Reliability in Pavement Design? Who's Kidding Whom?

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There is a considerable divergence of opinion among members of the pavement community about the various aspects of reliability in the pavement design process. Additional considerations have plagued the author while using the original work in Texas for 18 years. Confidence level, life cycle reliability, the consequences of failure, the 1986 AASHTO design guide, and reliability and the pavement type selection process are discussed, followed by a summary.

The background on the introduction of reliability into the pavement design process, based on an oral presentation at the 1992 Meeting of TRB's Committee on Flexible Pavement Design, is presented. Newt Jackson, who requested that the presentation be written so that it could be considered for publication, believes that there is a considerable divergence of opinion among members of the pavement community about the various aspects of reliability in the pavement design process. Additionally, the researchers Marshall Thompson and Ernest Barenberg have struggled with how to handle reliability in their NCHRP Project 1-26, ''Calibrated Mechanistic Design Procedures.'' Thompson and Barenberg have done a superb job of reviewing previous work published on this subject. However, additional considerations that are not published have plagued the author during the last 18 years of using the original work in Texas. Finally, industry reviewers of NCHRP Project 1-26 have differing opinions on this subject. This paper is an attempt to clarify the background, definition, details, weaknesses, and strengths of reliability in pavement design. Additionally, a correct interpretation of the subject is offered, and ideas on proper usage follow from that interpretation.

CONFIDENCE LEVEL

During the 1960s Frank Scrivner was charged with translating the AASHO Road Test findings to Texas' conditions and with developing a flexible pavement design procedure from the results (*1*). The author was the technical coordinator for the Texas Highway Department for much of the project. Scrivner's product was named the Texas Flexible Pavement Design (FPS) system (*2*). It was a life cycle cost pavement design system that attempted to minimize the costs of a variety of design strategies, each of which met certain design criteria. Trial implementation with engineers from five pilot districts revealed that all engineers believed that the pavement structures were too thin and unsafe (*3*). This was not unanticipated; no safety factor had been incorporated within the design system.

Scrivner's satellite study terminated and a large joint effort between the Center for Transportation Research, the Texas Transportation Institute, and the Texas Highway Department continued the effort (*4*). While a sensible sensitivity study was being attempted, it was discovered that the overall uncertainty in the mathematical system could be determined if the uncertainty in each portion could be estimated (*5*). This effort was influenced by Leland Barclay's error analysis methods from University of Texas surveying classes. The uncertainties (variance components) owing to the lack of fit, pure error, and the uncertainty owing to translating the AASHO Road Test to Texas in a time period different from the Road Test (exceeding the inference space) were all needed as well as materials, subgrade, traffic prediction, and environmental uncertainties. An enthusiastic doctoral candidate, Michael Darter, and colleagues undertook the challenge of trying to estimate these variance components (*6,7*).

The reader should note that the Texas Highway Department considered this approach to be valuable for two reasons, neither of which was the calculation of reliability. First, the procedure provided an excellent method of comparing the sensitivity of the output to each input variable while considering the other uncertainties in the process. Such a comparison was as valid because the relative uncertainties of the various components of variance were known.

Second, the method provided a convenient manner for applying a safety factor. All that remained was for someone to say how many standard deviations away from the mean we should design. No one had the slightest notion of what this should be. However, it was reasoned that if the experienced designers could determine that the originally proposed answers were unsafe, they could possibly tell us the safe or correct solution.

For various classes of highways ranging from rural secondary through urban freeways, pavement designs were prepared by using the mean design traffic and the mean design traffic plus one, two, three, four, and five standard deviations (overall standard deviation). The method described above was used to obtain the overall variance. (The log of traffic was used because the AASHO Road Test showed performance to be related to this transformed version of traffic.) From these six solutions the experienced designers were asked to select the right answer. A reasonably consistent pattern developed. For rural secondary roads the design that used the log of the mean design traffic plus two standard deviations was selected as the correct solution. For urban freeways the design based on adding four standard deviations was selected (*8*). The results as implemented are taken from the FPS user's manual as shown below. They were still in use in 1993.

> Rev. June 4, 1974
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> 3.5 Design Confidence Level
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> This variable controls the reliability with which the specified quality of pavement service will be satisfied. Its choice should depend largely upon the consequences of failing to provide the specified quality throughout the indicated analysis period. As an example, sup-

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pose one highway carrying 28,000 vehicles per lane per day must be overlaid or reconstructed prematurely. The consequences will be much more severe if it does not have continuous frontage roads or some other convenient detour with sufficient capacity available. (The designer is cautioned to remember that the FPS program takes into account user costs for *planned* overlays).

The problems arising because of failure to provide the specified quality throughout the analysis period depend upon the type of repair required to restore serviceability, the relative amount of traffic using the facility during this repair, and the availability of a detour for this traffic.

The designer must specify confidence levels by coding a letter A, B, C, D, E, F, or G. The reliability (probability of success) increases with each succeeding letter—A being the lowest reliability and G the highest.

It is recommended that the guidelines shown in Table 3.1 be used in selecting the Design confidence level.

	The highway will be operating at greater than 50 percent of capacity sometime during the analysis period.	The highway will be operating at less than 50 percent of capacity throughout the analysis period.
The highway is or will become urban before the end of the analysis period.	E	C or D
The highway will remain rural.	C or D	C

LIFE CYCLE RELIABILITY

One modeling problem that still exists today surfaced. As discussed above, the FPS design system models and uses the performance of an initial pavement construction and the performance after maintenance and rehabilitation interventions. The computed performance of the total strategy (the life cycle) will vary greatly depending on whether the various performance periods are connected in series or parallel or something in between. The following scenarios illustrate this problem and the solution chosen to handle it.

- *Scenario 1:* A series of pavements is designed to last at least 10 years with a probability of success of 0.95. The structural model being used says an overlay of *t* thickness will be required to make the pavement last at least 10 more years with a probability of success of 0.95. A similar overlay of *d* thickness is required for the third period. The pavements are always treated just as planned: that is, those that last until the end of the 10-year periods are overlaid with the preplanned overlays. Those that fail prematurely are completely reconstructed.
- *Scenario 2:* A series of pavements is designed to last at least 30 years with a probability of success of 0.48. However, a monitoring system that determines threshold conditions of needed rehabilitation is in place. These conditions are analyzed frequently, and whenever a threshold condition is reached, the pavement is redesigned and rehabilitated to last until the end of the 30-year period, again with a probability of success of 0.48. Note that rehabilitation funding is always available, there is always a structurally feasible solution available, and traffic can be handled in a safe and economically feasible manner.
- *Scenario 3:* A series of pavements is designed to last at least 10 years with an 85 percent probability of success. They are monitored, and when funds are available, the pavements that reach a needed overlay condition level are overlaid. For some of those in good condition at the end of 10 years, the planned overlay was postponed so that a better job could be done on the pavements that wore out early. The process is repeated throughout the 30-year period with enough average funding so that 85 percent of the pavements last the 30 years without requiring either more than two overlays or reconstruction.

What is the reliability of these designs? What are the key issues in deciding the answer to that question? Scenario 1 is analogous to the bad employee who does exactly what you tell him or her every time without thinking. Scenario 2 is most likely unachievable because some distresses cannot be corrected. Midcourse corrections may not be possible for either structural, traffic handling, or financial reasons. The composite, Scenario 3, is the most probable case.

The author's estimate of the interventions and failures that occur in each scenario is given in Table 1. The resulting reliability is also presented. A reader who computes different results for this table should not be alarmed. The author admits that he does not know how to compute an accurate answer for these scenarios, and he doubts whether anyone else knows either.

It should be readily apparent from these examples that the true reliability for a life cycle depends not only on design factors for the pavement and subsequent rehabilitation interventions but also on how these interventions are applied. Operational restraints such as unavailable funding or traffic-handling limitations can severely limit the advantages of midcourse corrections. Technical restraints

TABLE 1 Required Actions for Three Scenarios

Activity	Scenario One	Scenario Two	Scenario Three
No Overlay Required	0	53	0
Single Overlays	95	25	86
Double Overlays	95	12	86
Reconstruction*	15	15	15
Reliability	85	85	85

*Assuming that any pavement that failed to last 30 years with two overlays had to be reconstructed.

such as the inability to know when a correction is needed or not having a rehabilitation technique that can correct a specific distress can also limit the ability to make effective midcourse corrections. Conversely, in most cases it is incorrect, in the author's opinion, to adopt the approach taken in Scenario 1. Incidentally, this is the approach used in the 1986 AASHTO *Guide for Design of Pavement Structures* (*9*). Most state highway agencies have some ability to detect and treat potentially failing pavements. Probably all of them have the capacity to delay rehabilitation interventions when the pavement is showing no sign of distress.

As a middle ground, the Texas Highway Department adopted for the FPS system a predicted reliability (confidence level) for the entire performance period that is exactly equal to that used for nonstaged construction (*8*).

CONSEQUENCES OF FAILURE

One would be remiss in discussing the background to reliability if the very important contribution of J. W. Hewett was not noted. During the period under discussion, Hewett was Assistant Branch Chief of FHWA's Pavement Design Branch. In a conversation about the subject, he noted, "the correct confidence or reliability to select must depend upon *the consequences of failure*." To a pavement designer and one teaching pavement design, this statement has been invaluable. Such important but unquantifiable factors as availability of detours, amount of traffic, speed of traffic, difficulty of required repair, availability of resources (money, workers, and equipment to make the required repairs), and the public image cost vary a great deal from project to project and from agency to agency. Despite their nebulous natures these factors must be considered in assigning a factor of safety or confidence level or design reliability level. Hewett's simple explanation, that one must look at the consequences of failure to select an appropriate certainty level for design, has been useful to those who have been applying these concepts.

1986 AASHTO GUIDE

The 1986 AASHTO *Guide for Design of Pavement Structures* (*9*) introduced the reliability concepts of the Texas FPS system to a broad audience for the first time. In Appendix EE, Volume 2 and Chapter 4, Part 1, Paul Irick has treated the calculations with mathematical rigor. In Appendix EE, R. L. Lytton has collected, from the available data and from his experience, a set of estimates of the variances for all of the inputs to the design equations, much as Darter had done a decade before for the Texas equations. The author supplied the conceptual Figure 4.5, reproduced herein in Figure 1. The concepts illustrated in the figure grew out of the preceding discussion on the selection of a proper design reliability.

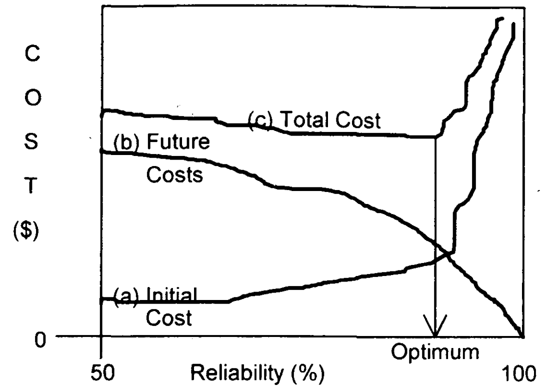

FIGURE 1 Approach to identifying optimum reliability level for a given facility (*9*,p.I-63).

The AASHTO Joint Task Force on Pavement Design, which is responsible for producing the guide, tried an exercise to select the appropriate reliability design in the same manner that Texas had used in the 1970s. They had questionable success. The effort was undertaken by having the task force members get the pavement designers from their home states to submit a correct design solution for a series of design problems. The staff then tried to match these answers to a reliability level required to achieve the same design solutions using the guide. The results were wildly scattered. The author contributes this scatter almost exclusively to one factor: the inference space over which the guide was being applied was much too large. As examples, neither thin-surfaced asphalt roads, such as those used in Texas with much success, nor continuously reinforced concrete pavements were even used at the Road Test. An even larger expansion of inference space is today's modern urban freeway loaded with traffic compared to anything being considered by the personnel developing the present serviceability concept at the Road Test (Table 2.2 of the guide). Suggested levels of reliability for various functional classifications (p. II-10 of the guide) is the result of that exercise. It is not so bad as a guideline. Any agency that uses the guide must recognize that it has total responsibility for adjusting the guide so that it matches the agency's experience. The agency must adjust the guide to the conditions under which it is to be applied.

RELIABILITY AND PAVEMENT TYPE SELECTION PROCESS

A troublesome bit of rhetoric evolved in the presentations that were used to introduce the new guide to the pavement community. It has created false expectations for the reliability concept. The statement usually takes a form like the following: "Reliability is the probability that a pavement will achieve its design function. Therefore, for comparing pavement designs for the purpose of pavement type selection, each competing design should have the same reliability."

Although this statement is correct, it has no practical application at this time. Let us examine it part by part. First, the term "its design function" implies that a single number, like the present serviceability index, represents the performance of the pavements. Only if the competing pavements are being designed for some global and equal functional design criteria does the statement work. It should be readily apparent that the reliability against faulting in a concrete pavement is not of the same importance as the reliability against rutting in an asphalt pavement. Another problem exists if we further consider the consequences of failure; it may be much easier to rehabilitate a thin-surfaced alligator-cracked asphalt pavement than a very thick alligator-cracked asphalt pavement.

The problem of staged construction or future interventions also makes the earlier statement almost useless in selecting pavement type. Life cycle costs must be considered in pavement type selection, yet we have not resolved how to couple future interventions for a specific design reliability.

SUMMARY

To summarize, the advantages and disadvantages of the reliability methodology were reviewed. First, however, it is stated again that by the reliability methodology the author means estimating and correctly combining all of the uncertainties associated with a particular design model into an overall variance. Such an exercise lets us examine the contribution of each uncertainty to the total. Knowing the importance of each design input lets us know how important it is for us to spend efforts to get better data for design. If subgrade stiffness is very important we can run more tests; if the present percentage of trucks is important we can count the trucks. If our prediction models are so poor that better design data will not improve our answers, we can spend more on research to improve the equations.

The reliability methodology provides a very convenient method for applying a safety factor to our design equations. We *must* calibrate any of our equations to our experience. This can be done by using the reliability methodology.

The disadvantages are all of the nature of misapplication, misunderstanding, or incomplete knowledge preventing us from reaching the full potential of this technology. First, we have the ''innocents,'' who use percent reliability as if they were precise with their calculations. In fact, they are very inexact and probably biased to the low side. It is not too hard to envision a representative in a congressional hearing saying, ''you designed it for 99.99 percent reliability and it failed anyway!''

Next comes the very difficult problem of how to handle the coupling of various stages in life cycle problems. All of us are going to have to give our operating processes a closer look before we select the model that should be used to couple these various stages.

Reliability as being applied today is the probability that the pavement will not exceed some distress criteria being treated by the design model. This probability is valid only for the inference space that was encompassed by the data set from which the model was derived. Our experience with the Strategic Highway Research Program's Long-Term Pavement Performance Program experiment designs teaches us that all of our present data bases are very limited.

Despite confusing rhetoric otherwise, reliability technology offers little help in the pavement type selection process. We can and should attempt to design different pavement types to have the same overall life cycle reliability. However, we must continue to let the responsible engineer weigh these results and make his or her final selection on the basis of all of the data and judgment that he or she can deploy. We cannot limit ourselves to using a very imperfect model instead of applying the wisdom of the ages.

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