SELECTION OF OPTIMAL PAVEMENT DESIGNS CONSIDERING RELIABILITY, PERFORMANCE, AND COSTS

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This paper deals with the overall problem of selecting the best or optimum pavement design strategy for a given project situation. Many alternative design strategies for any given project are possible because of the many possible combinations of alternative materials, layer thicknesses, and future maintenance and rehabilitation options. In addition, imposed in any given design situation are several constraints, such as maximum funds available for initial construction, limiting policies of a particular agency, and future availability of maintenance and rehabilitation funds. Each of the possible design strategies has associated costs (and benefits), performance, and reliability—3 important judgment factors that may be used to help select the optimal design strategy. This paper discusses the derivation of alternative design strategies, their associated costs, performance, and reliability, and the use of the total cost method of economic analysis to select an optimal design strategy within the various design constraints. The optimum design is defined here as the design that has the minimum total cost (including construction and future maintenance, rehabilitation, salvage, and user costs) and is within the various constraints that are specified by the designer. Certain practical constraints such as a minimum acceptable design reliability level or funding limitations may modify the selection of the optimum design strategy somewhat.

•SELECTION of the optimum or best pavement design strategy for an airport or highway pavement is of vital concern to the engineer. Factors such as pavement reliability, performance, and costs and their interrelations must be considered by the engineer in selecting the optimum design. The purpose of this paper is to outline a methodology and to make recommendations for selecting an optimal design strategy.

The recent development and implementation of computerized pavement design systems have focused attention on the many possible alternative designs that exist for any given project. Usually several material alternatives, many possible combinations of layer thicknesses, and many alternative future maintenance and overlay policies can combine to give a large number of possible alternative design strategies. There are also the inherent uncertainty in traffic prediction and the many inaccuracies involved in the design models and in the accurate estimation of design inputs for predicting future performance. Historically these variations have been considered in design by the use of safety factors or other arbitrary decisions based on experience. However, for more uniform overall design, a reliability concept is needed.

How can a pavement engineer sort out the variables, analyze the problem, and select the best design for a given project? What decision criteria should be used in selecting

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an optimal design? The scarcity of highway funds, materials, and fuel and the desire for adequate pavement performance make the need to select optimum designs greater than ever before. The use of basic considerations of pavement costs, reliability, and performance along with engineering judgment and a systems approach provides the framework for such selection procedures. Considerable experience in this area has been gained in developing and implementing flexible and rigid pavement design systems for the Texas Highway Department (3, 9, 10).

In this paper the nature of the problem is considered, and then pavement performance, reliability, and costs are discussed. Finally, the concepts needed to determine the optimum design strategy are presented.

ALTERNATIVE DESIGN STRATEGIES

A complete pavement design strategy includes not only the initial pavement structure to be constructed but also any future rehabilitation needs (i.e., maintenance, overlays, and seal coats) and the general traffic-handling methods to be used during rehabilitation. Each strategy is analyzed in terms of its predicted performance and estimated costs throughout the analysis period.

Consider the actual freeway pavement design situation given in Tables 1 and 2. These specific inputs were used in the Texas flexible pavement design system for the example problem considered.

1. The surfacing is to be hot-mixed asphalt concrete, the base is to be an asphalt-stabilized gravel, the first subbase layer if used can be crushed limestone or lime-stabilized material, and the second subbase layer if used can be untreated granular material or a layer of lime-stabilized subgrade soil.
2. Based on previous experience, the surface thickness is set at 1.5 in. (38.1 mm), the asphalt-stabilized base thickness is set from 5 to 8 in. (127.0 to 203.2 mm), and the subbase thickness if selected by the program is set from 5 to 10 in. (127.0 to 245.0 mm).
3. The pavement design may or may not provide for future asphalt concrete overlays for stage construction. Minimum time to the first overlay is set at 4 years with 6 years minimum between overlays. Routine maintenance such as spot patching and crack filling will be necessary.
4. Various safety factors could be applied to allow design at varying levels of reliability.
5. Several ways of handling traffic during overlay operations are available with probable differences in user delay costs, depending on traffic volume magnitude.

This design problem was run through the Texas flexible pavement design system, and the results illustrate the many possible design strategies that can occur through available combinations of materials, thicknesses, maintenance policies, traffic-handling methods, and safety factor levels for this typical pavement design. The total number of feasible designs considered was 2,671; several are given in Table 3. Examples of 3 alternative designs are shown in Figure 1. Figure 1a and 1b show designs with a reliability level of 50 percent, and Figure 1c shows a design with a reliability level of 95 percent. The problem is to select the optimum design strategy from among the many possible strategies of which these are only illustrative. The criteria to be used to select the best or optimum design strategy must be determined. Three important judgment or evaluation criteria to be used in the selection are pavement performance, reliability, and total costs. Engineering experience must be included in the evaluation process mainly because of inadequacies in the predictive capability of the pavement design procedures now available.

Thus a pavement design strategy may be considered in terms of its performance, which gives a measure of the level of serviceability the pavement is giving to the user throughout its design life; its reliability, which gives an index of the probability that the desired level of performance will be achieved; and total costs (and benefits if they can be estimated), which give a monetary value required to provide such a pavement strategy. Each of these factors is briefly described.

Table 1. Design input data for flexible pavement system example problem.

Input	Value
Basic design criteria	
Length of analysis period, years	20.0
Minimum time to first overlay, years	4.0
Minimum time between overlays, years	6.0
Minimum serviceability index P2	3.0
Design confidence level, percent	95
Interest rate or time value of money, percent	7.0
Program controls and constraints	
Number of summary output pages desired, 8 designs/page	3
Number of materials	6
Maximum funds available per yd^2 for initial design, dollars	9.99
Maximum allowed thickness of initial construction, in.	36
Accumulated maximum depth of all overlays (excluding level-up, in.)	8.0
Traffic data	
ADT at beginning of analysis period, vehicles/day	4,260
ADT at end of 20 years, vehicles/day	12,400
One-direction 20-year accumulated number of equivalent 18-kip single-axle loads	3,661,000
Average approach speed to overlay zone, mph	60.0
Average speed through overlay zone (overlay direction), mph	40.0
Average speed through overlay zone (nonoverlay direction), mph	50.0
Proportion of ADT arriving each hour of construction, percent	7.0
Trucks in ADT, percent	11.0
Environment and subgrade	
District temperature constant	30.0
Swelling probability	1.00
Potential vertical rise, in.	5.00
Swelling rate constant	0.15
Subgrade stiffness coefficient	0.24
Construction and maintenance data	
Serviceability index of initial structure	4.2
Serviceability index P1 after an overlay	4.2
Minimum overlay thickness, in.	0.3
Overlay construction time, hours/day	10.0
Asphaltic concrete compacted density, tons/yd^3	1.80
Asphaltic concrete production rate, tons/hour	90.0
Width of each lane, ft	12.0
First-year cost of routine maintenance, dollars/lane-mile	50.00
Incremental increase in maintenance cost per year, dollars/lane-mile	20.00
Detour design for overlays	
Traffic model used during overlaying	3
Total number of lanes of facility	4
Number of open lanes in restricted zone (overlay direction)	1
Number of open lanes in restricted zone (nonoverlay direction)	2
Distance traffic is slowed (overlay direction), miles	2.00
Distance traffic is slowed (nonoverlay direction), miles	0.20
Detour distance around overlay zone, miles	-0.00
Paving materials (Table 2)	

Note: 1 yd^2 = 0.8 m^2, 1 in. = 25.4 mm, 18 kip = 80 kN, 1 mph = 0.04 m/s, 1 ton/yd^3 = 1,329 kg/m^3, 1 ton/hour = 0.025 kg/s, 1 ft = 0.3 m, and 1 mile = 1.6 km.

Table 2. Design input data for paving materials.

Layer	Code	Materials	Cost per Yd^3	Strength Coefficient	Min Depth (in.)	Max Depth (in.)	Salvage (percent)
1	A	Asphalt concrete pavement	13.99	0.96	1.50	1.50	20.00
2	B	Asphalt-stabilized base	15.46	0.90	5.00	8.00	15.00
3	C	Crushed limestone	7.13	0.60	5.00	10.00	75.00
3	D	Lime-stabilized material	6.02	0.55	5.00	10.00	65.00
4	E	Untreated granular material	5.07	0.40	6.00	10.00	50.00
4	F	Lime-stabilized subgrade soil	2.87	0.30	8.00	8.00	0.00

Note: 1 in. = 25.4 mm, and 1 yd^3 = 0.76 m^3.

PAVEMENT PERFORMANCE

A clear definition of pavement performance is essential to the selection of an optimum design. Pavement performance has been defined as a "measure of the accumulated service provided by a pavement, i.e., the adequacy with which a pavement fulfills its purpose" (1). As used in this study, it is more explicitly defined as the integral of the serviceability curve over a specified time period for a section of pavement. Performance thus represents the area beneath the serviceability-time plot. Serviceability is defined as "the ability of a specific section of pavement to serve high-speed, high-volume, mixed (truck and automobile) traffic" (2). The measure of serviceability at any point in time is in terms of a subjectively based panel rating, which can be estimated by some equation that uses objective mechanical measurements. In Texas, this is known as the serviceability index, SI, which is based on the same 0-to-5 scale as used at the AASHO Road Test.

The models that currently exist for predicting the performance of a pavement are only approximate. Also, the serviceability of a pavement varies significantly along a project because of the random nature of distress. Serviceability index values can be determined for consecutive 0.2-mile (0.3-km) sections of pavement for example. A typical distribution of SI values for each 0.2-mile section in both directions along 15 miles (24 km) of highway pavement is shown in Figure 2. The mean SI is 2.7, but it varies from 1.6 to 3.9 along the project. A project average may be computed and plotted with time along with the distribution of SI values to completely characterize the project performance. User costs and rehabilitation costs are directly related to the serviceability (or performance) of a pavement as subsequently discussed.

PAVEMENT RELIABILITY

The following general definition of pavement reliability has been formulated (4): Reliability is the probability that the pavement system will perform its intended function during its design life (time) under the conditions (or environment) encountered during operation. The 4 basic elements involved in this concept of pavement system reliability are probability, performance, time, and environment. Reliability is the probability of success that a system has in performing its function. There are significant variations and uncertainties in prediction associated with all the models in any pavement design system, and, therefore, the chance of success will always be less than 100 percent. The phrase "to perform its function" refers to the actual serviceability time history being as good as or better than predicted during design. Time is an essential element in the definition of reliability because the reliability of a pavement must be considered over a design analysis period. The environmental conditions include the operating circumstances under which the pavement is used. The environment of a pavement greatly affects its life span, its performance, and consequently its reliability. Thus, if the environment changes significantly from that for which the pavement was originally designed, the pavement may not perform with the same reliability as it would have without the change.

An increase in the reliability of a pavement design may be accomplished by applying safety factors to various design parameters or directly to the components of the design strategy, such as pavement thicknesses. For example, the expected design traffic might be increased, or the allowable design subgrade strength might be reduced. This would result in different pavement design strategies that have a greater overall safety factor or higher reliability. The importance of this reliability concept may be illustrated by considering a design model that was derived by using a statistical least squares regression (such as that in the AASHO Interim Guide) and then by using average values of design inputs. The resulting pavement design strategy is only 50 percent reliable with respect to performing as intended. The overall performance safety factor is essentially 1.0 in this situation. The resulting average performance of this design may often not be satisfactory to the user or design engineer, and therefore some types of safety factors need to be applied.

A rational method for applying safety factors to pavement design so that pavement reliability may be estimated has been developed by Darter and Hudson (3). This theory

Table 3. Alternate pavement design strategies for example problem.

Output	Best Design Strategies in Order of Increasing Total Cost					
	1	8	12	18	20	24
Material arrangement	ABD	ABC	ABD	ABD	ABC	ABC
Cost, dollar/yd^2						
Initial construction cost	4.07	4.23	4.16	4.06	4.26	4.14
Overlay construction cost	0.57	0.55	0.57	0.72	0.57	0.72
User cost	0.03	0.03	0.03	0.05	0.03	0.05
Routine maintenance cost	0.16	0.16	0.16	0.16	0.16	0.16
Salvage value	-0.35	-0.38	-0.31	-0.31	-0.34	-0.36
Total cost	4.49	4.59	4.62	4.67	4.69	4.71
Number of layers	3	3	3	3	3	3
Layer depth, in.						
D(1)	1.50	1.50	1.50	1.50	1.50	1.50
D(2)	5.00	5.50	6.00	5.75	6.25	5.75
D(3)	8.00	6.50	6.00	6.00	5.00	5.50
Number of performance periods	3	3	3	4	3	4
Performance time, years						
T(1)	5.4	5.5	5.3	5.1	5.3	5.1
T(2)	13.1	13.4	12.7	11.7	12.6	11.9
T(3)	20.9	21.4	20.2	18.5	20.1	18.9
T(4)				24.5		25.0
Overlay policy (including level-up)						
O(1)	1.3	1.3	1.3	1.3	1.3	1.3
O(2)	1.3	1.3	1.3	1.3	1.3	1.3
O(3)				1.3		1.3
Swelling clay loss, units of serviceability index						
SC(1)	0.93	0.94	0.92	0.89	0.92	0.90
SC(2)	0.51	0.51	0.50	0.49	0.50	0.50
SC(3)	0.16	0.16	0.17	0.18	0.17	0.18
SC(4)				0.06		0.06

Note: 1 yd^3 = 0.76 m^3, and 1 in. = 25.4 mm.

Figure 1. Alternative design strategies.

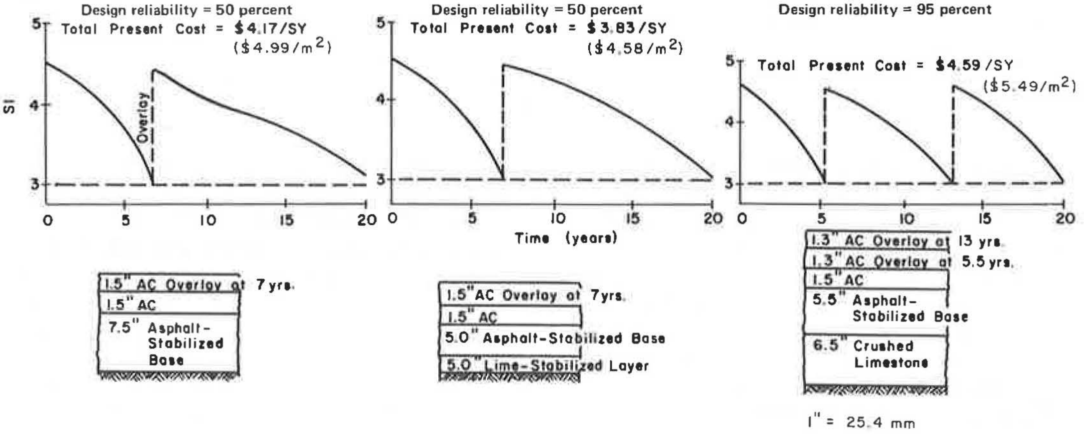
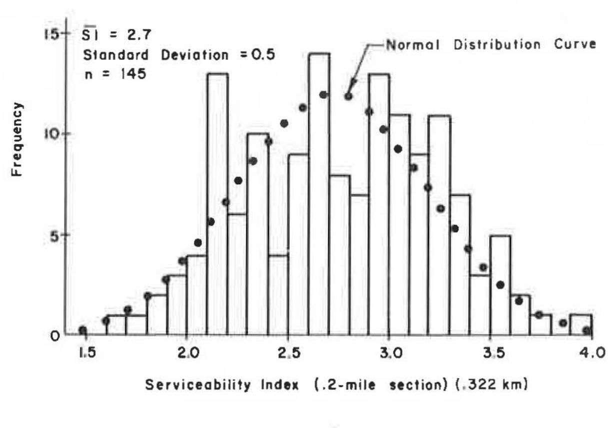


Figure 2. Frequency distribution of SI along in-service highway pavement of uniform design.



was applied to the Texas flexible and the rigid pavement systems (FPS and RPS), which are currently both undergoing implementation by the Texas Highway Department (3, 4, 5, 8).

A brief description of the approach for the application of safety factors to pavement design for determining pavement design reliability is given here, and details can be found in other reports (3, 4). The following conceptual equation illustrates some of the major factors that cause loss of serviceability of a pavement:

Serviceability loss = f(traffic loadings, subgrade shrink-swell, thermal cracking, . . .)

For simplicity of presentation, the probabilistic theory discussed here is limited to the consideration of serviceability loss due to traffic loadings only. The other factors are also important, and the theory should be expanded to consider them in future work.

Stochastic Nature of Design Variables

All pavement design methods that consider loss of serviceability due to repeated traffic loadings (i.e., fatigue) ultimately require the determination of 2 parameters: the prediction of equivalent traffic loads to be applied, n, and the prediction of the equivalent allowable load applications the pavement-subgrade system can withstand, N, to minimum acceptable serviceability. The allowable applications depend on many design factors, such as pavement thickness T, material properties M, and environment E. These are illustrative of the multitude of factors that can affect the multivariate N.

The actual number of applied loads n will depend on many factors, such as average daily traffic A, percentage of trucks t, axle-load distribution L, and equivalency factors F. These factors, estimated for a certain analysis period, are illustrative of those that are involved in the determination of n. To illustrate the process, we can show with appropriate models that N and n are functionally related to the several design variables as follows:

$$N = f(T, M, E, \ldots)$$

$$n = f(A, t, L, F, \ldots)$$

In existing design methods, N and n are assumed to be determined precisely by the input variables. In reality, there is considerable variability associated with each design factor. The 3 basic types of variations associated with flexible pavement design parameters may be considered as variation within a design project length, variation between estimated design and actual values, and variation due to lack of accuracy of the design models. The purpose of this study is to develop a method of accounting for this variability in the design process. As a first step, estimates of these variations of the design parameters must be made for in-service highway pavements.

Because all the factors are variable, it therefore follows that f(T, M, E, . . .) and f(A, t, L, F, . . .) are themselves stochastic variables determined by the combined statistical characteristics of the design factors. The N and n have been found to be distributed approximately log normal.

Because N and n are multivariates and stochastic in nature, the variance of each must be determined before the reliability theory can be applied effectively. This may be accomplished by using the partial derivative method (4, 8). The estimates of variance for N and n thus determined may now be used in the next phase where the reliability function is derived.

Reliability Function

Reliability R for pavements is defined here as the probability that N will exceed n.

$$R = P(N > n)$$

This is synonymous with the statement that reliability is the probability that the serviceability level of the pavement will not fall below the minimum acceptable level before the end of the design performance period. If N and n are assumed to be log normally distributed and statistical theory is applied, the following reliability function may be derived:

$$\overline{\log N_R} = \overline{\log n} + Z_R \sqrt{S_{\log N}^2 + S_{\log n}^2} \tag{1}$$

where

$\overline{\log N_R}$ = average number of equivalent 18-kip (80-kN) single-axle load applications to be used for design at level of reliability R,

$\overline{\log n}$ = average traffic forecast of equivalent 18-kip (80-kN) single-axle load applications, and,

Z_R = standardized normal deviate from normal distribution tables with mean zero and variance of one for given level of reliability R.

This reliability function may be used either to design a pavement for a specific reliability level or to analyze the reliability of a given pavement.

TOTAL PAVEMENT COSTS

There are several important costs associated with pavement systems. To ascertain the optimum design strategy from an economical standpoint requires that the total costs associated with the pavement facility be determined along with the user costs.

Facility Costs

Total facility costs include those of initial construction, rehabilitation, routine maintenance, and salvage value.

The initial construction cost of the pavement may be considered as the total construction cost of the pavement materials in place. Rehabilitation requirements such as overlays may also be determined by using an in-place construction cost of the overlay material used. The time after initial construction that rehabilitation will be needed and the amount required may be estimated by using various available rehabilitation design models or past pavement performance experience in a particular location. The costs of routine maintenance, such as crack filling, may be estimated from past experience by using maintenance cost records in a given location for a particular type of pavement structure.

There are also the costs associated with the inherent value of the pavement structure materials at the end of the design analysis period. The value of a material at the end of the analysis period may be predicted by estimating a percentage of its original construction value. This will be essentially a negative cost of the total facility cost. Those costs that occur after initial construction must be discounted to the present time by using an appropriate interest rate. These would include maintenance and salvage costs. Each of these costs could be converted to a cost/unit area of pavement. The total facility cost then may be determined as follows:

$$TFC = IC + RHB + RM - SV \tag{2}$$

where

TFC = present value of total pavement facility cost,
IC = initial construction cost,
RHB = present worth of the sum of rehabilitation costs,
RM = present worth of the sum of routine maintenance costs, and
SV = present worth of the salvage value of the pavement at the end of the analysis period.

Typical details for calculating and estimating each cost factor may be found in a Texas Highway Department manual (5) and a report by Scrivner et al. (6).

User Costs

User costs associated with pavement systems are determined from the increase in cost to users due to pavement maintenance operations and pavement roughness. This results from increased travel time delays, vehicle operation costs, accidents, and user discomfort.

Travel delays may result from both maintenance operations and rough pavements. A procedure to determine travel delay costs and vehicle operating costs due to overlay construction has been developed by Scrivner et al. (6). The model is included in the Texas flexible and rigid pavement design systems. Several traffic-handling techniques were modeled for various types of overlay and highway conditions so that the user delay cost can be estimated. The user delay cost may then be converted to a cost/unit area of pavement by dividing by the area of the pavement overlay operation. Delay in travel time due to a reduction in the serviceability index has been recently estimated by McFarland (7). The reduction in speed was assumed to vary with the serviceability index, type of road, and location (rural and urban) of the pavement. Travel time costs as a function of pavement serviceability index, type of road, and rural-urban location were estimated.

Vehicle operating costs, accident costs, and discomfort costs were also estimated by McFarland (7) as a function of the serviceability index, urban-rural location, and type of road. As the serviceability index decreases, the vehicle operating costs increase in a curvilinear manner. The accident costs were found to increase because of decreased serviceability index. Rural accident costs were determined as a function of the serviceability index and type of road. A final user cost factor related to the serviceability index was discomfort costs. Discomfort costs were determined to be a function of pavement serviceability index, urban-rural location, and type of road.

The total user costs may be approximately estimated from these results in such form as cost/vehicle-mile or cost/unit pavement area as follows:

$$TUC = DLM + DLS + VO + AC + DS \quad (3)$$

where

- TUC = present worth of total user costs,
- DLM = vehicle delay costs due to maintenance operations,
- DLS = vehicle delay costs due to rough pavement,
- VO = costs of vehicle operation caused by rough pavement,
- AC = costs of accidents due to rough pavements, and
- DS = costs of discomfort due to rough pavement.

This capability makes it possible to estimate, at least approximately, the user benefits (or cost savings to users) for a pavement section during its design analysis period. Therefore, a total pavement cost (facility plus user costs) may be determined for a given design strategy by first expressing these costs in the same units (such as dollar/yd^2, dollar/m^2) and then summing to obtain total pavement costs.

SELECTION OF OPTIMAL DESIGN STRATEGY

Basis for Selection

The pavement design strategy that is selected for construction is usually based on engineering design models, but the selection may also include considerations such as the following: past experience of the designer, including experience with the specific project location and available materials; policies and practices of the particular design agency or "owner" of the project; results previously achieved by the agency using the design procedure; and funds available for initial construction of the project.

The methodology developed in this study for selecting the optimum pavement design strategy is based on the following considerations.

1. There are many feasible design alternatives in any given design situation, and each should be evaluated as a possible candidate for selection. Different project situ-

ations will require different levels of performance and reliability. These levels must be carefully determined. An Interstate highway pavement requires a greater reliability than a farm-to-market road pavement, for example.

2. The costs associated with the pavement user due to travel delays and rough pavements must be considered in an effective pavement alternative design evaluation. The planned or even the unexpected, unplanned maintenance of airport and highway pavements is no longer just the concern of the maintenance foreman.

3. There exists an urgent need to allocate relatively scarce pavement funds and materials in the best manner possible so as to optimize the level of service to the pavement user (including minimizing fuel consumption).

Based on these considerations, the optimum pavement design strategy is defined as the design that provides a satisfactory level of performance to the user at a minimum acceptable level of reliability that the pavement will perform as expected and also has a minimum total cost. The total costs consist of facility and user costs as previously defined. The concept of satisfactory performance level and minimum acceptable reliability level depends on the project characteristics and will subsequently be defined.

Selection of Optimum Design at a Given Reliability Level

A designer usually examines only a few of the many possible design alternatives because of the time involved in manually deriving design strategies, or because of the inability of the design method to consider all alternatives or both. The Texas Highway Department has attempted during the past several years to develop and implement computerized pavement design systems for rigid and flexible pavements. These systems are well documented (3, 6, 9, 10) and provide the engineer with all feasible designs at several levels of reliability. They contain various structural, maintenance, and economic design subsystems that attempt to model the real-world pavement environment during its design life period. The SAMP program developed through NCHRP Project 1-10 is another example of a working system that provides a similar capability and is being prepared for implementation (11).

The alternative designs at a specific level of reliability (or magnitude of applied safety factor) range from strategies with heavy initial construction and low future maintenance to light initial construction with high future maintenance. These alternative designs may be generated on a deterministic basis by pairing all possible combinations of material types and layer thicknesses and then predicting their performance for various maintenance strategies. This process will result in a number of feasible design strategies at a certain reliability level. The facility and user costs may be calculated for each design and the total cost determined. The designs can then be arrayed in order of increasing total cost to facilitate the selection.

An example design situation is given in Tables 1 and 2 for an actual freeway project. The design confidence level or reliability indicated is 95 percent. The inputs include various constraints such as minimum and maximum layer thickness and maximum funds available for initial construction. The program generated 2,671 feasible alternative designs. This large number was mainly due to the several alternative material types, layer thicknesses, and various maintenance strategies. Several alternative output designs are given in Table 3. They are arrayed in terms of increasing total cost during the design analysis period. The total cost ranges from \$4.49 to \$4.71/yd^2 (\$5.37 to \$5.63/m^2) for the first to twenty-fourth strategy. It could be argued that there is no significant difference in the cost of the first several of these designs because of the difficulty in estimating the many costs involved. Therefore, all of the first several design strategies may be considered equal in cost and can be evaluated in terms of their level of effectiveness or performance, the experience of the engineer with the various materials, and perhaps other decision criteria. The most desirable design strategy may then be selected for this given level of reliability (or applied safety factors). This reliability means that the designer can be about 95 percent confident that the pavement will perform as good as or better than predicted. The effect of swelling subgrade soil in reducing the pavement serviceability index is also considered in this case (Table 3).

Optimum Design Strategies at Several Reliability Levels

Pavement design is usually carried out in practice at only one level of reliability by applying a specified safety factor to one or more design inputs. For example, three-fourths of the flexural strength of concrete is taken to be the "working stress" in one rigid pavement design procedure. The consideration of designs at various levels of reliability has been done in several ways in the past, however, but not on a formalized basis. A rational method of application of safety factors to pavement design, which has been implemented into the Texas design system, has been discussed. This approach requires that the magnitude of the uncertainties and variations associated with the design system be quantified. The consideration of design strategies at several levels of reliability is important because of the large differences in factors such as user costs and pavement performance at different reliability levels.

As pavement design reliability increases, pavement performance on the average increases, as shown in Figure 3 for 2 design strategies. The mean expected performance curve is higher for the strategy with greater reliability. The general conceptual relation between pavement reliability and performance for a given project situation is shown in Figure 4. At every reliability level a range of alternative designs exists as has been discussed, and each of these designs exhibits a certain performance. The range of performance of these alternatives is shown in Figure 4.

As the level of reliability increases, facility costs increase and user costs decrease. The increase in facility cost with increased reliability is due to the increased costs of more substantial and higher quality pavements needed to obtain higher performance reliability. In other words, to provide a pavement that will have a greater chance of performing as desired, and, on the average, of showing superior performance will result in higher facility costs. The general relation between pavement reliability and facility costs is shown in Figure 5. Again there exists a range of alternative designs at each reliability level as previously discussed. This possible range is shown by the band width in Figure 5. On the other hand, as reliability increases, the pavement user costs, in general, decrease. This occurs because pavements with greater performance reliabilities are, on the average, smoother and require less maintenance and rehabilitation, which results in decreased user delay, accident, vehicle operation, and discomfort costs. They result in greater benefits to the user.

The various interrelations that have been discussed can be summarized by considering the plot shown in Figure 6. This total cost plot was developed by summing ordinates of user and facility costs for each level of reliability. The shape can be logically explained by using 3 hypothetical design strategies, i, j, and k, for a given project, as is indicated on the plot. Strategy i represents a design at a low level of reliability or low safety factor (not less than 50 percent, however). Such a strategy would have a small chance of performing as expected and would on the average exhibit rather low SI throughout its design life and have associated with it several unexpected pavement failures that would require rehabilitation repairs. The facility costs may be relatively low, but user costs would be relatively high because of a low serviceability level of the pavement during its design life. This results in high user delay and vehicle operation costs due to excessively rough pavements.

Strategy k represents a pavement design at a relatively high level of reliability where the corresponding facility costs are very high and user costs are low because of a high performance level of the pavement. This strategy represents very heavy initial construction and minimal or no maintenance.

Strategy j represents a pavement somewhere between the extremes of i and k. This design strategy represents a design that has facility and user costs that combine to give an overall minimum total cost. The level of performance and reliability expected is between that of i and k.

If the total cost method of economic analysis is used, the level of facility cost should be increased until the total cost begins to increase. The point of minimum total cost as shown in Figure 6 represents the optimum design reliability from an economic standpoint. Because the decreases in user cost are the benefits that would be used in the benefit-cost method of analysis, the total cost method gives essentially the same level.

Figure 3. Mean expected performance curves for design strategy with relatively high reliability R_H and low reliability R_L.

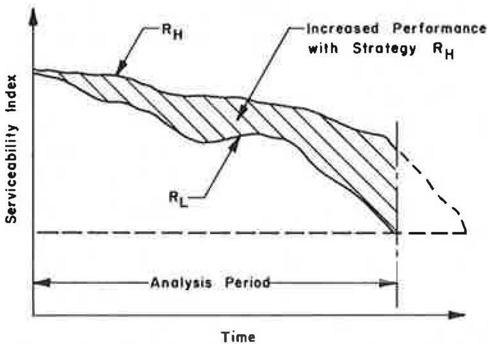


Figure 4. Conceptual relation of reliability and performance.

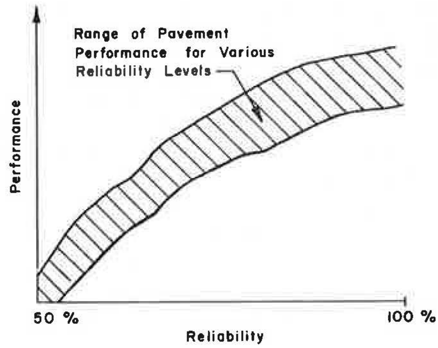


Figure 5. Relation between pavement costs and reliability.

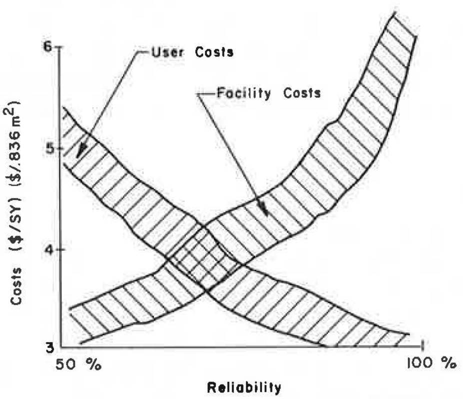


Figure 6. Relation between total pavement costs (user plus facility) and pavement reliability.

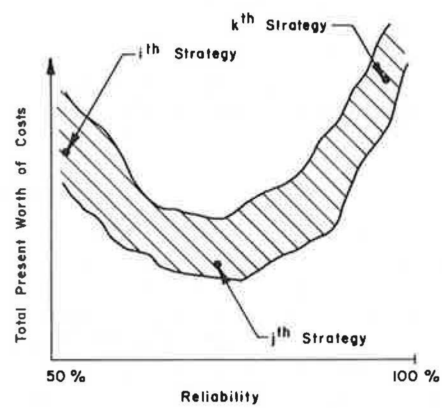


Table 4. Projects and selected design reliability level using FPS-11 program.

Project	Highway	Functional Classification[a]	ADT	Equivalent 18-kip Single-Axle Loads	Selective Reliability Level (percent)
1	FM-2625	Minor collector	135[b]-260[c]	30,000	95
2	FM-1840	Minor collector	730-1,215	289,000	95
3	US-70 and US-84	Minor arterial	955-1,950	658,000	95
4	SH-300	Major collector	1,100-1,850	637,400	99
5	SH-24	Minor arterial	1,600-3,200	800,000	99
6	US-84	Principal arterial	1,670-2,750	1,069,000	99
7	US-271	Minor arterial	1,350-2,150	1,450,000	99
8	SH-71	Principal arterial	2,800-4,900	1,562,000	99
9	US-290	Principal arterial	2,130-6,200	3,661,000	99
10	Loop-289	Principal arterial	2,725-16,400	2,840,000	99.99
11	SH-360	Principal arterial	6,800-15,100	4,657,000	99.99
12	Loop-1	Principal arterial	19,660-32,380	6,894,000	99.99

Note: 18 kip = 80 kN.
[a]From ref. 12. [b]Initial 1 direction. [c]End 1 direction.

The reliability associated with design strategy j represents the level that would generally give a minimum total cost for the project and therefore would give the highest benefit-cost ratio. However, other factors that must be evaluated in practice are performance and reliability. Does the expected performance curve give an adequate level of service to the user? This must be judged by the engineer from previous experience and from the magnitude of associated user costs. The variations in serviceability that are shown in Figure 1 must be considered in making this evaluation. Considerable research is needed in this area to better define user requirements. The other factor, which is perhaps easier to quantify, is the minimum practical level of design reliability.

An approximate estimate of the minimum level of reliability for Texas conditions was obtained by developing a series of flexible pavement designs for 12 projects, ranging from farm-to-market roads to urban freeways; the Texas FPS design system was used. Designs were made for each project at 5 levels of reliability, ranging from 50 to 99.99 percent. Experienced engineers then selected the design strategy that they considered adequate for each project. Table 4 gives the projects and levels of reliability selected. The reliability levels shown should be considered only as approximate. The selected design reliability increases with the function or type of highway pavement being designed and the traffic volumes and equivalent load applications.

Therefore, it may be concluded that the minimum level of design reliability increases with the magnitude of possible consequences of failure. These consequences may involve adverse public reaction due to rough pavements or to a new pavement requiring, soon after construction, major rehabilitation that would increase with traffic volume. User delay, accident, or discomfort costs may also be considered as an index of the consequences of failure. The consequences of failure are greater for a higher type of highway, and therefore the minimum design reliability level is greater. Tentative minimum levels of design reliability have been determined for the Texas pavement design system and are given in the manual (5).

SUMMARY

A methodology for determining optimal pavement design strategies is outlined. An optimal design strategy is defined as the design that gives a satisfactory level of performance to the user at a minimum acceptable level of reliability and also that has a minimum total cost. To select an optimal design, one should generate alternative designs at various levels of reliability and determine their associated costs and performance. An optimal design can be selected from these alternatives by using a methodology such as that described here. Engineering judgment and experience play an important part in this last selection process, as discussed.

Even though the designer is somewhat restricted by factors such as inadequate design procedures, agency design policies, and lack of control over maintenance operations, the state of the art of pavement design has progressed to the point that pavement costs (and benefits), performance, and reliability can be roughly estimated and used to assist in selecting optimal pavement design strategies. Considerations such as those presented here will, it is hoped, lead to improved practices that will result in better allocation of scarce pavement funds and in improved service to the user.

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