ies. TRB, Transportation Research Record 715, 1979, pp. 7-14.
5. Interim Guide for Design of Pavement Structures. AASHTO, Washington, D.C., 1972.
6. Evaluation of AASHO Interim Guide for Design of Pavement Structures. NCHRP, Rept. 128, 1972.
7. J.B. Rauhut, R.L. Lytton, and M.I. Darter. Pavement Damage Functions for Cost Allocation, Volume 1: Damage Functions and Load Equivalence Factors. FHWA, Draft Final Rept. FHWA/RD-82/126, July 1982.
8. F.N. Finn, C. Saraf, R. Kulkarni, K. Nair, W. Smith, and A. Abdullah. Development of Pavement Structural Subsystems. NCHRP, Project 1-10B, Final Rept., Feb. 1978.
9. J.B. Rauhut, R.L. Lytton, and M.I. Darter. Pavement Damage Functions for Cost Allocation, Volume 2: Description of Detailed Studies. FHWA, Draft Final Rept. FHWA/RD-82/127, 1982.
10. J.B. Rauhut and R.W. Kennedy. Characterizing Fatigue Life for Asphalt Concrete Pavements. TRB, Transportation Research Record 888, 1982, pp. 47-56.

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Abridgment

Estimation of Network Rehabilitation and Maintenance Costs over an Extended Planning Horizon

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RENU is a computerized procedure to estimate funding levels required for rehabilitation, preventive maintenance, and routine maintenance of a highway network. The overall highway network consists of one or more pavement systems and each system may include several types of pavements. RENU can also be used to estimate the cost impact of changes in the legal axle load limits. The model uses a serviceability and distress approach to determine the timing for rehabilitation. Performance, distress, and survivor curves are generated based on pavement data collected from the Texas pavement system. RENU has the capability of generating survivor curves for different desired performance levels; it also contains the options of multiple overlays and the addition of new mileage during the planning horizon. A particularly interesting feature of the program is the estimation of rehabilitation costs associated with the upgrading of all pavements already in critical condition at the beginning of the analysis period. In addition to these costs, RENU also estimates the costs of keeping the network at a desired performance level during a specified planning horizon.

The basic objective of the RENU model is to estimate the cost impact of vehicle loadings on a given pavement network; this impact is measured in terms of rehabilitation and maintenance costs for all subsystems of the pavement network during a specified planning horizon. One of the most important contributions of the model is the development of a combined serviceability and distress approach to investigate the effect of a change of legal axle load limits on the life-cycle costs of highways.

Past work on procedures for estimating road rehabilitation requirements due to changes in axle load limits has resulted in the development of computerized methods such as REHAB (1,2) and NULOAD (3,4). The overall development of the RENU procedure was undertaken in three phases. The objective of the first phase of the study was to perform a comparison between REHAB and NULOAD and propose an improved methodology that would take into consideration certain requirements concerning pavement classification, data availability, and district organization of the overall highway system. The results of the first phase of the study were summarized in a series of reports (5-7).

The second phase was the development of a computerized procedure to evaluate the effects on costs and pavement condition of changing legal axle load limits that would overcome the limitations in the REHAB and NULOAD programs. The results of the second phase are summarized elsewhere (8,9).

In the third phase the scope of RENU was expanded to include a budgeting mechanism that would consider the cost of upgrading the pavement network to a specified performance level in addition to the maintenance (routine and preventive) and rehabilitation costs needed to keep the network at that performance level (10).

OVERVIEW OF RENU PROCEDURE

Briefly, the overall methodology can be summarized in four steps:

1. Incorporation of a load-distribution procedure to investigate the shift in a traffic stream toward higher loads if a new legal axle load limit is established,
2. Generation of pavement performance functions based on statistical analyses of observed data to predict riding conditions and pavement distress,
3. Generation of survivor curves to forecast the extent of pavement rehabilitation requirements in each of the periods of a planning horizon, and
4. Determination of rehabilitation costs considering the life cycles of representative sections of pavement under both the current and new legal axle load limits.

In order to decide what factor is causing the need for rehabilitation, a terminal serviceability index is compared against a specified minimum present serviceability index (PSI) value that normally is not reached before pavement distress becomes serious. If the terminal value is below the specified value, it is assumed that the worsening riding condition of the pavement is not the reason for rehabilitation. In this case each of several distress types is checked to see which one may be the cause. As a result of this analysis, pavement rehabilitation may be necessary because a critical value of either area or severity has been reached for one or more of the following types of distress: rutting,

raveling, flushing, corrugations, alligator cracking, longitudinal cracking, transverse cracking, patching, and failures per mile. On the other hand, if the terminal PSI value is not below the specified value, it is assumed that rehabilitation is needed because of the deterioration of the pavement riding conditions.

PAVEMENT PERFORMANCE EQUATIONS

The input information required for the development of the flexible pavement performance equations used in the RENU model can be classified as follows:

1. Traffic factors: average daily traffic, 18-kip equivalent single axle loads (ESALs), average annual growth of traffic;
2. Climatic factors: temperature, annual average freeze-thaw cycles, annual average rainfall, wet-freeze index, Thornthwaite index;
3. Material properties: asphalt content, maximum deflection, liquid limit, plasticity index, percent passing No. 200 sieve, Texas triaxial class, volume of Dynaflect basin; and
4. Design and miscellaneous factors: initial PSI, final PSI, design period, condition surveys, structural number, layer thicknesses.

After field data concerning flexible pavement performance had been examined, the following function was postulated to represent the relative loss in serviceability index for Texas highways (9):

$$g(W) = \exp\,[-(K/W)^n] \tag{1}$$

where K and n are parameters and W is the traffic load in 18-kip ESALs. The damage function [g(W)] can also be expressed as the ratio of the loss in serviceability after W 18-kip ESALs to a specified maximum design loss. Let P_i be the initial PSI (at W = 0), P_t be the PSI after W_t 18-kip ESALs, and P_f be a lower bound on the PSI. Then the relative loss after W_t ESALs can be expressed as follows:

$$g_t = (P_i - P_t)/(P_i - P_f) \tag{2}$$

From Equation 2, it is possible to express P_t as a function of g_t: $P_t = P_i - (P_i - P_f)g_t$. This equation can be further rewritten after using Equation 1. The final result is as follows:

$$P_t = P_i - (P_i - P_f)\exp\,[-(K/W)^n] \tag{3}$$

The representation of P_t as a function of W is shown in Figure 1.

Typical equations for K, P_f, and n have been developed elsewhere (11). As an illustration, the equations for asphaltic concrete pavements with P_i = 4.70 are

$$K = 3.51 + 0.0092SN - 0.0042(TI + 50) + 0.014BASE - 0.023FTC + 0.0026PI - 0.18(TM - 50) \tag{4}$$

$$P = 2.06 \tag{5}$$

$$n = 2.06 \tag{6}$$

where

SN = structural number,
FTC = annual freeze-thaw cycles,
TI = Thornthwaite index,
TM = mean annual temperature,
PI = subgrade plasticity index, and
BASE = thickness of the flexible base.

When P_f is higher than P_t, the analysis of pavement distress can be accomplished by examining the degree to which a type of distress is extended (expressed as the percentage of the pavement surface area in need of repair) and the seriousness of the distress (expressed as crack width, crack depth, relative displacement at a joint, and so on). Usually the severity of a given type of distress can be subjectively estimated by comparing the observed distress with photographs of different levels of severity, such as slight, moderate, or severe, and then choosing numbers between zero and 1 (or 0 and 100 percent) to quantify the seriousness of surface failures.

The distress equations developed for Texas flexible pavements are of the same form as the PSI equations:

$$a = \exp\,[-(a_0/W)^n] \tag{7}$$

$$s = \exp\,[-(a_1/W)^n] \tag{8}$$

where

a = percentage of pavement surface covered by distress,
s = severity of distress expressed in numerical form,
a_0, a_1 = deterioration rates,
n = shape parameter, and
W = traffic level expressed in 18-kip ESALs.

Typical equations for a_0, a_1, and n have been developed (11). Sample equations for transverse cracking severity in asphalt-concrete pavements are

$$a = 1.40 - 0.094(TM - 50) - 0.0088FTC + 0.17H + 0.010PI \tag{9}$$

$$n = 3.28 \tag{10}$$

Similar equations for alligator cracking are

$$a = -0.87 + 0.88SN + 0.011(TM - 50) - 0.376H \tag{11}$$

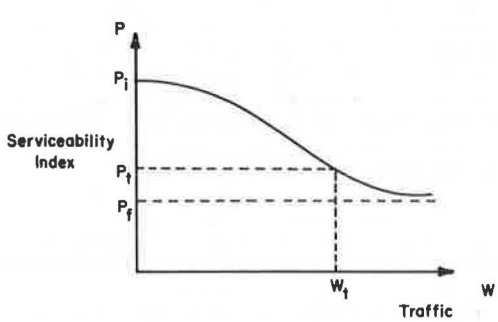
$$n = 2.27 - 0.072PI - 0.015(TI + 50) + 0.92H \tag{12}$$

where H is the thickness of the surface.

SURVIVOR CURVES FOR FLEXIBLE PAVEMENTS

Survivor curves are empirical probability functions used to predict the percentage of pavement mileage of a specific age that will not need rehabilitation in the near future. This in turn can be used to estimate the percentage of mileage that will need rehabilitation in the near future. This information, complemented with data on existing mileage and reha-

Figure 1. Pavement performance relationship.



bilitation cost, can be used to estimate the funds needed in each period of a specified planning horizon.

The survivor functions developed for RENU can generally be written as follows:

$$V = 1 - \exp(-q/W^r) \quad (13)$$

where

- V = percentage of surviving mileage,
- q = parameter affecting the location of the survivor curve,
- r = parameter affecting the shape of the curve, and
- W = traffic level since construction or last rehabilitation.

For each pavement system of a large-scale network, survivor curves have been developed for typical pavements that are rehabilitated or reconstructed at several different performance levels; these performance levels are defined as follows:

Highway System	PSI for Performance Level: High	Medium	Low
Interstate	3.2	3.2-2.3	2.3
U.S. and state	3.0	3.0-2.1	2.1
Farm to market	2.9	2.9-2.0	2.0

Table 1 gives typical values of the parameters q and r for 10 types of flexible pavement. A graphical representation of the three survivor curves used by RENU in the distress option is shown in Figure 2. As can be seen, the percentage of pavement surviving after a given traffic volume is less when the performance standard is higher.

SPECIAL FEATURES

The RENU program computes the initial cost required to upgrade the system to one of the three levels of performance and the cost of keeping the pavement at the specified level with the corresponding survivor curves. The following particularly interesting features can be used for identifying meaningful scenarios for the RENU procedure.

New Options for Pavement Below Critical Performance Levels

According to this feature, the user of RENU can input a strategy for upgrading in a prescribed number of years all pavements in critical condition at the beginning of the analysis period. The corresponding mileage is reduced uniformly over the specified period by placing overlays of thicknesses that may be different from those used in ordinary cases. Critical pavements are referred to as pavements older than terminal serviceability (POTTS) in the RENU program.

Multiple Overlays

The first overlay of a pavement is placed at the time specified by the survivor curve. Additional overlays are placed at time intervals prescribed by the user.

Routine Maintenance

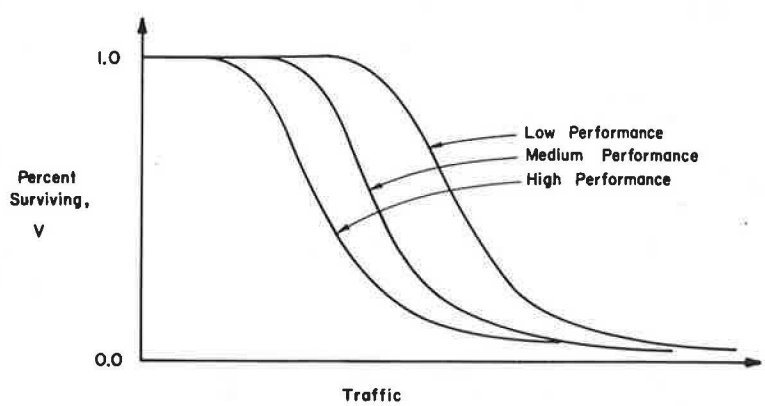
The POTTS mileage is considered part of the mileage that should receive routine maintenance. The corresponding rehabilitation costs are estimated by using the EAROMAR procedure (12) and cost information provided by the user. Three maintenance activities

Table 1. Constants for survivor curves for flexible pavements (distress option).

Type of Pavement	Constant by Performance Level: High r	High q	Medium r	Medium q	Low r	Low q
Rural, high-traffic HMAC	2.5	0.44×10^{16}	2.5	0.69×10^{16}	2.5	0.10×10^{17}
Rural, low-traffic HMAC	2.5	0.10×10^{14}	2.5	0.16×10^{14}	2.5	0.23×10^{14}
Urban, high-traffic HMAC	3.2	0.24×10^{22}	3.2	0.43×10^{22}	3.2	0.69×10^{22}
Urban, low-traffic HMAC	3.0	0.11×10^{18}	3.0	0.19×10^{18}	3.0	0.29×10^{18}
Rural, high-traffic overlay	2.5	0.21×10^{16}	2.5	0.43×10^{16}	2.5	0.76×10^{16}
Rural, low-traffic overlay	3.0	0.27×10^{16}	3.0	0.62×10^{16}	3.0	0.12×10^{17}
Urban, high-traffic overlay	3.1	0.19×10^{21}	3.1	0.46×10^{21}	3.1	0.91×10^{21}
Urban, low-traffic overlay	2.9	0.12×10^{17}	2.9	0.26×10^{17}	2.9	0.50×10^{17}
Urban, surface treated	2.3	0.12×10^{11}	2.3	0.25×10^{11}	2.3	0.45×10^{11}
Rural, surface treated	2.3	0.92×10^{9}	2.3	0.19×10^{10}	2.3	0.33×10^{10}

Note: HMAC = hot-mix asphalt concrete.

Figure 2. Survivor curves for three different performance levels.



are included in the analysis: patching, crack sealing, and base and surface repairs.

Preventive Maintenance

For each of the three levels of performance for which survivor curves were developed, preventive maintenance is provided in terms of seal coats. The user of the program specifies the time between seal coats and the cost per lane mile. This option is also available for pavements in POTTS.

New Mileage

New mileage can be added to the highway network as a result of reconstruction or new construction. This new mileage is considered by maintenance and rehabilitation in the same manner as existing pavements.

USE OF THE MODEL

The application of RENU reported in this paper can be summarized as follows. The Texas highway network was classified by system (Interstate, U.S., state, and farm to market), by pavement type (surface treated, asphaltic concrete, overlaid asphaltic concrete, and concrete), and by traffic level (low and high) for the five regional areas of the state. Age versus lane-mile distributions were identified for each of the previous classifications by using the state's road inventory file.

Overlay thicknesses were calculated for three possible desired standards of performance. These were based on typical deflection data and traffic levels. A sample of the values used in the procedure is given below:

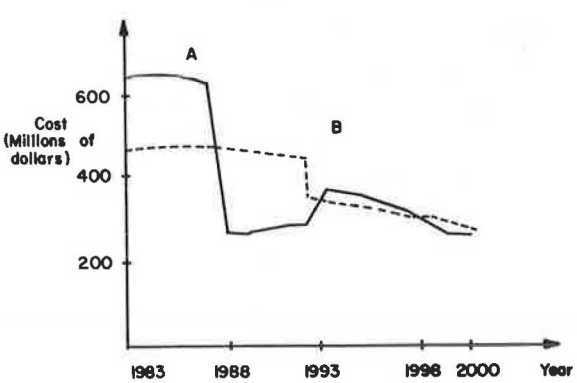
Highway Type	Overlay Thickness (in.) by Performance Level		
	High	Medium	Low
U.S. Interstate	1.75	3.50	4.50
U.S. or state	1.25	2.40	3.30
State or farm to market	0.40	1.40	1.90

Cost information on pavement rehabilitation and maintenance was obtained from the districts throughout the state. Average costs used in the application being discussed are summarized as follows: pothole repair, $125/yd³; crack sealing, $0.25/linear ft; base and surface repair, $12.50/yd²; seal coating, $3,200.00/lane-mile; and asphalt-concrete overlay, $69.00/yd³.

By using the RENU model, the Texas State Department of Highways and Public Transportation was able to compare the monetary requirements for different desired levels of performance and different strategies for upgrading pavements for which rehabilitation was overdue. Figure 3 shows a comparison of some of the possible strategies. Curve A shows the total annual rehabilitation, preventive maintenance, and routine maintenance costs, assuming that all critical pavements will be upgraded in 5 years. Curve B, the dashed line, shows the same total costs if the same pavements are upgraded in 10 years.

It may be noted in Figure 3 that there exists a considerable backlog of pavements due for rehabilitation and that once they are brought up to a specified performance standard, the total costs of maintenance and rehabilitation level off. From a budgetary point of view, funds need to be increased during the first portion of the analysis period to provide a desired pavement system quality; from then on, a reasonably constant budget will be required to maintain that level.

Figure 3. Total annual maintenance and rehabilitation costs.



REFERENCES

1. Guide to the Highway Rehabilitation Forecasting Model. McKinsey and Co., Inc., New York, N.Y., 1976.
2. Interoffice Memorandum with Updated Documentation for REHAB. State Department of Highways and Public Transportation, Austin, Tex., 1979.
3. Effects of Changes in Legal Load Limits on Pavement Costs, Volume 1. FHWA, Rept. FHWA-RD-79-73, July 1978.
4. Effects of Changes in Legal Load Limits on Pavement Costs, Volume 2. FHWA, Rept. FHWA-RD-79-74, July 1978.
5. A. Garcia-Diaz, R.L. Lytton, and D. Burke. Evaluation of Computer Programs NULOAD and REHAB, Volume 1. Texas State Department of Highways and Public Transportation, Austin, Res. Rept. 298/312-1, Sept. 1980.
6. A. Garcia-Diaz, R.L. Lytton, and D. Burke. Evaluation of Computer Programs NULOAD and REHAB, Volume 2. Texas State Department of Highways and Public Transportation, Austin, Res. Rept. 298/312-1, Sept. 1980.
7. A. Garcia-Diaz, R.L. Lytton, and D. Burke. Evaluation of Computer Programs NULOAD and REHAB, Volume 3. Texas State Department of Highways and Public Transportation, Austin, Res. Rept. 298/312-1, Sept. 1980.
8. A. Garcia-Diaz, R.L. Lytton, and D. Burke. Computerized Methods of Projecting Rehabilitation and Maintenance Requirements Due to Vehicle Loadings, Volume 4. Texas State Department of Highways and Public Transportation, Austin, Study 298/312-1, Aug. 1981.
9. A. Garcia-Diaz, R.L. Lytton, and D. Burke. Computerized Methods of Projecting Rehabilitation and Maintenance Requirements Due to Vehicle Loadings, Volume 5F. Texas State Department of Highways and Public Transportation, Austin, Study 298/312-1, Aug. 1981.
10. A. Garcia-Diaz. Documentation of the Modified Computerized Procedure RENU2 to Estimate Pavement Network Rehabilitation and Maintenance Costs. Texas Transportation Institute, Texas A&M Univ., College Station, Res. Rept. 992-1, March 1983.
11. R.L. Lytton, C. Michalak, and T. Scullion. Texas Flexible Pavement Design System. Proc., 5th International Conference on the Structural Design of Asphalt Pavements, Univ. of Michigan, Ann Arbor, Vol. 1, Aug. 1982.
12. B.D. Butler, Jr. Economic Analysis of Roadway Occupancy for Freeway Pavement Maintenance and Rehabilitation, Volumes 1-3. FHWA Rept. FHWA-RD-76-14 and FHWA-RD-76-15, 1974.

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