Prediction of Pavement Performance by Using Nondestructive Test Results

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The possibility of using nondestructive test results to predict pavement performance is examined. Preliminary analysis found that nondestructive test results and pavement age parameters correlate well with the pavement condition. Also, depending on the pavement type, other factors such as weighted traffic counts correlated with the pavement condition. The data used in the analysis were collected at a military installation located in Virginia. Pavement condition was rated by using the pavement condition index developed by the U.S. Army Corps of Engineers. Nondestructive testing was performed by using a falling-weight deflectometer. The preliminary results indicate that pavement performance can be predicted by using nondestructive testing data.

U.S. pavements are deteriorating rapidly and have an unoptimistic future. Maintenance and incidental user costs are increasing as maintenance and rehabilitation funds fail to keep pavements at an acceptable level of serviceability. Because a dramatic increase in funding is an unrealistic prospect, using available funds to the best advantage is imperative. A pavement management system (PMS) is precisely the tool needed to aid in performing such a task. Optimal use, priority ranking of projects, and pavement system inventory are all immediate benefits of any well-organized PMS.

There are many PMSs available and the key element to all workable systems is a consistent method for rating the condition of the pavement. These pavement condition ratings provide the necessary criteria to establish an effective maintenance policy by relating condition to maintenance needs. However, these rating systems provide only a measure of the current condition of the pavement and not the future condition. To make management benefits maximal, it is necessary to have a reliable method for predicting the future condition of the pavement. Developing a pavement performance model requires that a number of variables be considered, including traffic and structural capacity. The impetus of this paper is to establish whether nondestructive test (NDT) results (as a measure of pavement strength), in combination with other variables such as age and traffic, can be used as predictors of pavement performance.

Nondestructive testing is now being used for structural evaluation of pavements and is a common component in overlay design. Nondestructive testing can be performed quite rapidly and the test results can be applied in a PMS to select the optimum repair alternative for a given project. To have the additional ability to use nondestructive testing results in pavement performance prediction models is a distinct advantage to any PMS.

TEST PROGRAM AND DATA COLLECTION

In a continuing effort to improve the PMS called PAVER, the U.S. Army Corps of Engineers Construction Engineering Research Laboratory has collected NDT results for the pavements at a military installation in Virginia. The installation is currently using the PAVER system as its PMS. The U.S. Army Corps of Engineers Waterways Experiment Station performed the nondestructive testing with a Dynatest 8000 falling-weight deflectometer (FWD). All pavement sections included in the PAVER system were tested (191 sections).

The FWD was selected because of its modeling of moving loads. This has been documented by Hoffman and Thompson (1,2). A future phase of the project will be to compare the test results of the FWD and the model 2008 road rater to ensure that prediction models are not device dependent (road rater testing was performed concurrently with FWD tests).

The actual FWD test scheme consisted of the following:

1. Three test locations in a section;
2. Three impulse-load levels of approximately 5, 9, and 15 kips per test; and
3. Three deflection measurements per load obtained with geophones located at 0, 12, and 36 in. from the center of the load plate per test.

For a given pavement section and load level, the average deflection was calculated for each of the geophone locations. Corrections were made for the temperature at the time of testing. Load versus deflection and deflection-basin characteristics for each section were calculated based on the average responses.

In addition to the NDT data, other information on the pavement sections was obtained from the existing PAVER data base. This included information on pavement structure, pavement layer ages, traffic counts, and pavement condition. The condition rating being used at the military installation in Virginia is the pavement condition index (PCI) developed by the U.S. Army Corps of Engineers. It is an objective rating method based on measuring the quantity and severity of each distress type present in the pavement. The PCI is a numerical indicator that uses a scale of 0 to 100; the scale and associated ratings are shown in Figure 1. The PCI has been proven reproducible

Figure 1. PCI rating scale.

by field testing and correlates well wih the collective judgment of experienced pavement engineers. Additional information and documentation concerning the PCI are provided elsewhere (3).

All data were computer encoded into a data file for use with the Statistical Package for the Social Sciences (SPSS) computer software. The next section summarizes the analysis of data and describes the developed pavement performance prediction model.

MODEL DEVELOPMENT

Variables used for prediction model development include the PCI; pavement inspection date; pavement layer material types; pavement layer thicknesses; pavement layer construction dates; current traffic volume and classification; pavement distress types, quantities, and severities; and FWD test data, temperature, time, load, and deflections for each pavement section. These variables are grouped into six general categories representing specific variable classes:

1. Pavement type,
2. PCI and pavement distress data,
3. NDT information,
4. Pavement construction or inspection dates,
5. Traffic information, and
6. Pavement layer thicknesses.

Table 1 presents a typical variable from each category, the range of that variable, and a typical value.

Table 1. Typical variables for general data categories.

Typical Variable	Typical Value	Range High	Range Low
Pavement type	Asphalt concrete, no overlay	NA	NA
PCI	85	100	42
Maximum FWD deflection (mils), high load level	36.6	97.4	12.7
Surface construction date	June 1952	July 1974	February 1935
Current traffic volume (vehicles/day), type A	1,925	17,616	50
First overlay thickness (in.)	1.5	4.3	0.5

Note: NA = not applicable.

Table 2. Variables for prediction model.

Variable	Mean	Range High	Range Low	Standard Deviation
PCI	84.9	100	42	10.6
AGE	7.0	29	0	5.0
AGESOL	22.4	40	4	8.9
AGETOT	29.4	44	17	7.7
AGECOL	16.4	40	1.0	8.9
PMTOT	6,891	47,642	7.5	11,354
LPMTOT	3.16	4.68	0.875	0.928
DIFF	0.344	1.0	0.151	0.106
AREA	60.2	164.6	23.0	22.4
LOLTHICK	1.26	2.0	0.70	0.29
TOLTHICK	1.96	5.3	0.70	1.09
SURTHICK	2.37	5.0	1.00	1.06
TOTHICK	4.35	8.5	2.30	1.62

Note: AGE = age of pavement since last overlay (yr), AGESOL = age of pavement to last overlay (yr), AGETOT = total age of pavement (yr), AGECOL = age of previous construction to last overlay (yr), PMTOT = weighted traffic total (vehicles/day), LPMTOT = log of weighted traffic total (vehicles/day), DIFF = normalized deflection basin slope, AREA = area of FWD deflection basin at the high load level (in.^{2} x 10^{-3}), LOLTHICK = last overlay thickness (in.), TOLTHICK = total overlay thickness (in.), SURTHICK = surface thickness (in.), TOTHICK = total pavement thickness (in.).

In developing the performance prediction model, linear stepwise regression methods were used to analyze the data. The first step in this analysis was to divide the data by pavement type and run a general correlation matrix with the collected variables and pavement condition. The division of the data by pavement type indicated that there are sufficient cases (population) only to have a statistically significant prediction model for asphalt-concrete pavements with asphalt-concrete overlays. This lack of data does not signify that pavement performance cannot be predicted for other pavement types. In fact, preliminary analysis by using the limited data on other pavement types suggests that pavement performance can be predicted.

The preliminary correlation matrix for the asphalt-concrete overlay sections was used to select variables for further analysis. Variable selection was accomplished by minimizing the linear dependence or correlation between the independent variables (predictor variables). Once this selection process was complete, initial model development was possible. The specific variables considered during the model development are summarized in Table 2, in which the mean, range of values, and standard deviation for each of the variables are also given. Not all of the variables were found to correlate with PCI and these are not included in the prediction model. The model presented in Figure 2 includes pavement layer ages, a weighted traffic variable, and NDT parameters. The specific variables included in the model are described in subsequent paragraphs.

Statistics for the developed performance prediction model give a correlation coefficient equal to 0.765 and a standard deviation of 6.9. The relative significance of each variable group was approximately 60 percent for the age variables, 30 percent for the NDT variables, and 10 percent for the traffic variables. A plot showing the actual PCI versus the predicted PCI is given in Figure 3. These statistics show a significant correlation between predicted PCI and actual PCI, which indicates that NDT results used in conjunction with traffic and pavement age variables can be used to predict pavement performance.

Actual PCI values ranged from 42 to 100. However, the mean PCI value is 85 and as can be seen from the plot in Figure 3, most of the actual PCI values are above 60. Aside from indicating that a good functional pavement network exists at the installation, this data range does not allow low PCIs to be accurately predicted; therefore, a limitation of the current prediction model is that PCI values

Figure 2. Performance prediction model.

PERFORMANCE PREDICTION MODEL FOR
AC PAVEMENTS WITH AC OVERLAYS

$$
\begin{aligned}
\text{PCIP} = 96.6 - [&(.00156 * \text{AGE}^{1/2} * \text{AGETOT} * \text{LPMTOT} * \text{DIFF} * \text{AREA}) \\
&+ (.03062 * \text{AGE}^{1/4} * \text{AGESOL}^{2} * \text{DIFF}^{2}) \\
&+ (.0005728 * \text{AGE}^{2} * \text{LPMTOT} * \text{DIFF} * \text{AREA})]
\end{aligned}
$$

WHERE

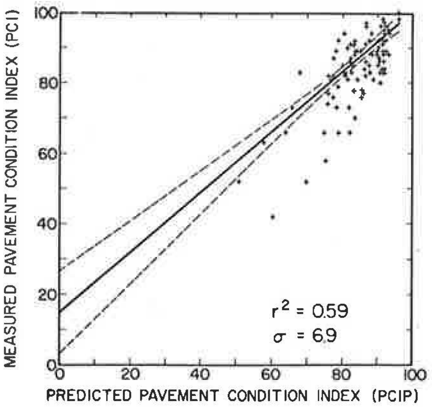
PCIP = PREDICTED PAVEMENT CONDITION INDEX

STATISTICS

CORRELATION COEFFICIENT (r) 0.765

STANDARD ERROR OF ESTIMATE (σ) 6.88

Figure 3. Measured versus predicted PCI.



of less than 60 cannot be predicted with a reasonable degree of confidence.

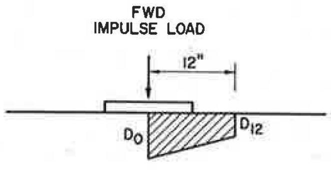
Two parameters calculated from the NDT deflection measurements are used in the performance prediction model. These parameters are determined by using the deflection measurements taken at 0 and 12 in. from the point of loading. Statistical analysis indicates that using only the deflection measurements taken at these two locations provides the best correlations. The parameters are a normalized deflection factor that gives a measure of the slope of the deflection basin (DIFF) and a measure of the deflection-basin area (AREA) at a given load level. Figure 4 presents the DIFF and AREA variables. Although not exactly the same variables are found in other literature on nondestructive testing, both DIFF and AREA correlate strongly with the variables defined by Hoffman and Thompson (1,2). Theoretically DIFF can vary from 0 to 1.0; stiffer pavements have lower values. For AREA the larger the value the less stiff the pavement.

These two variables, AREA and DIFF, were used in the performance model because they were found to have the best correlation with PCI. During the initial development of the performance prediction model, it was considered critical that NDT parameters having engineering significance and best correlation with PCI be used.

Thickness was not found to have a high correlation in the regression analysis. A number of thickness variables were examined, such as total pavement thickness, asphalt-concrete thickness, and a weighted total pavement thickness, yet none of these variables was found significant. However, both thickness and NDT results are used as measures of pavement strength, so it is not surprising that thickness was not found to be a significant variable. In fact, if the thickness were included in the model, it would weaken the effect of the NDT variables in predicting pavement performance.

As is expected, pavement age is an important variable in the prediction of pavement performance. Figure 5 gives the age variables with PCI. Three pavement-layer age variables are included in the prediction model--AGE, AGESOL, and AGETOT. AGE is the time since the last overlay, AGESOL is the time from construction to first overlay, and AGETOT is the total pavement age. Total pavement ages ranged from 17 to 44 yr; the time since the last overlay ranged from 0 to 29 yr. This represents a good distribution of ages for the given pavement type; therefore, pavement age is not expected to present itself as a limiting factor in the performance prediction model.

Figure 4. NDT variables used in regression analysis.



$$\text{AREA} = 12 \times (D_0 + D_{12})$$

$$\text{DIFF} = \left(\frac{D_0 - D_{12}}{D_0}\right)$$

Finally, a weighted traffic variable (LPMTOT) is included in the prediction model. LPMTOT is the natural logarithm of a weighted current traffic count. The current traffic counts are divided into different categories based on the vehicle size and load. Because heavier vehicles (trucks) cause more damage, the traffic counts must be weighted to account for this differential. Coefficients used in weighting the different traffic categories were obtained based on information from Yoder (4) and other researchers (5). The traffic types and weighting are presented in Figure 6.

The prediction model was developed from data obtained at one location and is applicable to that location only. Climatic effects limiting the use of the model to one geographical area have not been considered. A general model will require that data be obtained from different locations, so the number of freeze-thaw cycles and mean annual temperature can be considered.

A major assumption in using NDT data to predict pavement performance is that the NDT response does

Figure 5. Pavement age variables.

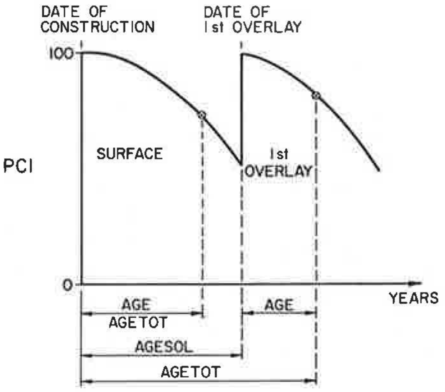


Figure 6. Traffic types and weighting.

TRAFFIC TYPE	DESCRIPTION
TYPE A	PASSENGER, PANEL AND PICKUPS
TYPE B	TWO AXLE TRUCKS AND BUSES
TYPE C	TRUCKS WITH THREE OR MORE AXLES
TYPE D	60^K TRACK VEHICLES AND 15^K FORKLIFTS
TYPE E	90^K TRACK VEHICLES AND 20^K FORKLIFTS

TRAFFIC WEIGHTING

PMTOT = .15 * TYPE A + 80 * TYPE B + 500 * (TYPE C +
TYPE D + TYPE E)

not change with time if other variables such as time of testing and temperature remain constant. Based on evidence from several researchers (6), this appears to be a reasonable assumption if the tests are performed on sound sections of the pavement. The response is expected to remain constant until the pavement starts to fail structurally. This concept is shown in Figure 7. Because the purpose of the predictions is to outline maintenance and rehabilitation requirements, pavement sections should not reach the level where NDT response would change drastically.

The performance prediction model as currently developed has some limitations. However, the statistics from the model indicate that NDT results can be used in combination with other variables to predict pavement performance. Continuing model development should remove the limitations now associated with the prediction model and allow it (or similar models for a given locality) to be incorporated into the pavement system PAVER.

USE OF MODEL IN PMS

Pavement performance prediction models will greatly enhance the usefulness of the PMS. On both the network and the project levels, pavement prediction models assist in the selection of the optimum maintenance strategies. Budget planning, priority ranking of projects, and inspection scheduling can be organized in such a manner as to maximize user benefits. In addition, at the project level, the prediction model information (NDT data, traffic counts, and so on) can be used to select and aid in design of the most advantageous maintenance and rehabilitation (M&R) alternative.

Effective use of the prediction model requires that the necessary information be included in the PMS. For the pavement network considered, nondestructive testing will have to be performed, traffic counts collected, and construction history determined for each pavement section. This information would then have to be stored in the PMS data bank.

A workable network-level application of the prediction model would be to enable optimal budget expenditures. As Figure 8 shows, the PCI has been found to correlate well with the needed level of M&R (3). Conceptually, as can be seen in Figure 9, the required level of M&R dollars for a given pavement decreases with increasing PCI. The prediction model can be used to determine those pavements that will most need repair or be deteriorating rapidly. By applying timely maintenance to those sections before more costly alternatives are required, spending of available monies can be made optimal. Also, the prediction models can be used for identification of critical pavement sections to plan future pavement inspection schedules.

At the project level, the available information can be used for pavement sections identified as needing repair. Available NDT, traffic, and pavement age data can be used in the design and selection of specific M&R alternatives for a given pavement section. This would allow the engineer to select the alternative that will maximize benefits.

Figure 7. Pavement deflection versus pavement life.

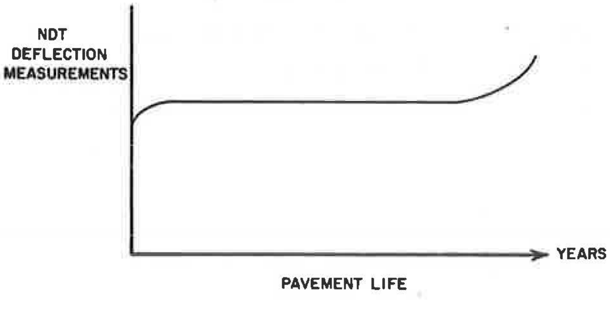
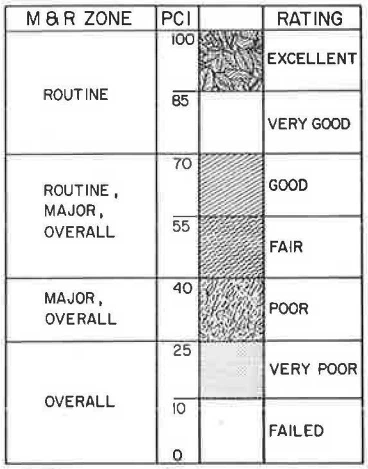
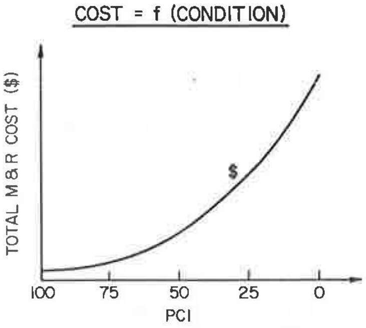


Figure 8. Relationship between PCI and maintenance requirements.



M & R ZONE	PCI		RATING
ROUTINE	100		EXCELLENT
	85		VERY GOOD
ROUTINE, MAJOR, OVERALL	70		GOOD
	55		FAIR
MAJOR, OVERALL	40		POOR
OVERALL	25		VERY POOR
	10		FAILED
	0		

Figure 9. Maintenance cost as a function of pavement condition.



Pavement performance prediction models have important engineering and management applications at both the project and the network levels. The degree of usefulness of the prediction models and the data associated with them, however, depends on how well the engineer uses the information available.

SUMMARY

Based on the findings presented in this paper, it is believed that NDT results do correlate with pavement condition and can be used as a predictor of pavement performance. Using NDT results in addition to other pavement data to accurately predict PCI will allow user benefits to be maximized. Including prediction models based on NDT results in the PMS will permit optimum planning, priority ranking, and scheduling on a long-term basis.

However, before the performance models presented in this paper become practical, further development is required. The possibility of improving the prediction model based on the concept of performance and strength level will be explored. Another application is to simply apply the proven form of the model to data from different locations and redetermine the coefficients for that location. This concept may also be applied to develop a family of curves for performance prediction. Additional data are required for the inclusion of climate factors and other pavement types. Comparisons must be completed to assure that the relationships developed between PCI and NDT results are not device dependent. Once sufficient data have been compiled and analyzed, an accurate pavement performance prediction model will be a welcome addition to any PMS.

REFERENCES

1. M.S. Hoffman and M.R. Thompson. A Comparative Study of Selected Nondestructive Testing Devices. TRB, Transportation Research Record 852, 1982, pp. 32-41.
2. M.S. Hoffman and M.R. Thompson. Backcalculating Nonlinear Resilient Moduli from Deflection Data. TRB, Transportation Research Record 852, 1982, pp. 42-51.
3. M.Y. Shahin and S.D. Kohn. Pavement Maintenance Management for Roads and Parking Lots. Construction Engineering Research Laboratory, U.S. Army Corps of Engineers, Champaign, Ill., Tech. Rept. M-294, Oct. 1981.
4. E.J. Yoder and M.W. Witczak. Principles of Pavement Design, 2d ed. Wiley, New York, 1975.
5. E.L. Skok, Jr., R.N. Doty, F.N. Finn, and J.W. Lyon, Jr. Traffic Factors Used in Flexible Pavement Design. TRB, Circular 240, April 1982.
6. R.C. Koole. Overlay Design Based on Falling Weight Deflectometer Measurements. TRB, Transportation Research Record 700, 1979, pp. 59-72.

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A Model for Predicting Service Life of Flexible Pavement and Its Impact on Rehabilitation Decisions

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A procedure has been developed to estimate the service life of a flexible pavement based on a combination of predicted ride and distress conditions. These conditions are calculated by using equations developed for Texas, taking into consideration measurable values of material properties, climatic conditions, and design factors. Predicted pavement lives were correlated with actual Texas data and acceptable results were obtained. The most significant contributing distress types that affect the service life were identified by using a discriminant-analysis approach. Discriminant functions were developed for each of the prevalent Texas flexible pavements to determine whether the probability of needing rehabilitation is high for calculated levels of ride and distress. An analysis is provided to assess the cost of a delay in rehabilitation once the predicted life has been reached. In this analysis maintenance, user, and rehabilitation costs are taken into consideration. Rehabilitation costs and strategies dependent on pavement condition are modified from those developed for the California pavement management system.

The development and use of a procedure for estimating the service life of an existing flexible pavement in Texas are described; the estimation of service life is based on predicted values of serviceability and distress. A discriminant-analysis approach is used in the development of the model to define the terminal point for rehabilitation.

The study also includes an analysis for assessing the cost of a delay in rehabilitation once the predicted life has been reached. A present-worth and benefit-cost analysis in which rehabilitation, maintenance, and user costs are considered is used in this assessment.

BACKGROUND

The Texas State Department of Highways and Public Transportation sponsored a project to estimate the remaining service life of a flexible pavement. For the purposes of this paper, service life is defined as the total number of equivalent axle loads or the total number of years that the pavement surface lasts, i.e., time or loads between resurfacings. Similarly, the service life of a surface-treated pavement is taken as the time or loads between seals or surface treatments. Following previous work done on flexible pavements in Texas, pavements are classified as asphaltic concrete, overlay, or surface treated for developing the life-prediction models.

An examination of actual data on flexible pavement performance has suggested the following function to represent the loss in serviceability or percentage of distress:

$$g(N) = \exp[-(\rho/N)^{\beta}] \tag{1}$$

where ρ and β are deterioration-rate constants and N is the number of 18-kip equivalent single axle loads (ESALs). Equations for each of the pavement categories have been developed (1) to estimate the deterioration-rate constants for predicting levels of distress and serviceability based on environmental, material, and design properties. The performance equations predict the affected area or degree of severity for each of the following types of distress: rutting, raveling, flushing, corrugations, alligator cracking, longitudinal cracking, transverse cracking, and patching.

Periodic pavement condition surveys have been performed on selected pavement sections in Texas to monitor the serviceability index and the severity and extent of distress. Distress area and severity are rated as none, slight, moderate, and severe, corresponding to numerical ratings of 0, 1, 2, and 3, respectively. In addition these ratings can be converted into percentages of area or severity; for applications reported in this study, 16.6, 33, and 50 percent correspond to ratings of 1, 2, and 3, respectively. This relationship is used in the development of the service life prediction model to numerically express the extent of each type of distress. Once the extent of distress has been estimated, the service life of a pavement can be determined from Equation 1.

MODEL DEVELOPMENT

Discriminant analysis is a statistical technique in which an observation of unknown origin is assigned to one or more distinct groups based on the value of