Table 2. Sample priority list for maintenance class 1, Interstate.

Section No.	ADT per Lane	SN	PSI	PCR	PCR Group	MUC	Traffic Category	Ranking
1350	5 000	40	2.5	80	5	8	B	14
1352	9 000	33	1.6	57	3	2	B	3
1354	3 000	53	2.2	69	4	8	C	12
1356	7 500	23	1.6	49	2	1	B	1
1357	2 200	59	2.6	71	4	8	C	13
1359	10 000	28	2.5	72	4	6	A	8
1360	3 500	57	2.5	74	4	8	B	10
1362	5 500	49	2.4	62	3	2	B	4
1364	6 100	29	2.2	68	4	6	B	9
1366	7 200	42	2.5	64	3	4	B	7
1367	4 200	54	2.0	53	2	2	B	2
1369	1 700	36	1.6	60	3	2	C	5
1381	2 900	55	2.2	67	4	8	C	11
1383	12 000	29	2.3	59	3	3	A	6

Note: Assume 10 percent PSI = 2.10.

lected by the maintenance management program about a particular roadway section.

The priority maintenance file would contain a listing of pavement sections and maintenance priorities established in accordance with the system presented previously. Section priorities can be assigned on both a statewide and districtwide basis, and sections should be listed by route so that district engineers can formulate maintenance projects by grouping together continuous sections of similar PCR groups or priority ranges. This file can be easily assembled by taking data from the pavement condition file and computing the priority by using the criteria shown in Figure 6. There should be cumulative mileage calculations for priority listings to enable early identification of total state or district network mileage for each PCR group or any given priority. Such listings should be completed by late fall or early winter of each year and be given to district personnel, together with the recommended trigger value of statewide priority ranking for maintenance planning, so that agency personnel can begin planning maintenance projects for sections that have priorities above the established value.

ACKNOWLEDGMENT

This paper includes results from a research study (5) for which financial support was provided by the U.S. Department of Transportation, FHWA, and the Ohio DOT. The study was conducted in cooperation with the Bureaus of Maintenance, Research and Development, and Transportation, Technical Services, and District 6 of the Ohio DOT. The paper reflects our views and not necessarily the views of the U.S. Department of Transportation, FHWA, or the Ohio DOT.

REFERENCES

1. M.Y. Shahin and M.I. Darter. Development of a Pavement Maintenance Management System: Volume III. U.S. Army Construction Engineering Research Laboratory, Champaign, IL, Rept. CEEDO-TR-77-44, 1977.
2. Pavement Management Guide. Roads and Transportation Assn. of Canada, Ottawa, Ontario, 1977.
3. D. Anderson. Rehabilitation Decision Model. Utah Department of Transportation, Salt Lake City, 1977.
4. K.W. Kampe. California Pavement Management Decision Criteria. Presented at FHWA Pavement Management Workshop, Olympia, WA, Nov. 1977.
5. K. Majidzadeh and M. Luther. Development and Implementation of a System for Evaluation of Maintenance Repair Needs and Priorities. FHWA, Final Rept., April 1981.
6. J.A. Epps and others. Roadway Maintenance Evaluation Users Manual. Texas Transportation Institute, Texas A&M Univ., College Station, 1974. NTIS: PB 243 010.
7. G.J. Chang and W.A. Phang. Manuals for Condition Rating of Flexible and Rigid Pavements. Ontario Ministry of Transportation and Communications, Downsview, Aug. 1975.
8. K. Majidzadeh. Pavement Condition Evaluation Utilizing Dynamic Deflection Measurements. Ohio Department of Transportation, Columbus, Final Rept. 13-77, June 1977.
9. K. Majidzadeh. Dynamic Deflection Study for Pavement Condition Investigation. Ohio Department of Transportation, Columbus, Final Rept. 16-74, June 1974.

Publication of this paper sponsored by Committee on Pavement Maintenance.

Prediction of Pavement Maintenance Expenditure by Using a Statistical Cost Function

SUE McNEIL AND CHRIS HENDRICKSON

Effective management and control of pavement maintenance expenditures are becoming increasingly important as the magnitude of these costs increases. The use of a statistical cost function as a means of inexpensively and quickly forecasting the level of pavement maintenance expenditure is described. The statistical cost function predicts the level of real expenditures as a function of (a) traffic levels, measured in equivalent single 18 000-lb axle loads, and (b)

pavement age, measured as the number of years since the pavement was last resurfaced. Calibration of the cost model was performed for several turnpikes in the northeastern United States. The function was found to yield average errors of less than 10 percent in application to a turnpike section from 1956 to 1979 and also to an entire turnpike in 1980. Application of the cost function to different regions or roadway types may require parameter recalibration to reflect these different conditions.

In recent years, there has been a greater concern with planning and control of expenditures for roadway maintenance. There are several reasons for this interest:

1. Such expenditures are large; approximately $94 billion was spent on highway maintenance and operation by all units of government in 1978 (1).
2. The paved highway system is not expanding as rapidly as in the past, so the average pavement is becoming older and, presumably, more expensive to maintain.
3. Budgets have been restricted in recent years, and this has spurred efforts to improve maintenance practices.

A critical element in the planning and control of maintenance expenditures has been the preparation of cost estimates. Traditionally, an engineering cost estimate of maintenance expenditure is used for estimating budgets and planning. Such estimates are obtained by summing the products of input quantities and their unit rates. For example, an organization might use the average cost per mile for shoulder maintenance multiplied by the number of miles of shoulders as part of an estimate of maintenance costs. These cost rates are derived from observed costs and quantities, are intended to be specific to a given situation, and rarely take into account factors such as weather, pavement age, and vehicle use. These cost estimates are calculated with the implicit assumption of linear proportionality between the input factors and the total cost.

A statistical cost function is an alternative for estimating maintenance costs for budgets and planning. This paper investigates the use of a statistical cost function for routine roadway maintenance based on turnpike data. This cost function relates roadway expenditures to traffic levels and pavement age, although other explanatory variables are considered.

Appropriate and accurate statistical cost functions would be quite useful in roadway management. First, they can be used to prepare cost estimates. Second, organizations are frequently faced with explaining large cost overruns, and a cost function may be used to indicate the origin of these overruns, such as particularly heavy traffic. Cost control may also be facilitated by checking that costs are not accumulating faster than scheduled or that a particular section of road does not have unwarranted costs, possibly due to mismanagement. Finally, the insights provided by a cost function are difficult to obtain any other way. The function captures the marginal effect of a change in any of the explanatory variables (such as roadway traffic) and the relations between such variables.

Despite these advantages, statistical cost functions have some limitations. The functions cannot be reliably extrapolated outside the range of the data used for calibration. When variables are not explicitly included, the transferability of the model is severely limited. For example, the use of turnpike data in this paper restricts the application of the cost function because each turnpike in the sample is always maintained to a high standard, maintenance is rarely deferred, and there are few problems of underdesign or overloading. The model is only reliably transferable to roads that are comparably managed. Similarly, the model might not be directly transferable to areas that do not have climatic, topographic, or soil conditions similar to those of the areas used for calibration. However, coefficients may be estimated for these conditions with appropriate data.

The cost function presented in this paper for roadway routine maintenance models the aggregate costs of such activities as joint cleaning and sealing, crack filling, drainage maintenance, and minor patching. Essentially, these costs pertain to the road surface. Drainage maintenance is included because of the interrelation between the maintenance of adequate drainage and a good pavement surface. The data were obtained directly from turnpike records and include labor, materials, supervision, and equipment costs.

In this paper, these costs are modeled as an algebraic function of a series of explanatory variables that influence the extent of maintenance required. Broadly, the objective was to develop a function that can be used for forecasting routine maintenance costs and gives some insight into the relations between costs and explanatory variables. The model is also used to test the following hypotheses:

1. Maintenance costs increase as traffic increases, measured as larger vehicle volumes and heavier axle loads.
2. Maintenance costs increase as the pavement surface becomes older.
3. Maintenance costs increase in years or locations with more severe weather.

Although these hypotheses are widely accepted, estimation of cost models can yield numerical estimates of the amount of cost increases due to increases in traffic, pavement age, and roadway area.

The organization of the paper is as follows: (a) an examination of the trends in routine maintenance costs over time with and without inflation; (b) a discussion of the model formulation, including the appropriate factors to be included and the sources of data; (c) a description of the estimation results and their implications; (d) a description of the use of the model for prediction and some experiences in validating the model; and (e) conclusions.

TRENDS IN MAINTENANCE EXPENDITURE OVER TIME

Pavement maintenance expenditures have increased rapidly in recent years, but the extent to which various factors are responsible for this increase is not clear. The solid line in Figure 1 shows the cost per lane mile of maintenance for a 30.2-mile section of the Ohio Turnpike between 1956 and 1979. With few exceptions, the cost of maintenance has increased nearly every year. Over the 24-year period, expenditure increased by more than 500 percent, from $644/lane mile in 1956 to $3917/lane mile in 1979.

One major cause of this cost increase has been inflation in the prices of the labor and materials used in the maintenance process. The extent of this inflation can be seen in the increase in the Federal Highway Administration Highway Maintenance and Operation Cost Index (FHWA MOC) (1). This index indicates the relative costs of typical maintenance inputs in terms of the cost of these inputs in a base year, 1967. The price of these typical inputs has increased more than 260 percent during the period from 1956 to 1979.

Although inflation has been a major cause of maintenance cost increases, it has not been the only

Figure 1. Maintenance cost per lane mile for section of Ohio Turnpike from 1956 to 1979.

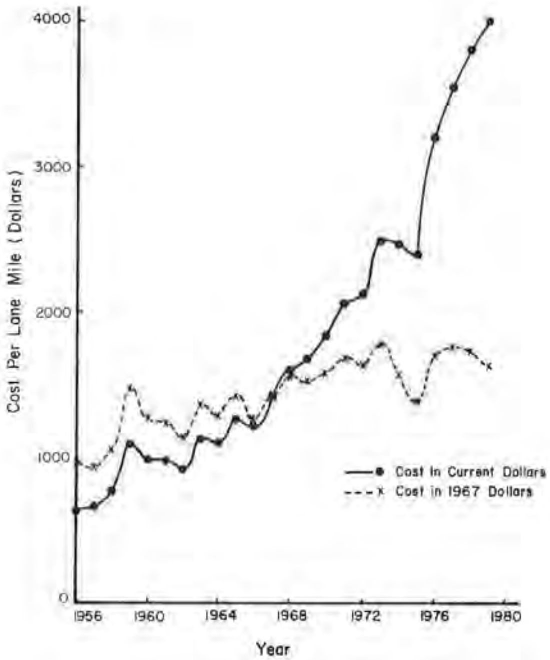
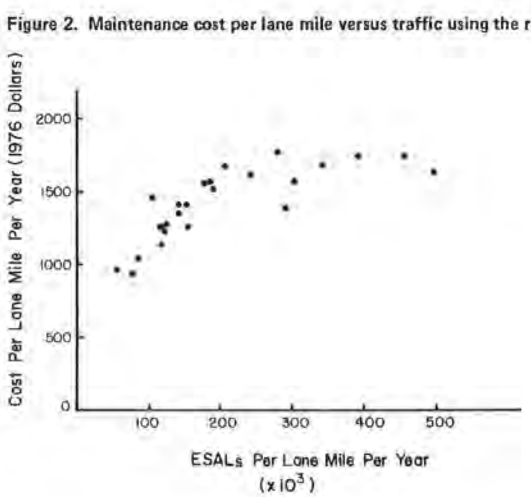


Figure 2. Maintenance cost per lane mile versus traffic using the road.



factor responsible. If the effects of input price inflation are removed by multiplying the costs in any year by the ratio of the FHWA MOC index in 1967 to the FHWA MOC index in that year, then maintenance expenses are converted to constant 1967 dollars. The broken line in Figure 1 shows the resulting trend in maintenance expeditures per lane mile in constant 1967 dollars on the same section of the Ohio Turnpike. Like the curve in which the effects of inflation are not removed, the costs tend to increase over time but at a much slower rate. Over the 24-year period shown in Figure 1, costs increase by 68 percent rather than by the 500 percent that occurs when the effects of input price inflation are not removed. In addition, the variation of these real costs is quite large from year to year.

Clearly, factors other than inflation influence the level of maintenance expenditure. For example, if the traffic that uses a section of road is found from historical records and converted to the number of 18 000-lb equivalent single-axle loads (ESALs) that use the road by using the appropriate factors (2) to account for the relative damage caused by heavier vehicles, the cost of routine maintenance tends to increase with increasing ESALs, as shown in Figure 2. Unfortunately, graphical analysis is insufficient to capture the simultaneous effects of several factors; therefore, multivariate statistical techniques are used here to model the effects of various factors on maintenance costs.

STATISTICAL MODEL OF PAVEMENT MAINTENANCE COST EXPENDITURE

Numerous factors could be postulated as affecting the amount of pavement maintenance expenditures. Among these factors might be the current state of the pavement (including age, pavement type, and the adequacy of past maintenance), stress on the pavement (including traffic and weather effects), the procedures used for maintenance (including the amount of mechanization and the type of materials used), and various institutional factors (including type of management structure, availability of funds, and wage levels of workers). Due to lack of data and knowledge, it would be difficult to include all of these various factors in a cost model. Accordingly, only a few of the most important of these factors can be included. Other factors are either assumed to be constant (so that their influence does not change from one year to the next) or are of lesser importance in determining costs.

For the statistical cost model, the only explanatory variables used are those representing the traffic-related stress and the age of the pavement. As noted above, it is hypothesized that maintenance expenditures will increase with increases in either of these two explanatory factors, which are denoted AGE and ESAL. AGE, the age of the pavement, is measured by the average number of years since a pavement section was last resurfaced. This variable is a proxy for the deterioration of the pavement over time due to the action of the weather. ESAL, the number of equivalent 18 000-lb axle loads, is used as the measure of traffic-related stress. The axle-load equivalency factors (ESALs) represent the relative effects on the pavement of axle loads of different weights (2). The number of ESALs reflects the effects of both increased vehicle volumes and heavier axle loads.

Several other factors and different measures of traffic were explored as additional or alternative explanatory factors. A later section in this paper describes the results of these alternative model forms. As noted above, a major problem with adding these additional factors is obtaining adequate data and variation in the explanatory factors to identify their actual effects.

In order to calibrate the model of maintenance expenditure, detailed data on expenditures, traffic volume (in ESALs), and pavement age were required, even without considering additional factors. Unfortunately, the accounting practices and volume-counting programs of many highway agencies do not report these three pieces of information at a sufficiently disaggregated level to permit meaningful model estimation. Fortunately, many turnpikes routinely gather the required information. Traffic volumes by vehicle types and pavement sections are recorded as part of toll-collection records. Maintenance expenditures and dates at which resurfacing is undertaken are also available by section since the original construction of the turnpikes. The various sources of the calibration data are given in Table 1, where observations are assembled for each year and each roadway section. McNeil and Hendrickson (3) include a detailed description of the

Table 1. Sources of turnpike data.

Turnpike	No. of Sections	Years of Data	No. of Lanes	Total Length (miles)	No. of Observations
Ohio	8	1956-1979	4	241	192
Pennsylvania	5	1978-1979	4	469	10
West Virginia	1	1955-1979	2	88	25

sources and the preparation of the data.

The choice of a model form is also necessary in specifying a statistical cost function. A linear and a log-linear functional form are used for the cost function presented here. These forms may be interpreted as first-order approximations to any function, but both forms have some disadvantages. The linear function implies that there are constant marginal effects that are independent of the level of any variable. A marginal effect in this model is the change in real maintenance cost associated with a unit change in traffic or pavement age. The log-linear form, so called because it is linear in the logarithms of the variables, does not allow any of the variables to take a zero value.

ESTIMATION RESULTS

The models were estimated as follows: For the linear equation,

$$\underset{}{\text{COST}} = \underset{(1.50)}{596\,\text{OH}} + \underset{(5.29)}{3525\,\text{WVA}} - \underset{(0.35)}{476\,\text{PA}} + \underset{(3.93)}{0.0019\,\text{ESAL}} + \underset{(1.93)}{21.7\,\text{AGE}} \quad (1)$$

and, for the log-linear equation,

$$\ell n(\text{COST}) = \underset{(7.19)}{4.22\,\text{OH}} + \underset{(8.71)}{4.94\,\text{WVA}} + \underset{(7.44)}{4.58\,\text{PA}} + \underset{(5.38)}{0.37\,\ell n(\text{ESAL}/100)} + \underset{(2.06)}{0.066\,\ell n(\text{AGE})} \quad (2)$$

where COST is the cost per lane mile (in 1967 dollars) for routine pavement maintenance; OH, WVA, and PA are dummy variables; and the remaining variables are as already defined. OH, WVA, PA take on the value one if the data refer to the Ohio, West Virginia, or Pennsylvania Turnpikes, respectively, and zero otherwise. For example, if the data are for a section of the Pennsylvania Turnpike, then OH = 0, WVA = 0, and PA = 1. The t-statistics are shown in parentheses under the appropriate coefficient in the above equations. For both models, the R^2 value was 0.88.

To account for variables not included and random effects, an error term is assumed in Equations 1 and 2 for calibration of the coefficients. These error terms were assumed to be first-order serially correlated (4). A first-order serial correlation implies that errors in one period carry over to the next. Various physical or economic effects cause this serial correlation. For example, the influence of bad weather in one year increases expenditures in that year and subsequent years. Similarly, the general economic climate may cause a reduction in expenditures from year to year. Statistical tests on preliminary estimates of the models indicated the existence of a first-order serial correlation of this type. The correlation coefficients for successive error terms were 0.93 for the linear model (Equation 1) and 0.78 for the log-linear model (Equation 2) in the final model. These correlations are useful for prediction, as described later in this paper.

Several of the estimation statistics reported above indicate the statistical properties of the models. The R^2 or goodness-of-fit measure is relatively high (R^2 = 0.88) for both models, which indicates a reasonable level of explanation for variations in costs. With the exception of the constants for Pennsylvania and Ohio in Equation 1, the hypothesis that the coefficient equals zero (implying that no relation exists) can be rejected with a 95 percent confidence level for all coefficients based on the values of t-statistics.

The partial derivatives of Equations 1 and 2 with respect to each of the variables give the greatest insight into the model. For the linear model, these derivatives represent the change in cost for a unit change in the variable. In all cases, the signs of the partial derivatives are positive; so, as ESAL and AGE increase, the cost of maintaining a section increases. This result is consistent with the first two hypotheses proposed in the introductory section of this paper; the third hypothesis is discussed in the next section. The equations do not permit economies of scale to be assessed with respect to the number of lanes and the length of the section, since multicollinearity prevented the separation of these effects.

The constants may be interpreted as fixed costs, such as supervisory costs. Different constants were estimated for each turnpike to represent the differences in management and scale. In the case of Pennsylvania, the low t-statistics for the constant and the fact that only 10 observations were available prevent any reliable conclusions being made regarding the differences in constant costs between the turnpikes.

The equations indicate that, as the age of the pavement increases, and the road is subjected to the cumulative effects of weather and time, the cost of maintenance increases. Simply stated, the linear equation (Equation 1) implies that, for each additional year of pavement age, the maintenance costs increase by $21.7/lane mile. In the log-linear equation (Equation 2), the marginal increase in maintenance cost varies with the pavement age, the length of the section, and the traffic, but an X percent increase in age will result in an increase of 0.066 x X percent in cost. For example, suppose a section is four years old and costs $2000 annually to maintain. Without considering serial correlation, one would expect that in another year the maintenance cost would increase by $22 if the linear equation were used and $33 if the log-linear equation were used, due to increased pavement age.

Figure 3 shows the cumulative increases in maintenance costs over 10 years due to the increase in age alone for initial maintenance costs of $1000, $2000, and $3000 annually. Figure 3 also shows the disadvantages of both the linear and log-linear forms: The linear form has constant slope whereas the log-linear form is only valid for pavements that are more than a year old. In effect, the linear model represents the effect of age on average pavements, since no interactive terms between age and other variables are included.

Similarly, the equations also indicate that maintenance cost increases with increased vehicle weights and volumes, expressed in terms of ESALs. Figure 4 shows a graph of the maintenance cost for the linear and log-linear equations for an arbitrary section of the Ohio Turnpike over a range of typical ESALs.

Both the linear and log-linear equations, as approximations to the true functional form of the cost function, verify the first two hypotheses as originally proposed. The graphs included in this section illustrate the implications of the functional forms.

ALTERNATIVE MODELS

In estimating Equations 1 and 2, several alterna-

Figure 3. Cumulative increases in maintenance cost due to age.

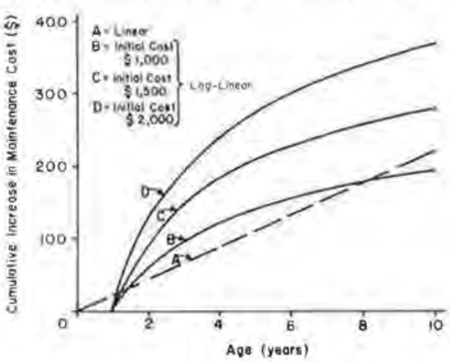


Figure 4. Maintenance cost versus traffic determined by using linear and log-linear equations for maintenance costs.

tives to ESAL values were used as indicators of traffic and additional variables were also included to account for weather. The models represented by Equations 1 and 2 gave the most reasonable fit, but the alternatives warrant some discussion.

ESALs were chosen as the best single measure of traffic that accounts for increases in both traffic volume and traffic weight. The total number of vehicles and the number of passenger-car equivalents (PCEs) using the pavement were also used. The model that used number of vehicles did not produce a good fit, and, although the fit with PCEs was comparable to that with ESALs, ESALs were believed to be a more appropriate measure of traffic. One reason for the comparable fit with ESALs or PCEs was that these two traffic measures were highly correlated in the calibration data set.

The problem of choosing a single measure for traffic could be overcome by estimating specific coefficients for each vehicle class. Unfortunately, there was insufficient variation in the data to permit accurate estimation of such coefficients. ESAL miles of travel seems to be a reasonable traffic measure, since it reflects both pavement stress and amount of traffic.

Equations 1 and 2 were also estimated so as to include two variables to account for weather effects: the number of freeze-thaw cycles (FR) and the amount of precipitation (PR) in each year. These variables were estimated from records of meteorological stations near each pavement section. Although the coefficient estimates had the correct signs and good t-statistics for these variables (except for FR in the log-linear equation), the R^2 only improved marginally (an increase of 0.006 for the linear equation and 0.008 for the log-linear equation) and large changes in FR and PR resulted in only small changes in cost. Typically, a 10 percent change in either PR or FR implied less than a 1 percent change in cost. The variables FR and PR were not included in the final mode because they pose a prediction problem for forecasting and show very little variability in the data used for calibration. Most of the variation in FR and PR occurs between states and is accounted for by the constants.

In addition to the two factors included in the final model--pavement age and traffic--other factors might also be expected to affect the level of pavement maintenance expenditure. Several of these factors were described earlier. Unfortunately, additional factors could not be added to the cost model because of the unavailability of data or the lack of variation of these factors in the calibration data set. In the latter case, the effect of the factor could not be distinguished from the constant term in the cost models. In transferring the cost models to different regions or pavement types, parameters in the model should be recalibrated to ensure good fit because these constant factors might be expected to change and thereby affect the amount of maintenance expenditure.

PREDICTION WITH THE COST FUNCTION

Prediction with either the linear or the log-linear equation may be carried out in two ways. The first method is the most obvious: Substitute for the expected values of the explanatory variables, AGE and ESAL, and obtain the predicted maintenance cost, as illustrated in the following example.

Suppose that an estimate of maintenance costs for section 1 on the Ohio Turnpike is required for 1980. In 1979, the average pavement age on section 1 was 4.8 years and the traffic level was 500 300 ESALs. In 1980, the pavement will be one year older (AGE = 5.8), and we shall assume that the same level of traffic occurs (ESAL = 500 300). With these values, the predicted maintenance expenditure in 1980 is

$$\hat{COST} = 596 + 21.7 * AGE + 0.19 \times 10^{-2}\ ESAL = \$1672 \quad (3a)$$

by using the linear Equation 1 and, taking exponentials on Equation 2,

$$\hat{COST} = 12.4\ ESAL^{0.37}\ AGE^{0.006} = \$1789 \quad (3b)$$

by using the log-linear equation.

Simply substituting for ESAL and AGE results in predictors that are unbiased but not "best" in the sense that the variance is large. This method does not account for serial correlation of the error terms (i.e., "carry-overs" from year to year), but it is inappropriate for a "ball-park" figure.

A more refined prediction estimate may be obtained by considering the serial correlation, but at the cost of more computational effort. Assuming year n was the last year for which actual costs are known, the predicted cost in year i ($\tilde{COST}_i$) is given by

$$\tilde{COST}_i = \hat{COST}_i + \rho^{i-n}(COST_n - COST_n) \quad (4a)$$

when the linear equation is used and by

$$\ell n\tilde{COST}_i = \ell n\hat{COST}_i + \rho^{i-n}(\ell n\hat{COST}_n - \ell nCOST_n) \quad (4b)$$

when the log-linear equation is used, where

$\tilde{COST}_i$ = best linear unbiased estimate of cost in year i;

$\hat{COST}_i$ and $\hat{COST}_n$ = predicted values of cost in the appropriate years, obtained by substituting for the explanatory variables;
$COST_n$ = observed value of cost in year n; and
ρ = correlation coefficient.

For the example described above, if it is known that $\rho = 0.93$ for the linear equation and 0.78 for the log-linear equation and $COST_{79}$ = \$1354, then, by using the linear equation,

$$COST_{79} = \$1354, \widetilde{COST}_{80} = \hat{COST}_{80} + \rho(\hat{COST}_{79} - COST_{79})$$
$$= \$1672 + 0.93(1354 - 1656) = \$1391$$

and, by using the log-linear equation,

$$\ell n\widetilde{COST}_{80} = \ell n\hat{COST}_{80} + \rho(\ell n\hat{COST}_{79} - \ell nCOST_{79})$$
$$= 7.49 + 9.78(7.21 - 7.48) = 7.48$$

or $\widetilde{COST}_{80}$ = \$1454.

After the functions were calibrated by using the data summarized in Table 1, two additional sets of expenditure observations were used to test the predictive ability of the models. Observations from 1956 to 1979 for the last maintenance section on the Ohio Turnpike (section 8) were kept as a hold-out sample to test the transferability of the model to locations similar to those used for estimation. Similarly, observations for all eight sections for Ohio for 1980 were obtained to test the usefulness of the model for forecasting maintenance costs for the sections used for calibration.

For section 8 of the Ohio Turnpike, fitted values were obtained by using the method described above and assuming that the actual cost in the previous year was known. The linear form resulted in an average absolute error in prediction of 9.5 percent for section 8 over the 24-year period. Similarly, the log-linear form resulted in an average absolute error of 8.5 percent. These errors indicate that the model is transferable to sections that have similar climate, traffic, and maintenance standards and that both equations produce similar predictions.

Two types of fitted values were calculated to compare with the 1980 data. The first is an estimation of the cost given the traffic in 1980, and the second is an estimate based on expected traffic for 1980. In practice, the latter method would be used since traffic levels are not known in advance. For illustrative purposes, a linear trend based on the traffic in 1978 and 1979 is used to estimate the 1980 traffic.

The average percentage prediction error and the average absolute percentage prediction are simple measures of the goodness of fit of the equations. The average percentage prediction error is an overall measure of the predictive ability. It is calculated by averaging the percentage difference between the actual and predicted values. The average absolute percentage prediction error is a measure of the magnitude of the expected prediction error in each section for each year. It is calculated by averaging the absolute value of the percentage difference between the actual and predicted values. If the equations underpredict some sections and overpredict others, then the average error of predictions will tend to be zero, whereas the average absolute error of prediction indicates the actual magnitude of the errors.

Assuming the traffic was accurately predicted or known, the average absolute error in predicting the maintenance cost was found to be 5.4 percent compared with an average absolute error of 9.6 percent in the Turnpike budget estimate (converted to 1967 dollars). All of these reported errors have been calculated by using the linear equation, but similar results can be obtained by using the log-linear equation.

By using the predicted traffic, the average absolute error of prediction is 9.1 percent and the average error of prediction is 8.1 percent. These errors are lower than those of estimates made by the Turnpike authority, which indicates that the model can be used successfully to predict maintenance costs. When either the known or the predicted traffic for 1980 was used, the average error of prediction was also below the error in the Turnpike budget estimates. Results are similar for both the linear and log-linear models.

The comparison of errors described here is in terms of real (1967) dollars. In practice, forecasts of the rate of inflation are also uncertain, so budget forecasts in current dollars have an additional source of error. For 1980, however, a simple quadratic projection of the FHWA MOC to 1980 resulted in a negligible error, and the errors reported here would be similar for real or current dollar forecasts.

CONCLUSIONS

This paper has discussed the possible uses of statistical cost functions, described the trends that have occurred in routine pavement maintenance costs on the Ohio Turnpike over the past 24 years, and developed statistical cost functions for routine maintenance expenditures. The cost functions may be used to forecast expenditure in real dollars based on the age of the pavement and the level of traffic on the roadway. The linear and log-linear model forms gave comparable results.

In addition to traffic levels and pavement age, there are numerous other factors that influence the level of maintenance expenditure. However, several validation exercises suggest that the simple cost function may be adequate for many managerial purposes. When used to predict expenditures on a section of the Ohio Turnpike and to forecast expenditures on all sections of that Turnpike, cost functions yielded average absolute errors of less than 10 percent. Recalibration of the model parameters may be necessary in applying the models to different roadway types or circumstances.

Our conclusion is that statistical cost functions can be an effective mechanism for predicting maintenance costs. Highway agencies may consider actions to gather appropriate data and estimate similar models.

ACKNOWLEDGMENT

This research was supported by FHWA.

REFERENCES

1. Federal Highway Statistics. FHWA, U.S. Department of Transportation, 1978.
2. The AASHO Road Test: History and Description of the Project. HRB, Special Rept. 61A, 1961.
3. S. McNeil and C.T. Hendrickson. Three Statistical Models of Pavement Management Based on Turnpike Data with an Application to Roadway Cost Allocation. Carnegie-Mellon Univ., Pittsburgh, PA, Tech. Rept., 1981.
4. J. Kmenta. Elements of Econometrics. MacMillan, New York, 1971.

Publication of this paper sponsored by Committee on Pavement Maintenance.