Model for Evaluating Rehabilitation Costs of Flexible Pavements under Different Climatic Conditions

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The development and application of a procedure for estimating rehabilitation and maintenance costs for the Texas pavement network are described. Key elements of the methodology include a clustering mechanism for partitioning the network into climatically homogenous regions; determination of serviceability and distress characteristics on the basis of the S-shaped performance function; evaluation of pavement failure probabilities using the Weibull distribution; and determination of rehabilitation, routine maintenance, and preventive maintenance costs by means of least-squares regression modeling. Using this computerized methodology, the Texas State Department of Highways and Public Transportation is able to project statewide costs of repair over a specified planning horizon, for pavements with asphaltic concrete on aggregate or bituminous base and asphaltic concrete overlays. Results of an application of the methodology to a selected Texas climatic region are discussed.

The methodology described in this paper constitutes a third-generation computerized decision-support system used by the Texas State Department of Highways and Public Transportation (SDHPT) for projecting pavement rehabilitation and maintenance costs. Similar procedures (*1*) developed during the last ten years address the determination of costs for only sample pavement sections, as well as the evaluation of the cost impact of changes in legal axle-load limits, with no consideration of the effect of climatic factors. For different types of pavement, these procedures estimate the lane mileage requiring rehabilitation work on the basis of performance and survivor curves and shifting mechanisms used when changes in legal axle-load limits are considered.

Several previously developed systems, such as REHAB and NULOAD (*2, 3*), have shown one or more limitations concerning the type and nature of the performance and survivor curves used. For example, REHAB requires that the user input pavement performance and survival curves. NULOAD uses the American Association of State Highway and Transportation Officials (AASHTO) performance equations, which in some cases do not accurately represent the performance of Texas pavements. It uses oversimplified normal distributions to study the survivability of pavements. NULOAD also precludes specific distress types, such as cracking, rutting, patching, flushing, and raveling. Other versions of the Texas system, although using characteristic performance and survivor data, possess important limitations, such as the lack of climatic differentiation, manual data input procedures, and the consideration of a limited number of vehicle types. Thus the primary objective of the new pavement cost procedure is to enhance the reliability of pavement rehabilitation and maintenance cost projections by

1. incorporating the effects of various climatic conditions;
2. developing an efficient procedure to minimize the error in the estimates of the parameters associated with the performance and survivor relationships; and
3. determining rehabilitation and maintenance costs by climatic areas for different pavement types.

The full scope of the study entails the following five tasks:

1. decomposition of the pavement network into five climatically homogenous regions by means of a statistical procedure known as cluster analysis;
2. development of basic rehabilitation and maintenance cost parameters by climatic area;
3. determination of performance and survivor relationships by climatic area for rigid pavements and three types of flexible pavements, i.e., asphaltic concrete on aggregate base (hot mix), asphaltic concrete on bituminous base (black base), and asphaltic concrete overlays;
4. development of strategies to rehabilitate pavements older than terminal serviceability in a specified number of years; and
5. development of an automated data input procedure.

This discussion is limited to the development and application of the methodology for the three types of flexible pavements. The scope of the discussion is also limited to these core elements of the methodology: climatic decomposition by means of cluster analysis, development of pavement performance and survivor curves per climatic area and type of pavement, and determination of rehabilitation and maintenance costs by climatic area over a specified planning horizon.

CLIMATIC DECOMPOSITION

Clustering procedures classify objects into groups according to characteristic data, in such a way that all objects in a particular group are similar to each other but dissimilar to objects in any other group. Reports of the application of these pro-

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TABLE 1 DISCRIMINATION INDICES (R^2) FOR EACH ATTRIBUTE IN EACH CLUSTERING

Attributes	Number of Attributes Considered											
	3	4	5	6	7	8	9	10	11	12	13	Ave
TI	.80	.80	.85	.83	.83	.83	.82	.83	.83	.82	.83	.82
FT	.86	.87	.85	.84	.84	.84	.84	.85	.84	.85	.85	.85
R	.78	.77	.81	.81	.81	.81	.80	.80	.81	.80	.80	.80
AVT1	–	.81	.74	.70	.70	.70	.71	.72	.72	.71	.71	.73
DP	–	–	.72	.73	.73	.73	.73	.72	.73	.73	.72	.72
AE	–	–	–	.69	.69	.69	.69	.69	.69	.68	.69	.69
MC2	–	–	–	–	.67	.67	.67	.67	.67	.67	.67	.67
MDCP	–	–	–	–	–	.68	.67	.67	.68	.68	.67	.67
PE	–	–	–	–	–	–	.64	.65	.65	.66	.65	.65
AVT2	–	–	–	–	–	–	–	.64	.64	.63	.64	.64
NCI	–	–	–	–	–	–	–	–	.47	.46	.46	.46
WFT	–	–	–	–	–	–	–	–	–	.64	.64	.64
MMT	–	–	–	–	–	–	–	–	–	–	.37	.37

cedures in science, management, and the social sciences abound in the literature (*4, 5*).

There are three basic clustering techniques, namely, hierarchical, overlapping, and disjoint. In hierarchical clustering, a cluster may be totally contained in another; overlapping techniques assign an object to one or more clusters, and disjoint clusters result when an object may only belong to one cluster. In the application considered in this article, the objective is to classify pavement sections into clusters on the basis of similar climatic features, so as to determine climate-sensitive performance relationships for pavement sections in different parts of the state. Thus, a disjoint clustering procedure is used. The following primary steps are needed in this application:

1. development of input data,
2. standardization of input data,
3. definition and computation of similarity coefficients, and
4. performing the clustering algorithm.

Development of Input Data

Input data consist of relevant climatic attributes that characterize each Texas county: 20-year monthly averages of Thornthwaite index (TI) (*6*), winter average temperature (AVT1), freeze-thaw cycles (FT), rainfall (R), minimum moisture change (MC1), maximum moisture change (MC2), actual evapotrans (AE), days with precipitation (DP), summer average temperature (AVT2), mean maximum temperature (MMT), potential evapotrans (PE), days with continuous precipitation (MDCP), and wet freeze-thaw cycles (WFT).

These primary input data were analyzed to determine their relative statistical significance with ten initial runs of the clustering procedure, using varying number of attributes ranging from 3 to 13. An attribute is considered significant when its R^2 statistic is higher than a critical value of 0.70. Table 1 shows R^2 values for each attribute and trial run. Examination of these results indicates TI, AVT1, R, FT, and DP as most significant. DP was subsequently dropped because it was considered logically correlated with R.

Standardization of Input Data

Standardization serves to convert original attribute measurements to new unitless numbers, so as to eliminate possible arbitrary effects of attribute units on the grouping of counties into homogenous climatic zones. Standardization is accomplished by the following transformation:

$$Z_{ij} = \frac{X_{ij} - \overline{X}_i}{S_i} \qquad (1)$$

where

X_{ij} = value of attribute i for county j;
X_i = statewide mean value of attribute i;
S_i = statewide standard deviation of attribute i; and
Z_{ij} = standardized attribute value.

Definition and Computation of Similarity Coefficients

The criterion for judging the "similarity" or "dissimilarity" of any two counties is known as the similarity coefficient, and usually varies with the technique used. In this article, a method generally categorized as K-means is used (*7*). The similarity coefficient under this system is defined as the Euclidean distance between the centroid and a point. Each climatic attribute constitutes a dimension in the Euclidean space, and the attribute values for a particular county define a point in that space.

Clustering Algorithm

Clustering is performed by means of a SAS utility named FASTCLUS (*8*). The basic steps performed by FASTCLUS can be summarized as follows:

1. Select the first K complete observations; these are used as seed values of the centroid for each cluster.
2. Calculate the similarity coefficient for each county.
3. Assign each county to the cluster for which it shows the smallest similarity coefficient until all counties are assigned.
4. Calculate new centroids for each cluster, and repeat steps 2 and 3.
5. Convergence is reached when two consecutive values of the centroid for each cluster remain unchanged.

Results and Validation

Clustering was applied to all 254 Texas counties, characterized by the standardized values of the final four climatic attributes. The result was a clustering of the counties into five climatic zones, with some outlying counties showing climatic identities different from their immediate neighbors.

The Texas State Department of Highways and Public Transportation (SDHPT) identifies pavement sections by their host districts, with each district made up of counties. For consistency with this administrative practice, it was necessary to report the climatic decomposition at the district level, such that a group of contiguous districts constitute a homogenous climatic region. To achieve this end, each district was assigned the climatic identity of the majority of its member counties. The final partitioning of the 254 Texas counties into the five climatic regions (Rl through R5) is shown in Figure 1. The 24 districts that encompass the counties were partitioned in this manner among the five regions:

R1 contains districts 1, 10, 11, 12, 19 and 20;
R2 contains districts 6, 7, 8, and 24;
R3 contains districts 4, 5, and 25;
R4 contains districts 13, 15, 16 and 21; and
R5 contains districts 2, 3, 9, 14, 17, 18 and 23.

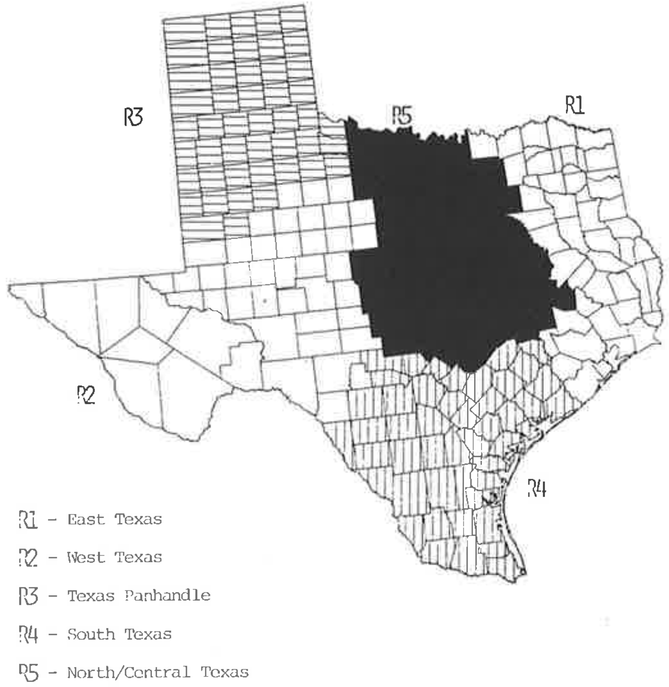

FIGURE 1 Climatic decomposition of Texas districts.

PAVEMENT PERFORMANCE EVALUATION

Performance functions predict the deterioration of pavements, as traffic loadings increase, in terms of the loss of present serviceability index (PSI) or the increase in area or severity of several types of distress. The life cycle of a pavement is completed when a given terminal performance level is reached. Garcia-Diaz and Riggins (*9, 10*) have extensively discussed the basic performance model used in this study; hence only the parameter estimation procedures for this application will be summarized here.

The performance function in terms of PSI can be expressed as

$$P_t = P_0 - (P_0 - P_t) \exp\left(-\frac{\rho}{W}\right)^{\beta} \tag{2}$$

where

P_t = PSI after W 18-kip ESALs
P_0 = initial PSI of pavement section
P_f = lower bound on PSI
ρ = a scale parameter
β = a shape parameter

Similar functions are defined for performance in terms of distress area:

$$A_t = A_0 - (A_0 - A_f) \exp\left(-\frac{\rho}{W}\right)^{\beta} \tag{3}$$

where

A_t = area after W 18-kip ESALs
A_0 = initial value of area index
A_f = lower bound on the area index

and in terms of severity

$$S_t = S_0 - (S_0 - S_t) \exp\left(-\frac{\rho}{W}\right)^{\beta} \tag{4}$$

where

S_t = severity after W 18-kip ESALs
S_0 = initial severity index
S_f = lower bound on severity index

Parameter Estimation for Serviceability and Distress

For deterioration in terms of PSI, the performance function of Equation 2 can be expressed as

$$P_0 - P_t = \alpha \exp\left(-\frac{\rho}{W}\right)^{\beta} \tag{5}$$

where

$$\alpha = P_0 - P_t \tag{6}$$

Taking logarithms of both sides of Equation 5:

$$\ln(P_0 - P_t) = \ln(\alpha) - \left(\frac{\rho}{W}\right)^{\beta} \tag{7}$$

Setting

$$e^{\tau} = \frac{1}{W}$$

we have

$$\ln(P_0 - P_t) = \ln(\alpha) - \rho^{\beta}(e^{\beta})^{\tau} \tag{8}$$

Equation 8 has the form:

$$z = a - bc^{\tau} \tag{9}$$

where

$$z = \ln(P_0 - P_t) \tag{10}$$

$$a = \ln(\alpha) \tag{11}$$

$$b = \rho^{\beta} \tag{12}$$

$$c = e^{\beta} \tag{13}$$

Equation 9 can be generalized as a least-squares regression model of the form:

$$z_i = a - bc^{\tau_i} + \varepsilon_i \tag{14}$$

Using observed values of data points P_i and W_i from pavement sections selected for each climatic region, the least-squares regression model in Equation 14 was evaluated to determine estimates of a, b, and c, which were then used to calculate α, P_f, ρ, and β from Equations 11–13. Table 2 shows the number of test sections used in a parameter estimation for each climatic region and type of pavement. Only a few observations are available for some pavement types in certain regions; however, while the statistical inadequacy of such small sample sizes is recognized, their use may be tolerated on the basis of an apparent similarity in observed PSI values within regions. The resulting estimates of ρ and β are shown in Table 3.

Distress parameter estimates are also obtained using the above procedure. For distress area, the variables z and a of the regression model in Equation 14 are defined as

$$z = \ln(A_0 - A_t) \tag{15}$$

$$a = \ln(A_0 - A_f) \tag{16}$$

Similarly, for distress severity, z and a are defined as

$$z = \ln(S_0 - S_t) \tag{17}$$

$$a = \ln(S_0 - S_f) \tag{18}$$

The parameters b and c in Equation 14 remain as previously defined for the PSI case, and the parameters A_f, S_f, ρ, and β are estimated with the same procedure as for that case. Estimates were based on the most significant distress type affecting each pavement type. Alligator cracking area, alligator cracking severity, and transverse cracking severity proved to be the most significant distress types for hot mix, black base, and overlaid pavements, respectively. Table 4 shows the least-squares estimates of ρ and β for each climatic region based on test sections.

ANALYSIS OF PAVEMENT REHABILITATION RATE

A survival function measures the percentage of mileage on a given pavement category that does not require rehabilitation when a specified critical performance level is reached. Because a pavement section reaches its critical performance index after a given number of load applications, and because a given traffic load is reached at a specific age of the pavement section, load application units are translatable into time units. Hence, the survival function can be used to predict the percentage of mileage not requiring rehabilitation at a specified time.

The time elapsed until a new pavement section needs a major rehabilitation, or the time between major rehabilitations for an existing pavement section, defines the service life of the pavement, often represented by a survivor distribution. The Weibull distribution (*11*) was selected to model the survivor characteristics of pavement sections. The probability density function, $f(W)$, and cumulative distribution function,

TABLE 2 NUMBER OF TEST PAVEMENT SECTIONS BY PAVEMENT TYPE AND CLIMATE REGION

Pavement Type	Region 1	Region 2	Region 3	Region 4	Region 5
Asphaltic Concrete on Aggregate Base	4	9	14	5	4
Asphaltic Concrete on Bituminous Base	0	5	24	13	9
Overlays	20	11	16	8	21

TABLE 3 PERFORMANCE PARAMETERS (PSI) FOR FLEXIBLE PAVEMENT BY CLIMATE REGION

Pavement Type	Region 1		Region 2		Region 3		Region 4		Region 5	
	β	ρ	β	ρ	β	ρ	β	ρ	β	ρ
HOT MIX	0.182	0.116	1.209	0.854	3.170	1.392	0.501	1.324	2.180	1.494
BLACK BASE	0.501	2.710	1.209	1.291	3.003	1.996	0.501	2.710	0.742	5.749
OVERLAY	2.313	4.180	0.140	0.013	2.054	0.118	1.858	1.289	0.975	1.245

$F(W)$, of the Weibull distribution are given by

$$f(W) = \gamma\lambda^{\gamma}W^{\gamma-1}\exp(-\lambda W)^{\gamma} \quad (19)$$

$$F(W) = 1 - \exp(-\lambda W)^{\gamma} \quad (20)$$

where λ and γ are scale and shape parameters, respectively.

In the study of pavement survivability, W represents the number of 18-kip ESALs at which the pavement reaches its critical performance level. The survival function, $s(W)$, is defined as the probability that an individual mile of pavement of a given type survives a traffic load larger than W. Thus:

$$\begin{aligned} s(W) &= 1 - F(W) \\ &= \exp(-\lambda W)^{\gamma} \end{aligned} \quad (21)$$

The maximum likelihood estimators of λ and γ can be found by solving the following nonlinear system of equations (*9*):

$$\left[\sum_{i=1}^{n} W_i^{\hat{\gamma}} \ln(W_i) \Big/ \sum_{i=1}^{n} W_i^{\hat{\gamma}}\right] - \frac{1}{\hat{\gamma}} - \frac{1}{n}\sum_{i=1}^{n} \ln(W_i) = 0 \quad (22)$$

$$\frac{1}{\hat{\lambda}^{\hat{\gamma}}} - \frac{1}{n}\sum_{i=1}^{n} W_i^{\hat{\gamma}} = 0 \quad (23)$$

Equation 22 can be solved by means of the Newton-Raphson method (*12*) for $\hat{\gamma}$. This value of $\hat{\gamma}$ is then used in Equation 23 to find $\hat{\lambda}$.

The following steps are followed to generate a survivor curve for a particular type of pavement in each climatic zone:

1. For each test sample of n sections, obtain (W_i,P_i), (W_i,A_i) and (W_i,S_i); W_i is the cumulative traffic load in year i and P_i, A_i, and S_i are the corresponding PSI, area, and severity measurements.
2. Develop performance functions from the above data using Equations 5–18.
3. For a specified critical value of the performance index, P_c, A_c, or S_c, calculate a corresponding standardized value, g_c, defined as:

$$\begin{aligned} g_c &= \frac{P_0 - P_c}{P_0 - P_f} \quad \text{(for PSI)} \\ &= 1 - A_c \quad \text{(for Area)} \\ &= 1 - S_c \quad \text{(for Severity)} \end{aligned} \quad (24)$$

4. Find W using Equation 25 and obtain the maximum likelihood estimators of the survivor parameters from Equations 22 and 23.

$$W = \frac{\rho^{\beta}}{\ln(g_c)} \quad (25)$$

Tables 5 and 6 show values of the parameter estimates obtained for the three pavement types in each climatic region. Three critical performance levels were considered for both PSI and distress.

PAVEMENT REHABILITATION AND MAINTENANCE COST EVALUATION

Three primary repair activities were considered, namely, rehabilitation, routine maintenance, and preventive mainte-

TABLE 4 PERFORMANCE PARAMETERS (DISTRESS) FOR FLEXIBLE PAVEMENT BY CLIMATE REGION

Pavement Type	Region 1		Region 2		Region 3		Region 4		Region 5	
	β	ρ	β	ρ	β	ρ	β	ρ	β	ρ
HOT MIX	1.257	1.207	3.219	1.433	2.063	2.430	2.027	0.160	1.876	0.938
BLACK BASE	2.128	0.496	6.390	1.391	6.390	1.391	2.128	0.496	2.128	0.486
OVERLAY	0.685	1.597	3.354	0.921	1.240	0.100	2.111	0.705	5.742	0.476

TABLE 5 SURVIVOR PARAMETERS (PSI) FOR FLEXIBLE PAVEMENT BY CLIMATE REGION

Pavement Type	Pc	Region 1		Region 2		Region 3		Region 4		Region 5	
		γ	λ	γ	λ	γ	λ	γ	λ	γ	λ
HOT MIX	1	0.670	0.193	2.088	0.618	3.041	0.160	0.670	0.193	0.670	0.193
	2	1.030	0.078	0.763	0.252	3.476	0.314	1.242	0.184	0.954	0.549
	3	1.216	0.290	1.425	0.656	0.032	0.0001	0.528	0.141	1.288	1.985
BLACK BASE	1	14.128	0.171	1.480	1.234	5.522	0.292	1.603	0.072	14.128	0.171
	2	0.933	0.158	0.775	0.537	0.962	0.194	0.700	0.062	0.933	0.158
	3	0.899	0.363	1.154	1.670	0.539	0.117	0.574	0.037	0.899	0.363
OVERLAY	1	0.940	0.125	1.905	0.273	4.980	0.569	2.201	0.138	2.201	0.136
	2	1.276	0.221	0.029	0.0003	4.591	0.627	1.718	0.278	1.398	0.134
	3	1.639	0.424	0.632	0.393	4.514	0.004	0.939	0.540	0.787	0.555

nance. Rehabilitation consisted of asphaltic concrete overlay on existing pavement; preventive maintenance entailed seal coating; routine maintenance included pothole patching, crack sealing, and base and surface repair.

Rehabilitation Costs

The cost of pavement rehabilitation was represented by the linear regression model defined as

$$TC = C_0 + C_1V_1 + C_2V_2 + \varepsilon \tag{26}$$

where

TC = rehabilitation cost per lane mile
V_1 = cubic yards of overlay per lane mile
V_2 = cubic yards of unpaved shoulder per lane mile

Least-squares estimates of the parameters C_0, C_1, and C_2 were obtained using data from 71 completed and/or awarded rehabilitation projects distributed across different climatic regions.

Routine Maintenance Costs

The EAROMAR cost model was used for routine maintenance cost evaluation, with some modifications for Texas conditions. The modified model was formulated as

$$C_t = \frac{110C_1 + 1000C_2 + 5C_3}{1 + \exp\left(-\dfrac{t - 10}{1.16}\right)} \tag{27}$$

where C_t is the cost in year t per lane mile to be maintained.

TABLE 6 SURVIVOR PARAMETERS (DISTRESS) FOR FLEXIBLE PAVEMENT BY CLIMATE REGION

Pavement Type	Pc	Region 1		Region 2		Region 3		Region 4		Region 5	
		γ	λ	γ	λ	γ	λ	γ	λ	γ	λ
HOT MIX	0.17	0.177	0.0002	0.177	0.0002	0.177	0.0002	1.072	0.960	1.072	0.960
	0.35	2.661	0.949	2.661	0.949	2.574	0.609	2.661	0.949	2.661	0.949
	0.50	2.586	1.047	2.586	1.047	1.313	0.387	0.707	1.085	0.707	1.085
BLACK BASE	0.17	0.177	0.0002	0.177	0.0002	0.177	0.0002	1.072	0.960	1.072	0.960
	0.35	7.216	0.357	7.216	0.357	7.216	0.357	7.216	0.357	7.216	0.357
	0.50	10.758	0.479	10.758	0.479	10.758	0.479	10.758	0.479	10.758	0.479
OVERLAY	0.17	0.177	0.0002	0.177	0.0002	0.177	0.0002	1.072	0.960	1.072	0.960
	0.35	0.387	0.257	0.257	0.256	0.257	0.256	1.394	1.317	1.394	1.317
	0.50	0.661	7.672	7.672	0.913	0.757	0.875	0.614	0.311	0.614	0.311

The parameters C_1, C_2, and C_3 were obtained from SDHPT and modified for various climatic regions on the basis of average daily vehicle miles.

Preventive Maintenance Costs

As for rehabilitation costs, linear regression models were used to represent the cost of seal coating, with a general model formulation given by

$$C_s = C_1\,ADT + C_2\,TSY \tag{28}$$

where

C = cost of seal coating
ADT = average daily traffic
TSY = square yards to be coated

For the purpose of estimating the parameters C_1 and C_2, data from 565 seal-coating projects distributed across various climatic regions were used.

CONCLUSION

The subject methodology amounts to a significant enhancement of the procedure for projecting rehabilitation and maintenance costs for Texas pavements. The clustering mechanism that divided the pavement network into five climatically homogenous regions facilitates the definition of performance and survival parameters along regional lines so that the subsequent evaluation of damage intervention costs reflect varying pavement environmental conditions.

Unit cost matrices for rehabilitation, routine maintenance, and preventive maintenance, as defined for climatic regions and integrated with the performance evaluations, significantly improve the cost evaluation methodology. The result is the ability to analyze and report rehabilitation and maintenance costs at either district or regional level for any combination of traffic level, pavement type, and highway system.

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