors that effect pavement deterioration in North Dakota.

To develop curves that fit the North Dakota performance trends, it was necessary to determine what could be predicted with the most accuracy to also meet the local conditions and constraints on availability of historical inventory. A number of indexes were analyzed for their predictability, including those for structural deterioration, overall distress, climate- and environment-related distress, individual distress, and roughness.

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DEVELOPMENT OF PERFORMANCE CURVES FOR NORTH DAKOTA

The first stage in developing performance curves for any pavement management system is that of identifying the pavement-related attributes to predict. At its initial meeting, the North Dakota PMS steering committee discussed to great length which attributes should be used to best model typical pavement performance. The suggestions ranged from using a composite condition index to represent overall condition to predicting individual distress types such as alligator cracking for the selection of rehabilitation strategies. Structural-versus-environmental pavement deterioration was discussed also. The environmental, or nonstructurally induced, deterioration issue arose from a committee discussion about some of the very low commercial volume roadways in the state that carry relatively light loadings and deteriorate primarily because of weather and age. The committee believed that some method of predicting either structural or nonstructural deterioration would be important for selecting appropriate rehabilitation strategies that address the cause of the deterioration. Thus, the individual parts of the state's condition survey forms were divided into structural and nonstructural distresses. The predictability of either group of distresses was discussed by the committee.

The committee decided to test the applicability of using multiple performance curves for the predictions. It was believed that doing so could improve the department's decision-making capabilities by providing more detail to the performance curves.

GROUPING OF HIGHWAY SECTIONS

To develop pavement performance curves for a pavement management system, a method of categorizing pavements must be chosen. Three methods of grouping were investigated.

The first and simplest way is to group pavements that have similar characteristics such as surface type, traffic, and structure. This approach assumes that pavements with the same grouping will perform similarly throughout their lives. This method is easy to understand and modify in the future.

The second, and more complex, method is to place all variables in determining pavement condition on the right-hand side of the equation. Each and every pavement section then has its own performance pattern. This technique is an example of a multiple linear regression model. The performance of each pavement is a function of individual items relating to that section. Some of the individual items in the prediction equations could include commercial traffic levels, subgrade strength, maximum surface deflection, and climate. These items tend to become very complicated and usually require complex and comprehensive data.

The third method is also the most complex. It is a combination of the first two methods that groups pavements to represent similar performance patterns, and particular variables are predicted. Because the continuous interaction of variables on each side of the equation makes this approach so complex, it was not thought to be easily modifiable.

After discussing the grouping methods, the PMS steering committee decided to evaluate the effectiveness of the first. The pavement categories were identified by the committee for the initial groupings. These categories included 3 ranges of in situ structural strength, 13 pavement classes (type of cross section), and 4 ranges of traffic [equivalent single axle loads (ESALs)].

At the final meeting of the performance subcommittee, the pavement groups were made final. The subcommittee discussed in detail the difference between the performance of pavements in the asphalt/granular group and in the asphalt/stabilized group. The subcommittee decided that there was no measurable difference between the two groups as indicated by a plot comparison of the two types and recommended they be combined. The final number of groupings agreed upon by the committee resulted in 42 groups of performance classes or cells that had pavement sections in them.

Performance curves were also customized for each of the seven local jurisdictions involved in the implementation. The number of groups of pavement performance at the local level ranged from 5 to 12. This smaller number was due to a less variance in types of pavement cross sections that the cities had historically used in construction.

DATA BASE ANALYSIS AND MANIPULATION

The key ingredient in any pavement performance prediction is the data used in making the prediction. The quality of the historical North Dakota pavement management data base was such that analysis could begin directly without any changes or modifications to the actual raw data numbers. The pavement management data base was composed of 128 different pavement data attributes. The condition assessment method used by the state was a windshield survey recording three levels of severity and three levels of extent for each of the pavement distresses.

The North Dakota data base contained more than 1,000 pavement sections on the state highway system. The first step in the performance curve development was to assign each section a pavement category number. A computer program was developed to assist with categorizing the pavement sections. The program also groups sections according to any subsequent deletions, additions, or changes in category definitions throughout the development process.

A second program was developed to assist in identifying the structural and environmental components of the condition index for each year the condition assessment had been surveyed. The summarized pavement data base maintained by the state stores only 1 year of individual distress elements. In addition, there was no information in the summarized data base combining the individual distress elements into structural or environmental components.

Therefore, it was necessary to build a data file from the 5 years of individual mile-by-mile historical distress information available. A computer program was developed that accessed all the individual mile-by-mile distress data (8,500 mi/year) and built the historical pavement section files for all of the performance curves to be generated.

Quality control of the data was important to maintain the data integrity. Without quality control checks during the many data manipulations, the potential for erroneous performance prediction was imminent. Quality control was provided by manual verification of a sample set of all the data analysis.

SELECTION OF PERFORMANCE PREDICTION METHODOLOGY

Several prediction techniques were evaluated to develop performance curves for North Dakota that reasonably reflect actual deterioration patterns, that can be updated easily, and that can be adapted to local jurisdiction applications. The results of these evaluations follow.

The first method used in developing prediction curves was a linear regression analysis. This resulted in a straight-line least-squares prediction to the first degree of the index over time. The method used a single independent variable in making the prediction.

The first iteration using this procedure identified a significant problem in the state's data storage format. The graphical output of the scatter plots shown in Figure 1 indicated that many data points were stacked at years for which in actuality the age indicated there were only one or two pavement sections. After careful investigation of the data, it was found that there was an error in the methodology in which the data base had originally been set up by the state. As a result, all of a pavement section's current and historical data were plotting as one analysis year.

This required the development of a computer algorithm that back-distributed the historical data to the proper age of the pavement. This process simply involved proper determination of the age of the pavement and the corresponding condition. The state's data file contained only the current age with 5 years of historical distress data. The algorithm also had to take into account any major rehabilitation that had occurred in the past 5 years to develop a proper age-versus-condition distribution.

Subsequent runs using the linear regressions resulted in more complexities. The data plots indicated the trend in performance generally started as a downward trend. These same plots began to show an increase in the amount data scattered

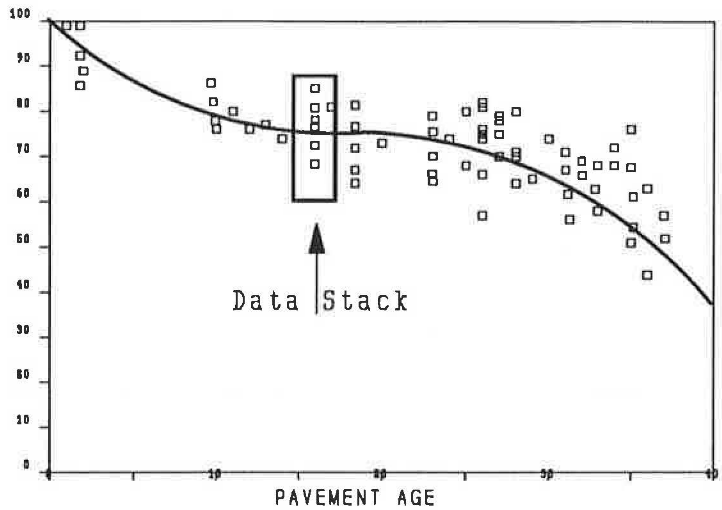

FIGURE 1 Data stacking.

as time progressed. Through critical evaluation, discussions with the state, and extensive reviews of the individual data elements, it was concluded that the maintenance effort was producing a significant effect on the performance curves shown in Figure 2 as a flattening or a rise in the performance.

It became necessary to address this complex issue as part of the pavement management system development. Surface seals were thought to be the major influence from the maintenance effort that was being reflected in the performance curve development. An analysis of maintenance-related performance curves developed by the state for chip seals resulted in the development of another computer program that eliminates records in the analytical pavement section data base that are under the influence of seals according to the seal performance curves (*1*).

Subsequent regression analysis indicated an improvement on the data scatter after the removal of the visual effect of the seals on the surface distress surveys; however, the results of the linear regression analysis were not satisfactory. Many groupings other than those initially identified were tried in an effort to improve the results of the analysis and feel out the data for what might work using other procedures. Modifications to the groupings that were attempted to improve the results included

- Asphalt/granular pavement class and fewer than 100 ESALs,
- Asphalt/granular pavement class and more than 100 ESALs,
- All pavements with an asphalt/granular pavement class,
- All flexible pavements with fewer than 100 ESALs,
- All flexible pavements with more than 100 ESALs, and
- All pavements with an asphalt/stabilized pavement class.

Even these broad groupings produced less-than-satisfactory results. Hundreds of different performance curves were gen-

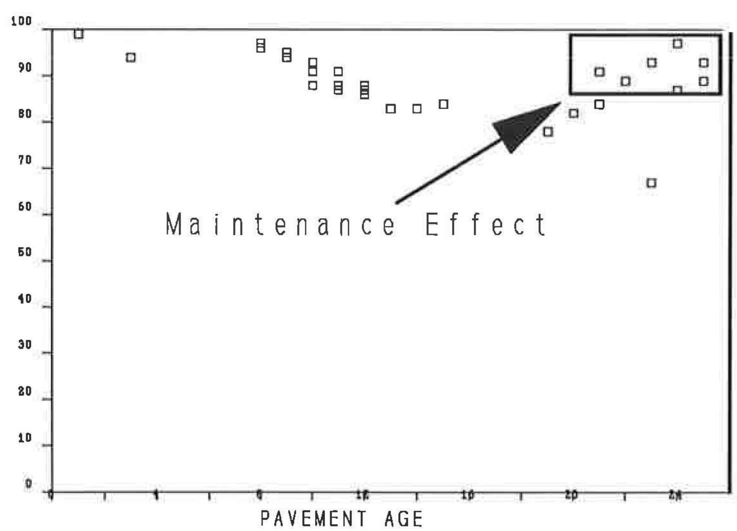

FIGURE 2 Maintenance effect.

erated for all types of condition indexes. The indexes tried were for (a) combined distress, (b) roughness, (c) sum of environmental distress deduct factors, (d) a sum of structural distress deducts, (e) alligator cracking, and (f) combination of factors. The overall output was not satisfactory enough that the prediction models could be used with any confidence. The r^2-values were too low, and the data scatter plots were unacceptable. The analysis did give insight into what combinations of data would work using other analysis techniques.

Several important benefits were gained from this analysis, the two most significant being the elimination of historical data stacking and the reduction of the maintenance effect. These were obstacles related to the data base and to performance, which made them critical to the success of the analysis. They had the potential to affect the predictability of the performance curves dramatically.

AASHTO ROAD TEST PERFORMANCE METHODOLOGY

The concepts and methodology developed in the AASHTO road test pavement performance were comprehensively investigated as to their application to this project. The road test presents a method that predicts serviceability from accumulated axle loadings and describes it as a loss in serviceability as a power function of axle load applications.

This concept was applicable with the data the state has available, but again the lack of data and their complexity at the county and city levels did not make it a desirable method. Many of the same complexities described with the multiple linear regression approach also hold true with the AASHTO road test methods.

EVALUATIONS OF PERFORMANCE MODELS DEVELOPED NATIONWIDE

Pavement performance models already developed from other sources were evaluated for possible application in the development of performance curves for North Dakota. Once again, the complexity of the data required was prohibitive for use by the cities and counties.

NONLINEAR ANALYSIS

The final approach investigated was the development of the performance curves using a nonlinear analysis (*2*). There were several reasons to look at this methodology. The multiple regression analysis indicated that (a) the performance of the pavements was indeed predictable, and (b) the scatter of the data was represented not by a straight line but by more of an S-shaped or a multifunctional line, as shown in Figure 3.

The nonlinear approach has several features that fit well with what the North Dakota system is trying to do. The first is the effect of maintenance. There are many low-volume surfaced roads in which maintenance had a great impact on the pavement performance by flattening out the curve with time as shown on Figure 4. The use of the processing technique called outlier analysis (*2*) allows the user to identify ranges of reasonable data over the life span of the pavement by identifying extreme observations. Another technique that sets boundaries of reasonable data ranges at a given point in time was used in adjusting the original curves only on the basis of historical data with some of the maintenance influence in them. This was an important feature for North Dakota because it allows the use of expert opinion to say what would happen to these pavements if this maintenance had not been performed, representing the Do Nothing condition shown in Figure 4.

Another feature that is applicable is the mathematical models that use either a normalized B-spline approximation or constrained least-squares estimations (*2*). These procedures result in a polynomial equation to the fourth degree. The use of these mathematics allows the multishaped curves to be described. The models are constrained if there is any shift upward on the mathematical curve.

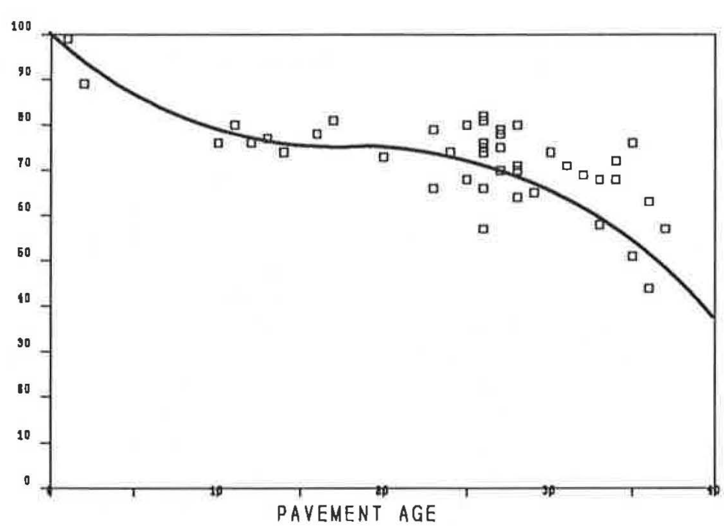

FIGURE 3 S-shaped curves.

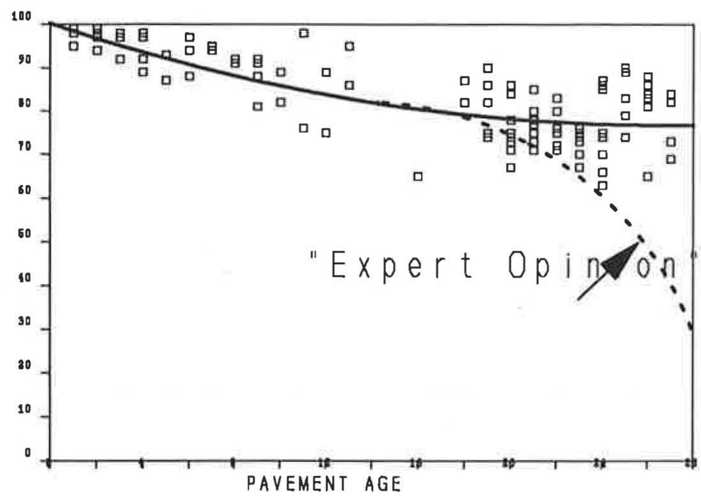

FIGURE 4 Expert augmentation of historical curve.

There are several primary benefits in using the nonlinear analysis, including

- The process is adaptive to incorporation of the expert system approach;
- Annual updates to the performance curves are readily accomplished;
- The software side is simplified as performance curves are easily added, changed, or subtracted; and
- The data-filtering procedure indicates the goodness of fit concerning the pavement category groupings that have been made and indicates whether any grouping changes should be made.

The use of the nonlinear analysis required some additional software manipulations. The use of a 100-to-0 condition index as the common scale for all the indexes required that some of the condition components be converted. A listing of the values represented in the data base that were converted for analysis follows; the asterisk denotes final curve predictions.

Type of Condition Factor	*Range of Values*
Distress index*	99 to 0
Structural distress deduct*	54 maximum deducts
Structural index*	54 to 0
Nonstructural index	45 to 0
Roughness index*	5 to 0
Alligator cracking	18 to 0

For each indicator, the software manipulated the possible values to a common scale indicating a value of 100 for the best condition and 0 for the worst condition. The resulting software converts any of the numeric North Dakota data, regardless of the variations mentioned, into a 100-to-0 scale through a simple algebraic ratio conversion. The software also converts the data from the original format into the proper data input file format for processing by the nonlinear analysis program. This allows the possibility of investigating performance curves for any data element in the historic data file.

The statistical properties of the different curves were evaluated using standard statistical methods. Initial investigations revealed r^2-values ranging from about .6 to 0. The lowest values were for the alligator cracking curves: there tended to be much scatter within the alligator cracking groupings. The values for combined distress and structural index varied from high to low but were within reason for the initial stages of development and indicated that work should proceed with this methodology. From the results of the final performance prediction curves, the distress index and the structural index tended to be the most predictable on the basis of the historic data and are the recommended indexes to be used by the state. The final r^2-values for each of the performance curves are shown in Table 1. The equations developed as a result of this task take the form of the constrained least-squares equation (*3*)

$$P_0 + P_1 * x + P_2 * x * x + P_3 * x * x * x$$
$$+ P_4 * x * x * x * x$$

The complete set of equations, data plots, and statistical checks was delivered to the state (*4–6*).

ROUGHNESS PERFORMANCE PREDICTION

The prediction of roughness proved to be the most difficult to model of all the indexes analyzed. Another complexity in the prediction development was that the state collected historical roughness data with a Mays Ride meter, but all future data would be collected with a profilometer producing the international roughness index (IRI). It was necessary to take this all into account during the development of methodology to predict roughness performance.

The investigation of a reasonable method to predict roughness on the basis of the quality of the existing historical data led to the method described in the following text. It was believed that the resulting method would satisfactorily approximate roughness and lend itself to incorporation of the profilometer data in future years.

The roughness was grouped according to the groupings shown in the following. The split of the flexible pavements by average

TABLE 1 R^2-VALUES FOR FINAL CURVES

Performance Curve #	Distress Index r^2	Structural Index r^2	Performance Curve #	Distress Index r^2	Structural Index r^2
1	0.789	0.731	22	0.940	0.987
2	0.922	0.894	23	0.776	0.769
3	0.778	0.828	24	0.931	0.914
4	0.877	0.720	25	100% expert	100% expert
5	0.482	0.458	26	0.856	0.522
6	0.913	0.845	27	0.649	0.849
7	0.857	0.834	28	0.463	0.401
8	0.13	0.951	29	0.655	0.340
9	0.834	0.938	30	0.872	0.894
10	0.782	0.466	31	0.848	1.00
11	0.860	0.377	32	0.972	1.00
12	0.552	0.303	33	0.902	1.00
13	0.586	0.190	34	0.971	1.00
14	0.799	0.958	35	0.893	1.00
15	0.898	0.456	36	0.945	1.00
16	0.797	0.877	37	0.462	1.00
17	0.450	0.882	38	0.701	0.678
18	0.784	0.903	39	0.719	1.00
19	0.592	0.014	40	0.641	1.00
20	0.999	0.991	41	0.974	1.00
21	0.658	0.832	42	0.850	1.00

daily traffic (ADT) was made in line with the levels set in the decision matrices. R_i is initial roughness; R_t is terminal roughness; R_c is current roughness; $R(p_n)$ is predicted roughness; A_i is age from present forward; A_t is terminal age defined by distress curves; and A_{tn} is terminal age of the corresponding distress index curve n.

Group	R_i	R_t	R^2
Continuously reinforced concrete pavement (CRCP)	3.99	3.1	.12
Rigid jointed	3.59	2.7	.19
Asphalt > 2,000 ADT	3.57	3.1	.11
Asphalt < 2,000 ADT	3.74	2.7	.36

The example in Figure 5 depicts how one of the roughness curves was used to predict roughness for all of their corresponding pavement performance categories by varying the slope of the curve. This approach to the roughness curves produced 4 initial roughness groups and 42 total roughness curves to match each of the pavement performance categories.

The rationale behind the approach to varying the slope of the roughness curve is as follows: take, for example, the flexible roughness curve for less than 2,001 ADT as shown in Figure 6. If only one curve were used, the amount of roughness would be less for shorter terminal age pavements than for longer ones. In other words, the shorter the pavement age, the smoother the pavement will be at its terminal serviceable age. This does not make sense. The method that was developed varies the slope of the curve to match the terminal age of the roughness to the terminal age of the distress. This follows a logical sequence of events in that as the severity and extent of surface distress increase, the pavement becomes rougher. This was also shown by plotting distress and roughness on the same graph in past reports (7).

The final step in the process was determining the amount that the roughness would deteriorate each year if nothing was to be done to improve it. The entire process comes down to

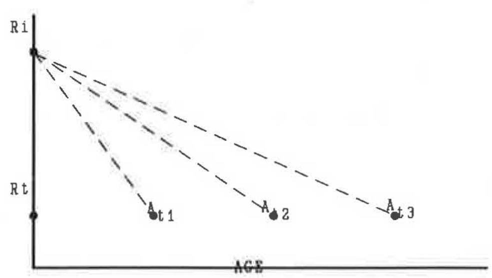

FIGURE 5 Flexible pavements ≤ 2,000 ADT.

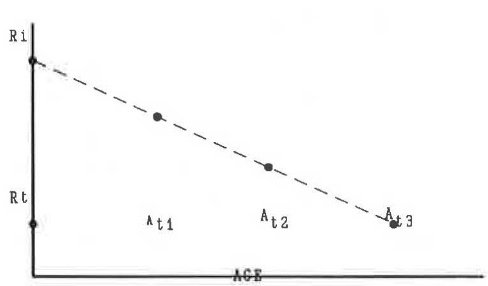

FIGURE 6 One curve.

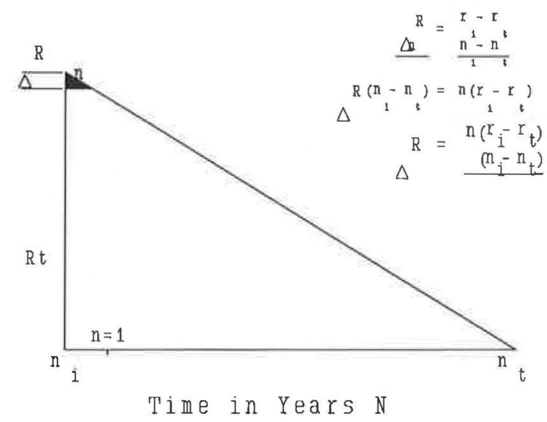

FIGURE 7 Slope equation.

a simple algebraic determination of a variable slope line. The equation derivation is shown in Figure 7.

The resulting equation was that for any given roughness (R), the predicted roughness $R(p_n) = R_c - \Delta R * n$. This equation is easily modified in the PMS software: the user can simply change the initial and terminal roughness levels on the straight-line curve through the software.

The four straight-line predictions were recommended considering the quality of the current roughness data available. The quality problems concerned annual comparisons of roughness primarily related to calibration difficulties of the equipment. The Mays Ride data indicated a variance between pavement sections within the year analyzed, but year-to-year comparisons were difficult. These predictions will improve when information from the profilometer becomes available to the department and new performance curves can be generated using the nonlinear approach. The historical Mays Ride meter data were not recommended to be useful in determining future rehabilitation projects based solely on roughness through the pavement management system.

EXTRAPOLATION OF CURVES IN PREDICTION MODELS

The pavement performance prediction models used in developing the overall pavement management system will individually predict the performance of every pavement section in the data base. Individual section predictions are made by using their relative positions to the prediction curves that represent them. This is based on the assumption that the decline in pavement condition is similar on all sections within the performance group represented by the group's performance curve. The future condition of each section is a function of its current condition relative to age. A curve is drawn through the index-age point for the section being predicted parallel to the representative prediction curve.

EXPERT SYSTEM AUGMENTING OF PERFORMANCE CURVES

Pavement management relies on predictions of performance on the basis of some historical information. This is the most critical link in the pavement management system. The predictions must make sense and follow the traditional line expected by the pavement engineer on the basis of past experience. If this basic principle is overlooked or not achieved through the development process, the pavement management system has failed.

Three areas needed the augmentation or concurrence of the expert opinions. The first area is that in which there were not enough historical data points. Several of the performance curves had points along the curves where data were missing or limited. Expert opinion was used to say whether the curve shown was reasonable or not and gave alternative or additional points where they should be. In other cases, performance curves cover too short a life span because there were no historical data to support the expected life performance of a particular rehabilitation alternative. One example of this is the recycled concrete pavement class: the state anticipated a life of 30 years, but there were historical performance data for only 5 years. Expert opinion was used to finish the curve. In another case there were not enough historical data; in other instances there were no data at all. An example of this was the performance of CRCPs that were to be rubblized and overlaid with asphalt. This technique is new to the department, so no historical condition information existed. The expert opinion was used to develop the entire curve until enough historical data are collected.

The second area that needed augmentation concerned the maintenance effect. Several of the performance curves, especially the low-volume roads, slope downward at first but flatten out. The performance curves based solely on the historical data are showing the effect of the maintenance effort. The condition of the highway sections is not allowed to fall below certain levels through maintenance effort. The expert judgment was used to answer the question, What would happen if this level of maintenance were not provided and the highway sections were allowed to deteriorate? The expert provided additional data points and specified ranges in which the performance curve reasonably should be at a certain time to represent the do-nothing condition.

The third area in which expert opinion was used was in augmenting the establishment of the terminal serviceability and life span of the performance curve. Performance prediction curves must have an ending point for the system to operate properly. The expert opinion was used to establish the terminal serviceability and terminal age of the pavements.

The people providing the expert data points were the state's design engineer, district maintenance engineer, district engineer, materials and research engineer, and pavement management coordinator, along with the consultant. The expert rules were to validate historical data, provide insight into do-nothing curves, set ranges of reasonable data, and provide additional points when historical data were unavailable.

The steering committee originally specified that a structural index be developed for each of the pavement groups. The resulting index was on a scale that was converted to be the same as the distress index (100 to 0). It became apparent at the first meeting of the pavement performance subcommittee that it was difficult to understand the converted structural index. The structural index was converted into a structural deduct that was easier to understand, and a subsequent meeting was set up for the expert augmentation of the structural deduct.

The performance subcommittee also determined the terminal serviceability level of 50 on the distress index. They believed that few if any pavements would ever reach this level of distress. They also set the relative age of the pavement when it would reach this level if nothing was done to stop it from deteriorating.

The final step was to regenerate the performance curves. The result was the curves representing the historical data and the expert opinions. The curves as they are shown in their final form (*8*) represent the reasonable expected pavement performance for the department's use in generating pavement management outputs.

BENEFITS AND CONCLUSIONS OF SELECTED PERFORMANCE PREDICTION METHODOLOGY

The development of performance curves for the North Dakota pavement system presented many unique and interesting challenges. The objective was to find the methods and the performance curves that best fit the situation.

The North Dakota system is unique because of its installation locations: besides being used by the state, it was installed at seven city and county jurisdictions. All jurisdictions had to be able to use the performance curves. The local jurisdictions also had gravel-surfaced roads for which performance curves were developed. The local jurisdictions were a challenge to develop reasonable performance prediction.

The amount of historical data also varies dramatically. The state has an excellent 5-year historical pavement management data base that stores a wide variety of data. The information that the cities and counties have varies from some historical distress information to none.

While identifying the most appropriate modeling technique for developing the performance curves, the following criteria were identified as being most important:

- New performance curves can be developed when needed,
- Existing curves can be developed readily,
- Curves can be developed with 1 year of data,
- Expert opinions can be used to set up initial curves for new designs or sections,
- Any number of performance curves are allowed,
- Curves can be modified readily, and
- Performance predictions realistically represent historical performance.

The use of the combined distress index and the structural index or deduct performance curves gave the opportunity to also represent nonstructural deterioration mechanisms. The area between structural deducts and the distress index is the nonstructural deficiency in most instances. This was mainly due to the low number of truck loadings in the state. On the higher-ESAL routes, there was some interaction between the distress types.

The nonlinear analysis approach recommended provides the methodology to satisfy all of the requirements established by the state. This approach also incorporates the expert system technique in a straightforward manner. The expert data points and boundary setting were structured into the outlier processing and the raw data base files.

The software developed and used to generate the curves was structured to allow the addition, modification, or deletion of the mathematical coefficients created by the nonlinear analysis. A change in a performance curve will not require a change in the software code. A sophisticated computer program for developing additional curves, and revising these performance curves, was available for modifications to the performance prediction curves.

The curves apply to both newly constructed as well as rehabilitated pavements. The pavement management system calculates the structural component by use of AASHTO layer coefficients for current and future pavement thicknesses. This makes up the structural component of the grouping. The traffic component is calculated at future dates by the use of an ESAL growth factor. The surface types are determined by the resulting pavement section.

The most critical parts of the pavement management system have been established with the development of flexible performance curves that are easy to understand. The result was the development of a pavement management system for the entire state of North Dakota that was flexible, adaptable, and understandable.

RECOMMENDATIONS

A substantial effort has been expended in developing the best predictive performance curves possible from the available historical data and expert augmentation. The curves will need updating as more historical data become available. Historical data are needed in areas that rely heavily on the expert opinion and also for the roughness.

The roughness is a unique situation because the state is converting to a profilometer from a Mays Ride Trailer. When historical profilometer roughness data for 1 or 2 years are available, the prediction curves should be reevaluated and updated.

An area that the state may wish to consider is the establishment of pavement performance sections to monitor. Representative sections for each of the pavement groups should be monitored closely on a yearly basis. Items to monitor may be a more detailed distress survey, recording of maintenance information and effect, close monitoring of truck traffic, and nondestructive testing.

Pavement performance prediction is the most technologically difficult portion of pavement management and the most influential on the system. It is critical that the integrity of the performance curves be maintained and updated over time.

ACKNOWLEDGMENTS

The authors would like to thank all the many members of the North Dakota Department of Transportation who took the time and effort necessary to successfully complete this project.

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Publication of this paper sponsored by Committee on Pavement Management Systems.