impact of subgrade variability on pavement construction-maintenance cost trade-offs

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A philosophy for determining design values for parameters that display stochastic variation is presented. An illustrative example is given that uses the subgrade CBR of a flexible airfield pavement as the stochastic parameter whose design value is desired. The analysis takes into account several plans for pavement maintenance. Based on the trade-off between construction costs and maintenance costs, the optimal maintenance and reconstruction plan and the optimal design CBR are chosen. It becomes clear from the discussion and example that it is just as possible to arrive at an uneconomical design by using too low a design CBR as it is by using too high a value. The only way to determine the proper design CBR is to consider life-cycle costs and evaluate the construction-maintenance cost trade-offs.

•There is within the pavement engineering profession a growing awareness of an interest in the life-cycle approach to pavement design. Simply stated, the life-cycle approach requires that all costs anticipated over the expected life of the pavement be included in the economic evaluation of alternate pavement systems. With this approach, realistic economic trade-offs can be made between factors affecting the average annual cost of pavements, with specific emphasis on the trade-offs between initial construction costs and maintenance costs.

If entire pavement sections failed uniformly as units, economic evaluation of the trade-offs between initial construction costs and maintenance costs would be straightforward and relatively simple to accomplish. Unfortunately, pavements do not fail uniformly but have service lives that vary over a wide spectrum. Thus, the problem of evaluating costs and benefits becomes a stochastic problem and must be treated as such.

Many factors influence the performance of pavements such as climatic conditions, traffic, and material properties, each of which may cause variability in pavement performance trends. It is generally agreed, however, that one of the more dominant factors affecting pavement behavior and performance is the subgrade support condition. Because subgrade support is a dominant factor controlling pavement performance and because subgrade soils are variable, the question arises of whether it is more economical from a life-cycle costing standpoint to design pavements based on the least expected support condition with little or no expected maintenance or on some more favorable support conditions such as the mean value, to expect some distress, and to repair the pavements as needed to sustain the pavement in a serviceable condition.

The purpose of this paper is to present a philosophy that considers the stochastic nature of paving materials as integral to the economic trade-off between initial construction and maintenance costs of pavement systems. Because subgrade support is a dominant factor in pavement performance the paper is developed around the effect of subgrade variability on the trade-offs between initial construction and maintenance costs. Use of subgrade variability is for illustrative purposes; similar analysis could just as easily be made with other parameters whose variability affects pavement service life.

When considering the stochastic nature of pavement system parameters, one is immediately faced with the problem of the size of area to consider for establishing appropriate statistical parameters. Point-to-point variations in measured subgrade parameters are partially the result of testing errors rather than variation in the materials. Even if these variations over very small areas are due to real variations in the subgrade properties, they will likely have little effect on the performance of the pavement as a whole.

Conversely, variations in the subgrade that occur over relatively large areas may have a significant effect on pavement performance. The areal size that has a significant effect on pavement performance has not been defined and is probably a function of pavement system parameters, including the thickness of the pavement layers and the properties of the paving materials. No attempt will be made here to determine the size of area required to influence pavement performance, but it will be assumed that the variations indicated are characteristic of sufficiently large areas to have an effect on the pavement.

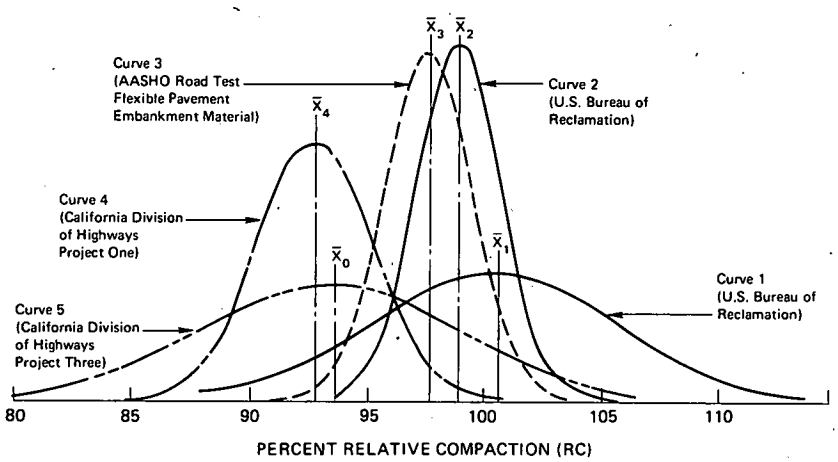
The variability of subgrade soils (Fig. 1) is well known (1, 2, 3). Causes of this variability range from the inherent stochastic nature of natural soils to the effects of nonuniform construction procedures. Minor changes in moisture content during compaction and nonuniform distribution of compactive effort will likely produce significant variations in the support characteristics of the soils. Figure 2 shows the effects of moisture content and density on the CBR values for a typical subgrade soil. For purposes of this paper it is assumed that the effective changes in moisture content and density will occur over portions of the pavement large enough to affect pavement performance (probably several square yards).

Figure 3 shows the variation in the CBR properties of the in situ subgrade for the AASHO Road Test. If we consider only the variation due to changes in the compacted density, and thus eliminate much of the variation due to testing error, the range of values for the CBR can be significantly reduced. Further eliminating the variations that occur over areas too small to influence pavement performance results in an additional reduction in the expected range of CBR values. This reduction is reflected in an assumed distribution of CBR values for the analyses presented (Fig. 4).

The distribution shown in Figure 4 is assumed to represent the entire pavement area. This is intended as an estimate of the distribution expected at the completion of construction and during the life of the pavement. It must be remembered that, if this procedure is used for design, the designer does not know at the time of the design what the ultimate distribution will be and, therefore, must make an estimate based on prior experience with the materials, the specifications used, and the level of quality control during construction. An illustrative evaluation of the sensitivity of the cost trade-off to changes in the standard deviation of the subgrade CBR is made later in the paper.

As an illustration of the points alluded to above, a specific example is presented. The example used is based on the Corps of Engineers design procedure for flexible airfield pavements (4). The philosophy expressed herein applies to the design of any pavement system; it could be illustrated just as well for highway pavements or rigid pavements. Furthermore, other design procedures could serve equally well to illustrate the principles involved, but this procedure was chosen because it has been programmed by

Figure 1. Variation in subgrade density (1).



CURVE NO.	1	2	3	4	5
Minimum Specification Limit, % RC	98	98	95	90	90
Compaction Test Method	Proctor E-11	Proctor E-11	AASHO T-99	Calif. 216	Calif. 216
Average Compaction	100.7	99.0	97.7	92.9	93.6
Standard Deviation	5.0	1.8	1.9	2.4	5.5
Approximate % Less Than Minimum Specification Limit	29.5	28.9	7.8	11.3	25.6

Figure 2. Effect of density and moisture content on CBR of AASHO Road Test embankment soil (2).

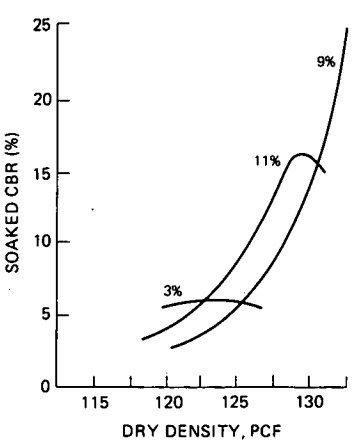
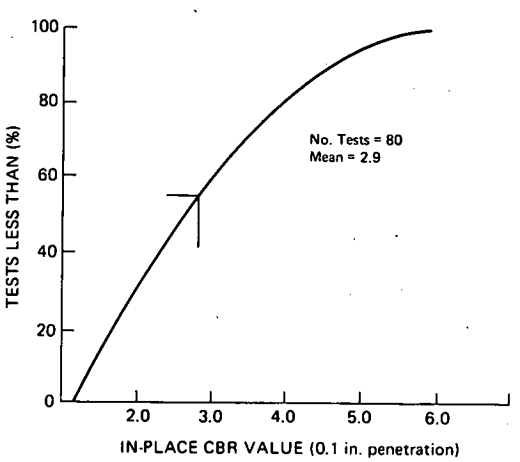


Figure 3. In-place CBR determination of embankment on flexible tangents at time of paving (3).



the U.S. Army Engineers CERL staff for life-cycle analysis of pavement systems. Many of the calculations for the development of this paper were made with the computerized program LIFE 1.

PROCEDURE FOR DETERMINING LIFE-CYCLE COSTS

As has been discussed, the designer is faced with determining a design value for the subgrade CBR expected to be effective at the completion of construction. In addition to determining such a design value, the designer must also select a service life for the pavement. For purposes of this paper, design life is assumed to be an arbitrary period of time over which life-cycle costs are evaluated for various maintenance and reconstruction plans. Service life is the period of time from initial construction until a structural overlay is required. Thus the designer considers a design life, but he could design for a service life that is less than the design life and schedule a structural overlay at that time. Such a plan could lead to a more economical solution for the entire design life. In cases where a structural overlay is projected, the overlaid pavement system must be evaluated for the remainder of the design life in much the same manner as the initial pavement system is evaluated for the proposed service life. All costs incurred during the design life must be considered in comparing alternatives.

To make the process clear, an example is presented of the kind of analysis that must be used in order to estimate the effect of design CBR and service life. The example consists of the design of a 12,000- by 150-ft section of airfield. The area of the section of pavement is 200,000 yd^2, and it is considered a B traffic area. The same materials will be considered in every design. These materials are described in Figure 5.

The design life considered is 20 years, with the following traffic: 50 passes/day, Boeing 747, and 300 passes/day, Boeing 707.

Three overall plans are considered for maintaining the pavement system for its design life:

1. Initial construction designed to last the design life of 20 years before initial failure;
2. Initial construction designed for a service life of 8 years before initial failure (an AC overlay is scheduled at that time and designed to last through the design life of 20 years); and
3. Initial construction designed to last a service life of 12 years before initial failure (an AC overlay is scheduled for that time and designed to last through the design life of 20 years).

The procedure used is to determine, for each of the plans considered, all the costs expected to be incurred in construction and maintenance over the design life of 20 years. The cost categories to be considered are construction, structural overlays, routine maintenance, and reconstruction of prematurely failed areas. Costs for construction are simply added up from the unit costs shown in Figure 5. Costs of structural overlays are estimated at $0.60/$yd^2$/in. Routine maintenance costs are taken to be a function of the length of time the pavement must be maintained without benefit of structural overlays. For the purpose of the example, the relationship shown in Figure 6 was assumed.

For plan 1 the routine maintenance cost for the section of pavement considered is 200,000 × $2.50 = $500,000. This results in an average annual cost of $0.125/$yd^2$/yr.

Costs for reconstruction of failed areas are computed as a combination of the service life assumed and the design CBR used. For the sake of simplicity, the procedure was as follows.

Figure 4. Distribution of subgrade CBR.

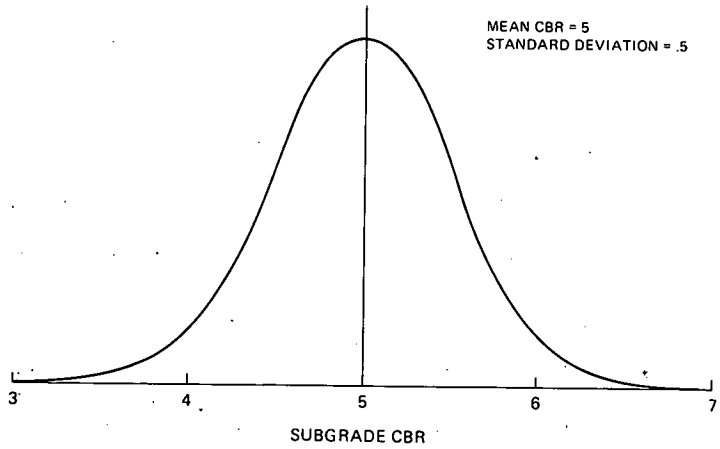


Figure 5. Material properties and unit construction costs.

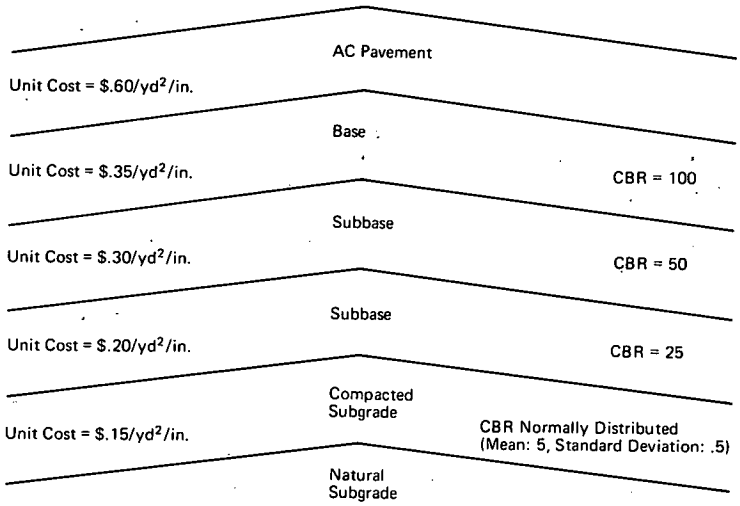
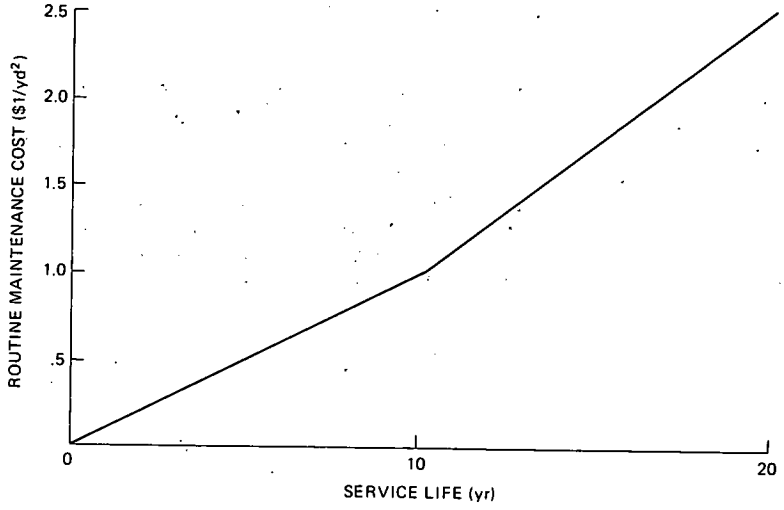


Figure 6. Routine maintenance costs.



1. For a given service life and design CBR, find the required total thickness of pavement. This includes rounding thicknesses off and meeting the specified minimum thickness requirements.
2. Using the thickness obtained in step 1, determine the CBR value that will cause that thickness of pavement to fail during the first third of its service life, during the second third of its service life, and during the remaining third of its service life.
3. Using the assumed probability distribution (based on engineering judgment and on all the sources of variation discussed above) and the CBR values from step 2 above, determine the percentage of the total area expected to fail in the designated time periods.
4. Set the cost of reconstruction as follows: equal to the construction costs for areas failing in the first time period; equal to two-thirds of the construction costs for areas failing in the second time period; and equal to one-third the construction costs for areas failing in the third time period. Determine the cost of reconstruction up until the specified service life. (In considering the time period from the time of a structural overlay to the end of the design life, include the thickness and cost of the overlay.)
5. Add the costs incurred during the initial period before a structural overlay to the costs incurred after the structural overlay to determine the total reconstruction costs.

To illustrate this procedure, the results for the design analysis of a pavement with a mean CBR of 4 and a service life of 12 years are given in Table 1 and shown in Figure 7.

To these costs must be added the cost of the overlay (200,000 × \$0.60 × 4 = \$480,000) and the cost of routine maintenance both before overlay (200,000 × \$1.30 = \$260,000) and after overlay (200,000 × \$0.8 = \$160,000), which totals \$420,000, to arrive at the total maintenance and reconstruction costs for the 20-year design life. This gives a total cost for maintenance and reconstruction of \$924,260. The cost of the initial construction is \$3,160,000. The total life-cycle cost thus becomes \$4,084,260 or \$20.42/yd^2.

If this procedure is repeated for a range of CBRs consistent with the variation assumed and for the three maintenance and reconstruction plans, the total costs will provide the information necessary to choose an alternative that is most cost-effective. Naturally, for given soil conditions, as lower CBR values are used for design, maintenance and reconstruction costs become smaller but the construction costs are larger. Conversely as higher CBR values are used for design, maintenance and reconstruction costs become larger and the construction costs smaller. The design CBR will influence the economic ranking of the three plans on a cost-effective basis.

There are limitations in the procedure used in the example. Only one type of overlay plan was used, and only one design type and choice of material and layer combinations were considered. Finally, the calculation was done at discrete points at fairly wide spacing. In spite of these limitations, the results show the trends that can be expected and demonstrate that a cost trade-off exists and should be considered during design.

The designs for the different service lives were calculated by using a computer system LIFE 1, which performs life-cycle design and maintenance calculations for airfield pavements based on the design methods of the Corps of Engineers. The system has more capability for considering overall plans for maintenance and reconstruction for a design life than displayed in the example. However, the stochastic nature of the reconstruction requirements, due to the variability of many design parameters, is not yet taken into account in the LIFE 1 program. When these capabilities are included, this system should allow the designer to make choices such as the ones described herein and, in doing so, to consider a much richer variety of alternatives.

Results from analyses described above for the three proposed plans and for several CBR values in the range from 3.5 to 5.0 (3 standard deviations) are shown in Figure 8. The cost trade-off is quite pronounced in terms of design CBR and is clear for the maintenance and reconstruction plans at reasonable design CBRs. For the example

Table 1. Costs incurred before and after overlay.

Item	Before Overlay			After Overlay		
	Service Life	Second Time Period	First Time Period	Remaining Life	Second Time Period	First Time Period
Time period, years	12	8	4	8	5.33	2.67
Failure CBR[a]	3.86	3.78	3.64	3.46	3.39	3.22
Percentage of area failed[b]	0.40	0.40	0.33	0.1	0	0
Costs for each area[c], dollars/yd^2	5.27	10.54	15.80	6.07	12.14	18.20
Reconstruction cost[c], dollars	4,210	8,450	10,400	1,200	0	0
Total cost, dollars	23,060			1,200		

Note: Pavement thickness (step 1) is 61 inches; AC overlay is 4 inches. Total reconstruction cost is $24,260.

[a]Step 2. [b]Step 3. [c]Step 4.

Figure 7. Illustration for service life of 12 and design CBR of 4.

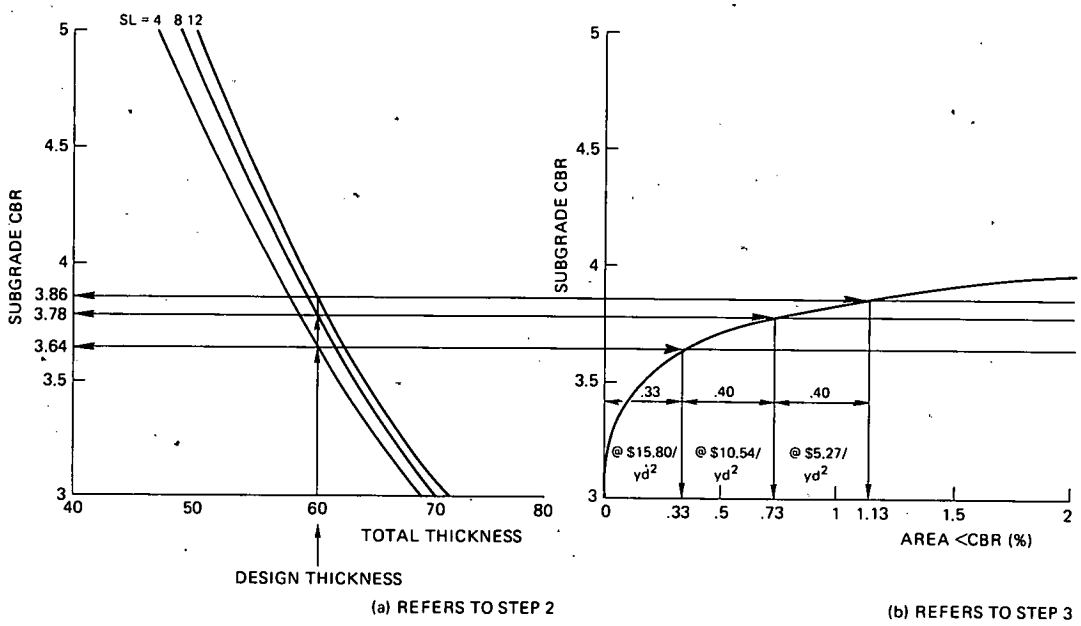


Figure 8. Cost trade-off trends.

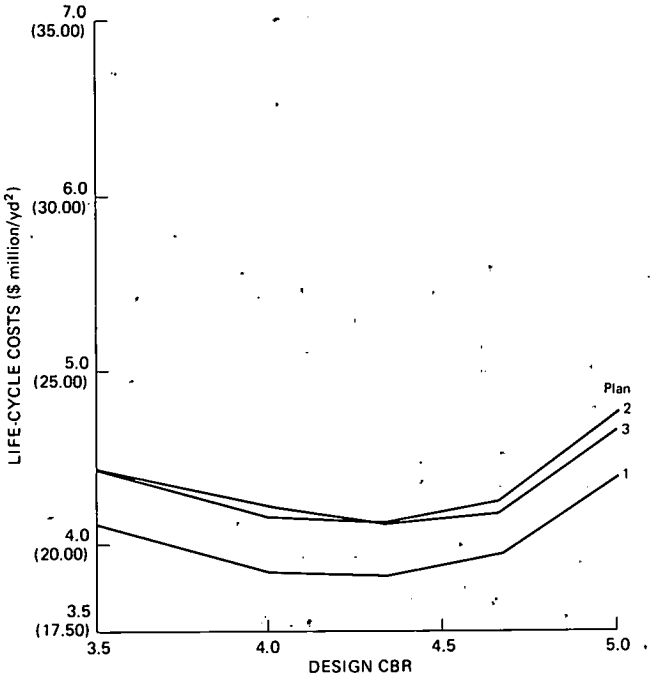
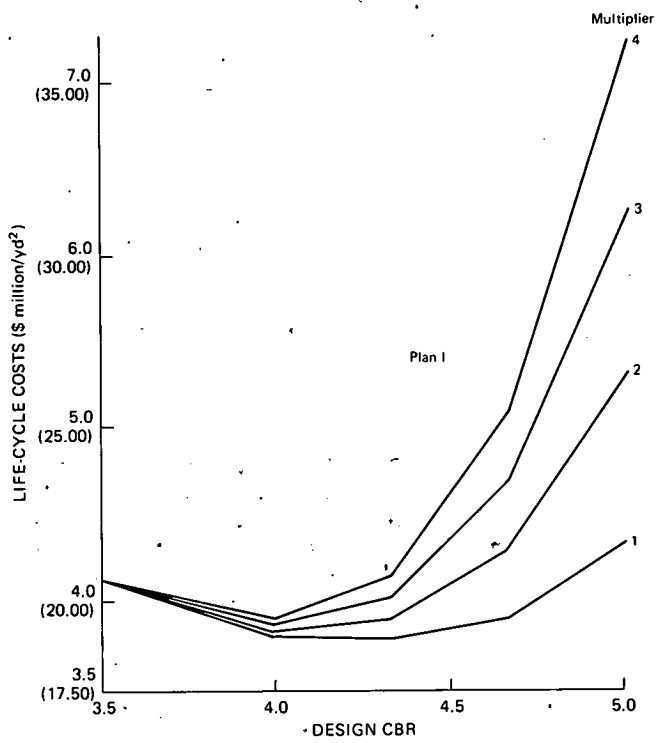


Figure 9. Effect of reconstruction unit costs.



used, the most cost-effective approach is to design for 20 years (plan 1) with a design CBR of approximately 4.25 (1.5 standard deviations below the mean). It is interesting to note that, if one were to seemingly play it safe and use a design CBR of 3.5 (3 standard deviations below the mean), the resulting design would be uneconomical because the increase in initial construction costs more than offsets the estimated maintenance and reconstruction costs. Correspondingly, if the mean value were used as the design CBR, maintenance and reconstruction costs would outweigh savings in the initial construction costs (this assumes that about 50 percent of pavement area will require reconstruction or extensive maintenance during the service life).

The assignment of costs for reconstruction of failed areas is quite arbitrary in the example used. With the idea that reconstruction probably costs considerably more per unit area than initial construction, Figure 9, based on plan 1, shows several cost trade-off curves with multiples of the reconstruction costs used in the example. Naturally, as a higher multiplier is used, the effects of distressed areas are more pronounced and consequently the cost optimal design CBR values are lower. Figure 10 shows all three plans with a reconstruction unit cost multiplier of 4.

To illustrate the sensitivity of the results to the standard deviation of the CBR distribution, assumed to be effective at the time of construction, the results for plan 1, with a multiplier of 1 on the reconstruction unit costs, are shown in Figure 11 for several standard deviations. The mean is assumed to remain at 5, whereas the standard deviation is varied from the 0.5 used in the example to 0.8 and 1.0. It is clear that, as the distribution bands broaden (higher standard deviations), the cost-effective design CBR decreases. However, if the design CBR is expressed in terms of the mean value minus a multiplier of the standard deviation, it is evident that in each of the cases shown the most cost-effective design CBR is approximately equal to the mean minus 1.5 standard deviations.

Naturally the results of such an analysis as presented herein only account for part of the interactions of parameters that exist in a pavement design situation. In addition, assumptions have been tacitly made that

1. The design procedures used are perfectly adequate for determining pavement structural life.
2. An accurate cost estimate can be arrived at by using as elementary an approach as is used in the example (note, however, that the analysis used need only be accurate enough to distinguish between alternatives).
3. The design engineer, looking ahead to the anticipated conditions of construction and operation of the pavement system, can adequately estimate such things as the pattern of routine maintenance expenditures required to keep the system functional and the distribution of CBRs expected to be effective at completion of construction.

CONCLUSION

The philosophy presented can be expressed very simply as "look at the consequences of design decisions." Often designers try to design pavements that are inexpensive and that are expected to "last forever," without consideration of the resulting maintenance and reconstruction costs. Clearly pavements have finite and widely varying service lives that will affect these costs. Thus, designers should consider the consequences of the variability of design parameters in choosing design values. In addition, it is wise to schedule structural overlays ahead if they are a part of the economic life-cycle cost for the pavement system.

It is evident from discussion and example that at least a rough cost trade-off analysis must be performed before design values can be chosen that will lead to a good design. It is just as wrong to use too low a design CBR as it is to use too high a value, though

Figure 10. Cost trade-off trends with a multiplier.

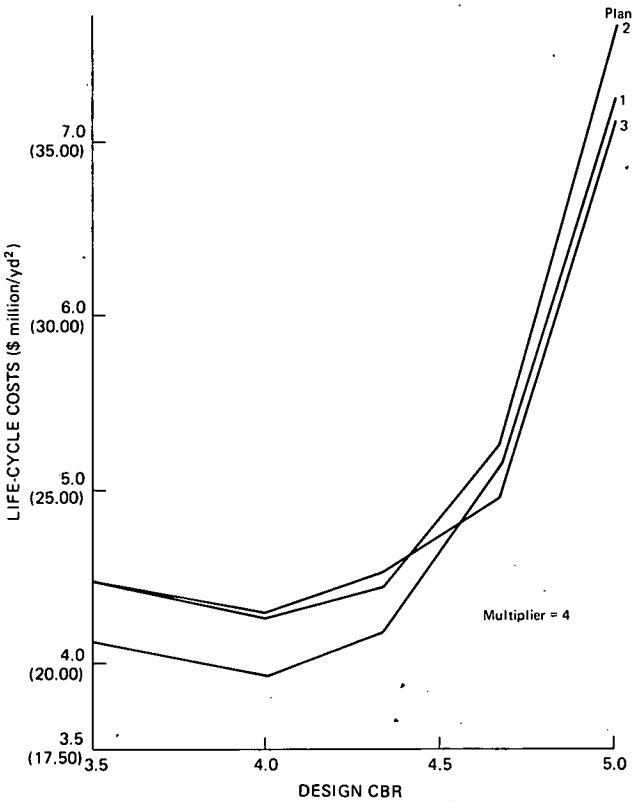
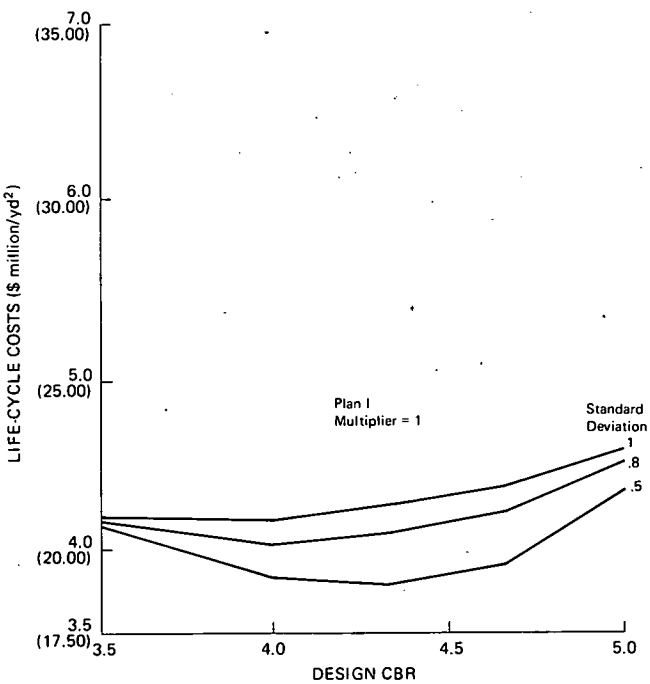


Figure 11. Sensitivity to assumed standard deviation.



perhaps less embarrassing in terms of the subsequent failure rate. The only way to play it safe in pavement design is to make the most comprehensive analysis possible of the appropriate cost trade-offs.

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discussion

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The paper by McManus and Barenberg, in which they present the matter of variability of subgrade strength values, discusses concepts also presented by this writer (5).

This writer agrees with the authors' philosophy: "look at the consequences of design decisions." In the paper on soil strength values mentioned above a generalized solution to the problem of looking at the trade-offs is presented. The paper is based on soil test data from a wide variety of physiographic units both in the United States and in other countries.

It is the writer's belief that the variability values used by McManus and Barenberg may be somewhat low. For example, in the paper by Hampton, Yoder, and Burr (6), the data show that the coefficient of variability of CBR data may be as high as 40 percent for highly variable soils. This serves to illustrate the critical nature of selecting soil strength values that account for initial, road user, and maintenance costs (both routine and major).

Another point of interest is shown in Figure 9 of the McManus and Barenberg paper in which they present multipliers to the cost data. In the writer's paper on soil strength values, this technique was used and was called the "cost ratio." The need for applying a multiplier to unit costs is important in remote areas where cost of mobilization of maintenance crews can be extremely high. This need is also apparent in highly urbanized areas where added road user costs resulting from shutdown of the facility are high.

In summary, the writer agrees with the authors that soil variability is a complex problem that should be evaluated on an individual basis. However, and as illustrated in the writer's paper, guidelines can be set that are useful to the design engineer. The trade-offs, incidentally, as illustrated in the reference paper are a function of traffic, climate, and a wide variety of factors.

References

5. Yoder, E. J. Selection of Soil Strength Values for the Design of Flexible Pavements. Highway Research Record 276, 1969, pp. 1-13.
6. Hampton, D., Yoder, E. J., and Burr, I. W. Variability of Engineering Properties of Brookston and Crosby Soils. HRB Proc., Vol. 41, 1962, pp. 621-649.

closure

The authors wish to thank Yoder for his discussion of the paper. Yoder's earlier work in this area (5) was an inspiration to the authors to undertake such an analysis, but reference to his work was inadvertently omitted.

The authors agree that the variability values used in the paper are lower than would be expected from field data. At the AASHO Road Test, for example, the coefficient of variation for CBR values just before paving was between 40 and 45 percent compared with the 10 percent used in the paper. Less controlled construction sites could be expected to have even higher values.

The lower value for the variability used in the paper was justified on two criteria. First a CBR test represents only a very small area, an area much too small to influence the behavior and performance of pavement systems, especially airfield pavements. Thus, an attempt was made to select a variability that reflected areas large enough to have a significant influence on pavement behavior. Although the extent of such an area is not known, it was assumed that the variability representative of such areas would logically be much smaller than variability of individual test points. Second, the authors were describing a procedure and were not necessarily trying to define prototype conditions. Furthermore, the authors were trying to operate with data that would produce a relatively low variability, for it was believed that, if materials with high variability were used in the example, the results would be such that many engineers would simply not accept the numbers produced and would subconsciously reject the approach presented. Thus, because some judgments were required to select the appropriate input values, an attempt was made to deliberately keep these values in a range to produce relatively moderate variability in the final result. The authors agree with Yoder that these results, low though they may be, indicate the critical nature of selecting values for engineering properties, not only for the subgrade, but for all paving materials.

The authors also agree with Yoder's final comment; that is, the trade-offs are a function of many factors such as traffic and environment. In many areas, because of traffic problems, the indirect cost of closing a facility for maintenance will far outweigh the direct maintenance costs. These factors should all be included in the trade-off analysis when appropriate values for paving materials are selected.