COST EFFECTIVENESS OF SAMPLING AND TESTING PROGRAMS

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16. Abstract
This report documents studies aimed at providing a means of establishing priorities among quality control tests and of optimizing sampling frequencies for each test, based on the effects of material properties measured on the performance of the pavements. Appropriate procedures were developed and are discussed in the report, including critical considerations and limitations due to lack of suitable stochastic models to predict performance and contractor response to changes in testing frenquency.

These procedures are embodied in computer program "COSTOP1", which was developed to assist State highway agencies in determining the optimum test frequency for a single test or the optimum test program for multiple tests to produce the greatest return for every dollar spent on testing. COSTOP1 is general and modular so that the testing programs for all paving construction and materials can be evaluated, and new models and differing repair strategies may be easily defined and input.

Preliminary results based on limited models indicate that higher frequencies of testing than commonly used would be cost effective, decreasing the equivalent annual pavement costs by much more than the additional testing costs.

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METRIC CONVERSION FACTORS

APPROXIMATE CONVERSIONS FROM METRIC MEASURES

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km

AREA

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.6	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha

MASS (weight)

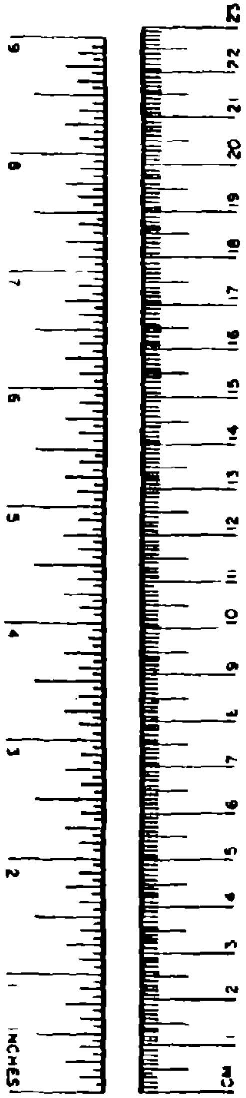
SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t

VOLUME

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3

TEMPERATURE (exact)

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS FROM METRIC MEAS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND
mm	millimeters	0.04	inches
cm	centimeters	0.4	inches
m	meters	3.3	feet
m	meters	1.1	yards
km	kilometers	0.6	miles

AREA

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND
cm^2	square centimeters	0.16	square inches
m^2	square meters	1.2	square yards
km^2	square kilometers	0.4	square miles
ha	hectares (10,000 m^2)	2.5	acres

MASS (weight)

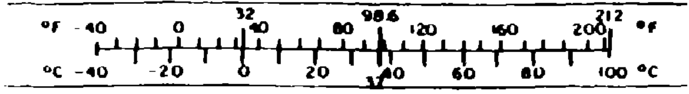
SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND
g	grams	0.035	ounces
kg	kilograms	2.2	pounds
t	tonnes (1000 kg)	1.1	short tons

VOLUME

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND
ml	milliliters	0.03	fluid ounces
l	liters	2.1	pints
l	liters	1.06	quarts
l	liters	0.26	gallons
m^3	cubic meters	36	cubic feet
m^3	cubic meters	1.3	cubic yards

TEMPERATURE (exact)

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature



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CHAPTER 1

INTRODUCTION

BACKGROUND

Materials sampling and testing programs practiced in most States have helped to assure the construction of a high quality national highway system. These programs are estimated to cost approximately $200,000,000 per year for federal aid highway projects alone. While this cost is not too much to pay to guarantee the quality of our multi-billion dollar annual investment in highway construction, it is unknown whether the same high quality could be attained with less costly testing or whether better quality could be attained with alternative programs.

Material and construction specifications often were developed by a "trial and error" process supplemented by research and development efforts and were aimed at duplicating successful projects. This evolutionary process produced a variety of quality control tests and testing frequencies intended to assure that the materials and construction procedures used were those required by the specifications.

Tests were standardized, and experiences in their use and the consequent results were shared through direct contact, technical meetings, and technical publications. This resulted in a certain amount of uniformity in types of tests conducted for specific control purposes. Nevertheless, the types and frequencies of tests conducted and the test procedures used vary widely among the various highway agencies. This is not surprising since there are hundreds of organizations using a variety of different materials and design procedures for different environmental conditions and traffic volumes.

The specification values assigned to specific tests and the recommended frequency of testing required have been largely a matter of judgements made by individual engineers, since it is very difficult to objectively relate control test values and the frequency of testing to the actual pavement performance. This in part is due to the complexity of pavement behavior and analyses, partially caused by numerous interacting factors such as construction procedures, environmental factors, traffic differences, and variable materials.

While there has always been a need for material sampling and testing programs, escalating costs, increased traffic loads and volumes, and recent administrative and legislative pressures to keep costs and personnel levels at a minimum have resulted in research aimed at improved specifications and more cost-effective testing or quality assurance programs. The Federal Highway Administration has established Project 4E, "Construction Control and Management" as a coordinated effort to accomplish these goals. Accordingly, this study was initiated to provide a basis or methodology to determine and evaluate the cost effectiveness of individual tests and associated sampling frequencies used in controlling the quality of pavement materials as related to pavement performance.

The resulting methodology will provide a means for individual agencies to answer the following questions:

1. Does a specific test or group of tests provide information which directly relates to performance, and how sensitive is performance to variations in test values which could normally be expected to occur?

Certain tests may not measure properties which are important to the performance of the pavement, or the performance may not be significantly affected by variations which might occur. Thus, conducting the test may not be cost effective; or the expected variation or the effect of such variation may be so small that additional testing is not cost effective once a given level has been established.

2. How frequently should tests which relate to performance be conducted?

   Most specifications concerning test frequency are established with respect to statistical concepts related to obtaining an accurate estimate of the engineering properties being measured. While this is important, another important question relates to how frequency affects the quality of materials and construction, which in turn will affect the performance of the pavement. Thus, will additional tests cause a contractor or supplier to provide a higher quality product? Generally it is assumed that more tests will cause an improvement in quality, but at best there is a point of diminishing returns which is also a function of how the specifications are written and the penalties associated with poor quality materials and construction.

OBJECTIVE AND SCOPE

The objective of this study was to provide a means by which an organization can determine the cost effectiveness of individual tests and associated sampling frequencies used in controlling the quality of pavement materials as related to performance.

A methodology has been developed that takes into account the relationship between the test value and the performance of the highway, the effect of variations from the specifications, and the consequences of accepting unsuitable material. This methodology provides State agencies with a means of establishing priorities among quality control tests and of optimizing sampling frequencies for each test. This includes the necessary level a test parameter must achieve to provide the desired quality and the frequency at which testing must be performed to minimize the possibility of having defective materials because of poor construction practice.

The methodology is applicable to all highway materials, which includes asphalt concrete, portland cement concrete, processed aggregates, soils, paints, joint seals, reinforcement, and other materials. However, the demonstration phase for the methodology was limited to asphalt mixtures and concentrates on those properties that are used as standards by most State agencies.

Specifically, information is included in the report which pertains to the following topics:

1. Models relating quality control test values to pavement performance.
2. Variation in materials properties, which includes:
    a. The effect of testing frequency on our knowledge of the pavement and on contractor performance.
    b. The relationship between frequency of testing and consequential anticipated pavement performance.
3. Cost of materials testing.
4. Cost associated with repairing defective materials and pavements.
5. The comparison of the differential cost of testing to the differential pavement costs by means of benefit/cost analyses.
6. The computer program which combines these elements to allow the cost effectiveness of proposed quality assurance programs to be evaluated.

Chapter 2 provides an overview of the important topics significant to this study and Chapter 3 describes the methodology employed. Chapters 4 and 5 provide additional detail relative to testing cost determinations and performance models, respectively. Chapter 6 describes the computer program developed to implement the methodology and Chapter 7 provides examples of its use. Chapter 8 provides guidelines for evaluating test programs. Chapter 9 summarizes the research effort and the resulting methodology and its limitations, and also recommends research requirements to further develop this initiative.

CHAPTER 2

TOPICS CRITICAL TO EVALUATION OF COST EFFECTIVENESS

The critical topics requiring detailed consideration were enumerated in the previous chapter and are discussed in detail here. Each of these topics was carefully studied and decisions reached as to how they were to be handled in the methodology developed.

PAVEMENT PERFORMANCE AND PREDICTIVE MODELS

The concept of basing a materials test program directly on its effects on the performance of the pavement is clearly logical and appropriate. It is also logical and appropriate to base new initiatives for optimizing test programs on their effects on performance, but unfortunately the mathematical models needed to support the methodology do not exist. As their existence was a basic assumption for the project, it was necessary to reach a coordinated agreement with the FHWA as to how to deal with this problem.

It was originally expected that the performance models developed by Majidzadeh, et. al. (Ref. 1) would include models for rigid pavements that could be used in this project. However, these models predicted a composite index representing a number of distresses rather than individual distresses, and were therefore far too general for the purposes of this project. Review of the literature discovered only a few models that predicted distress on the basis of material properties derived from conventional testing, and these were also quite limited. Models were more plentiful that predicted pavement distress or performance with relation to material properties obtained from more sophisticated test procedures not commonly conducted, such as resilient moduli, fatigue potential, and permanent deformation potential. There were also a few models that predicted stiffness or resilient modulus in terms of conventional test results.

The approach recommended by project staff and approved by the FHWA was two-fold: 1) the computer program embodying the methodology was to be very modular such that it could accept any model; and 2) limited models were to be developed as part of the project with the sole intent of demonstrating the methodology. The approach used to develop models, in some cases, was to combine two models, one of which would predict an engineering property such as material stiffness in terms of conventional test results, and the other that would predict a particular distress in terms of the engineering property so derived.

The simple approach described above produces a deterministic model without the capability of considering variability in the material properties that could be affected by the test program. The deterministic equations were transformed into stochastic equations by expansion into first-order Taylor series, allowing the propagation of variance from material property to engineering property to calculated distress measures. Resulting stochastic equations for predicting pavement distress or performance in terms of material property values and their variations obtained from conventional testing are believed adequate for demonstrating the methodology, but no claim is made for their adequacy for general use. These equations, which allow for the introduction of variance of the independent variables, will be discussed in more detail in the following chapters.

GENERAL VARIABILITY IN PAVEMENT MATERIALS

It is a generally recognized statistical rule that the accuracy with which the mean value of a population may be estimated increases with the number of samples from the population measured. The accuracy of the estimate for standard deviation or variability from the mean also increases with sample size. It follows then that the greater the number of material tests conducted, the higher the confidence level that the mean will be identified with sufficient accuracy, that the variability will be better defined, and that substandard materials will be identified. This logic leads to the question of how many tests should be conducted in order to satisfactorily identify the characteristics of the material. This assumes that the test result is related to performance. These subjects are examined in this report.

There is an assumption necessary for optimization of number of tests: the ability to better evaluate material properties is rewarded by improvement in the properties themselves. Here we again suffer from lack of information and lack of models to relate the effects of number of tests in a test program to actual material properties produced (as opposed to more accurate evaluation of the mean and variance). Therefore, this assumption is necessary but cannot be corroborated without long-term data collection efforts.

VARIABILITY RESULTING FROM CONTRACTOR RESPONSES TO TESTING FREQUENCY

Superficially, it appears simple that a contractor would be expected to produce a superior product with the knowledge that testing frequency is high. Superior in this sense is defined not only as always exceeding specified minimum test values, but also as maintaining a reasonable level of uniformity. This factor is conceptually illustrated in Figure 1, Curve A.

Discussion of this concept with State highway agency (SHA) officials revealed that some officials believe testing frequency has no effect on contractor performance (Figure 1, Curve B). In fact, others believe that if data were plotted, the resulting curve would show that material variability increases with testing frequency. This phenomenon is believed to occur because States tend to subject contractors with poor control histories to greater amounts of testing. The result, shown conceptually in Figure 1, Curve C, is that apparent variability of paving materials may statistically increase with testing frequency due to the correlation of two related effects and not as a cause-effect relationship.

Another complexity is the presence of "lag time" in the contractor responses. For instance, it is doubtful that the effects of a change in the established testing program for a State agency would appear immediately on current projects. It is more likely that these effects would show up over a period of time on later projects and in varying fashions for different contractors.

Unfortunately, the complexities of the responses by a single contractor or contractors in general are not well understood and have not been subjected to mathematical modeling that could contribute to this project. These responses are likely to include changes in construction costs as well. How to predict contractor responses in terms of materials properties was studied in detail, and a very general model was adopted. This

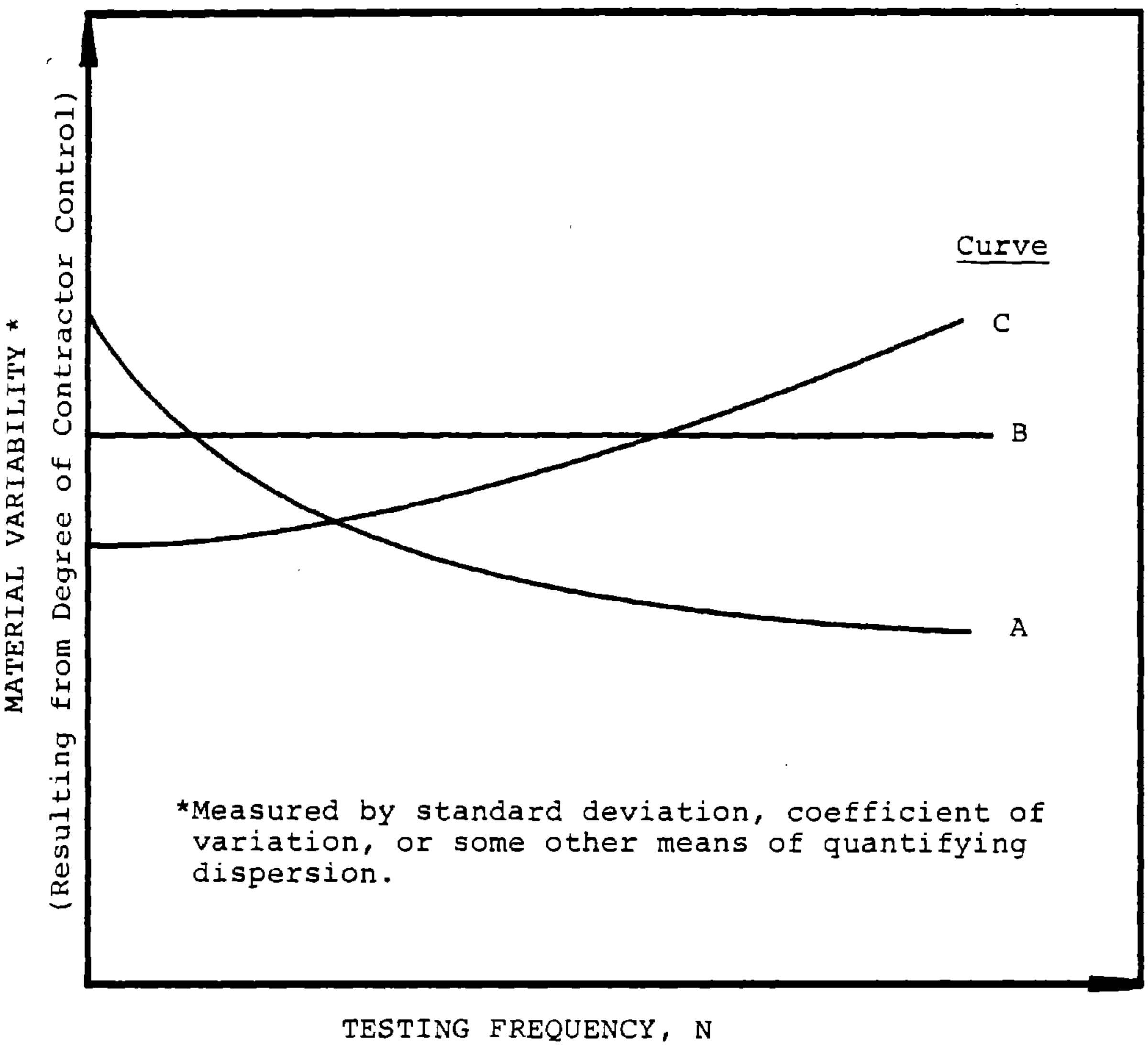


Figure 1. Effect of Test Frequency on Material Variability (Conceptual Curves, not Based on Actual Data)

model allows inclusion of this consideration into the methodology, but leaves broad flexibility for individual users to define this response based on their own experience or perceptions.

TESTING COSTS

The effectiveness of the proposed methodology in optimizing materials test programs is dependent on the accurate evaluation of costs per test. In estimating costs for their activities, State agencies frequently leave out significant indirect costs and even direct costs. Therefore, a standard and reasonable methodology was selected through modification of a procedure used by the Louisiana Department of Transportation and Development to ensure meaningful estimates of testing costs. This procedure for determining the costs of quality control and acceptance tests is described in detail in Chapter 4 of this report, and includes on a per test basis the following:

1. Salary costs,
2. Equivalent depreciation cost,
3. Vehicle and equipment rental cost,
4. Travel cost,
5. Supply cost,
6. Administrative overhead costs,
7. Administrative engineering costs,
8. Total cost per test (the sum of the items listed above).

It is believed that use of this procedure will yield more accurate estimates of testing costs for anyone making such estimates, but experience on this project indicates that the accounting systems of many State highway agencies will not provide all of these data.

PAVEMENT REHABILITATION AND MAINTENANCE

Assuming that stochastic models are available to predict distresses in terms of variables, including both the means and the variances of material properties, levels of distresses of various types can then be predicted in terms of numbers and types of quality control and acceptance tests. This leads to the necessity for identifying the consequences of distress or deterioration in terms of what rehabilitation or maintenance will result and what it will cost. As the rehabilitation or maintenance strategies and their costs vary widely from State to State and from district to district within a State, it was necessary to develop a very flexible system for defining these strategies in terms of levels of distress of various types, and for assigning costs for these strategies. The details of this are included in Chapter 6 and in Appendices C and E.

COST ANALYSIS

An incremental benefit-cost analysis is used to compare alternate testing schemes. Each alternative has the following costs with which it is associated:

1. testing,
2. construction,
3. maintenance,
4. user,
5. rehabilitation.

For each alternative, construction, maintenance, user, and rehabilitation costs are combined into an equivalent uniform annual cost over the life of the pavement. Similarly, testing costs are converted to equivalent uniform annual costs. Alternatives are then arranged in order of increasing (annual) testing costs. A challenger-defender approach is used to directly compare alternatives in terms of benefit-cost (B/C) ratios. If the B/C ratio is greater than one, the challenger becomes the defender to the next challenging alternative. Conversely, if its B/C ratio is less than one, the defender remains a defender to the next challenger. This procedure continues until all alternatives have been examined. With the development of this system, the components necessary were available for considering: 1) the initial cost of construction, 2) costs for various materials test programs, 3) the effects of the materials test programs on performance of the pavement, 4) the rehabilitation or maintenance strategies that may result from various distress levels, and 5) the costs for those rehabilitation or maintenance strategies. This provided the opportunity to optimize costs with consideration of all these factors.

CHAPTER 3

METHODOLOGY

To evaluate the cost effectiveness of alternative tests or testing plans, one must be able to determine the probable benefits of each test frequency and the costs of the particular test being evaluated. The relative benefits will accrue from increased performance or lower maintenance and rehabilitation costs, while the relative cost will be the increased cost either of performing more tests or of changing to a test procedure that has a better relationship to performance. Of course, just the opposite situation could also be cost effective. One may be able to reduce the testing frequency and testing cost while only marginally decreasing performance with an attendant slight increase in maintenance and rehabilitation costs.

To determine the cost effectiveness of a particular test frequency, five primary questions must be answered. These are:

1. What effect does the material property (both mean and standard deviation) have on pavement performance? Chapter 5 provides a detailed discussion on performance models.
2. What is an acceptable variation of the material property?
3. Will construction practices or production techniques be affected by altering the testing and sampling frequency, and if so, what is the effect?
4. What is the cost of testing to measure the material property? Chapter 4 provides a detailed procedure and discussion to compute the total unit costs to perform a particular test.
5. What is the cost to maintain, repair and/or replace defective material that was accepted?

The basic strategy for the project was to develop a computerized alqorithm that is both general and modular in nature. A general program was desirable to provide the ability to accept and process certain similar types of information expressed in a variety of ways to answer the above questions. The form this information takes usually varies depending on the SHA or even material or tests to be evaluated. The following discusses each particular part of the computerized alqorithm and overall methodology, as shown in Figure 2.

PROCEDURE FOR DETERMINING SERVICE LIFE

A pavement's service life is defined as that period of time or number of load applications from completion of construction until the condition of the pavement is considered to be unacceptable and rehabilitation or replacement is required. However, it is common knowledge that at that time the entire pavement surface will not have failed. In fact, only a small percentage of the surface area may be categorized as "failed." It is enough though to give the driver a feeling that the pavement is bad and that something must be done to improve its characteristics. The actual percentage of "failed" area depends on the particular distress type and how important each prevalent distress is on reducing the level of service.

The basis for development of a methodology to evaluate cost effectiveness depends on availability of relationships that predict performance as a function of commonly used quality control test parameters. A hypothetical example of such a relationship would be a model that predicts an increase in rutting within the asphalt concrete layer (exclusive of permanent deformation in the base or subgrade) as a function of the mean value and variation of hot mix asphalt concrete (HMAC)

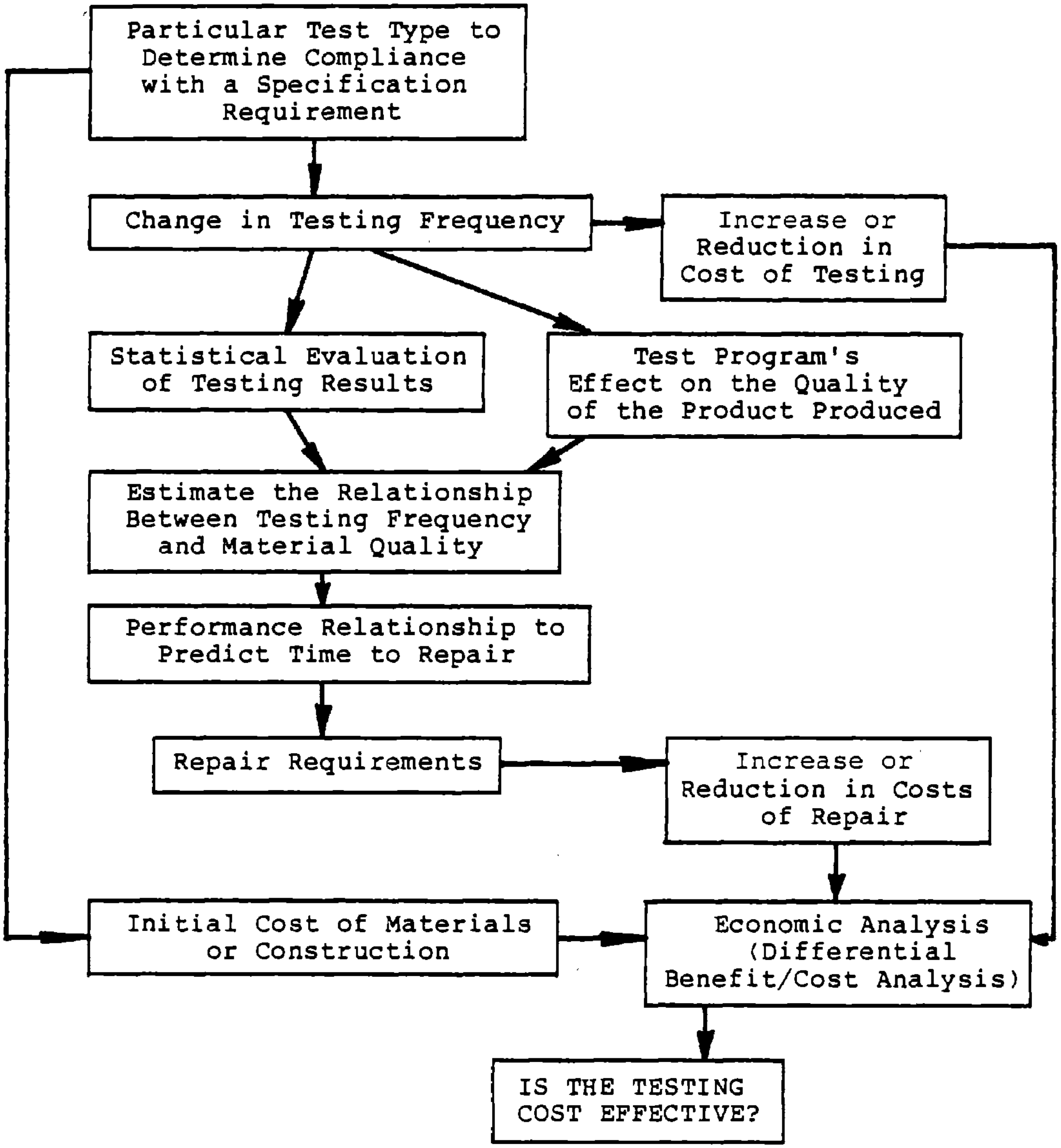


Figure 2. Simplified Flow Chart Illustrating the Cost-Effectiveness Methodology to Determine Optimum Test Frequency for a Particular Test

density. Figure 3 represents a hypothetical relationship between a material property (HMAC Density) and pavement service life (defined by rutting), assuming homogenous conditions. Further, a desirable relationship should also take into account the variability, as well as the mean value, of a test parameter. Figure 4 represents the variability of the material from a pavement construction project or material production process. Combining Figures 3 and 4, the development of failures along the pavement surface can be represented by the curve shown in Figure 5.

The pavement service life in this case would be the period of time or number of traffic applications until the percentage of "failed" area became unacceptable. This suggests that the mix property level that controls pavement life is generally not an average value, but some lower value consistent with the percentage of surface area actually "failed" in an unacceptable pavement. The problem is in defining the relationship between material performance and quality control test parameters for paving construction and materials. Chapter 5 discusses those performance models selected for asphalt concrete pavements that were initially incorporated into the methodology for demonstration purposes. However, it should be understood that these models are quite limited, are used for demonstration only, and should be replaced with better models before the methodology is used for evaluation of an existing test program.

SYSTEM FOR CONSIDERING MATERIAL VARIABILITY

Variations from target values or accepted standards are generally permitted. The important question is how much variation is permissible. Variations, as measured in the field, are an accumulation of the variation from several sources including:

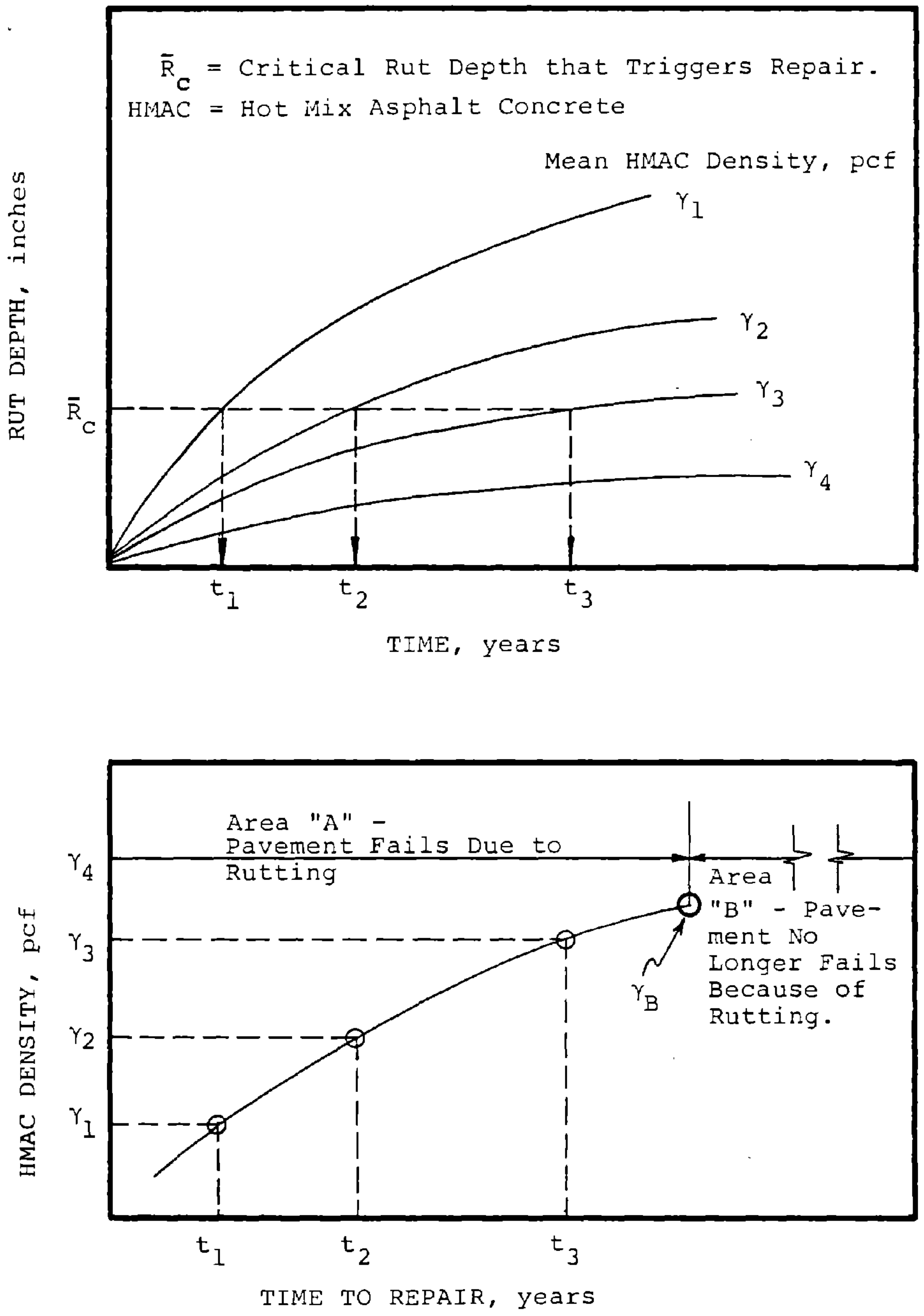


Figure 3. Illustration Showing a Hypothetical Relationship Between Rutting and Hot Mix Asphalt Concrete (HMAC) Density

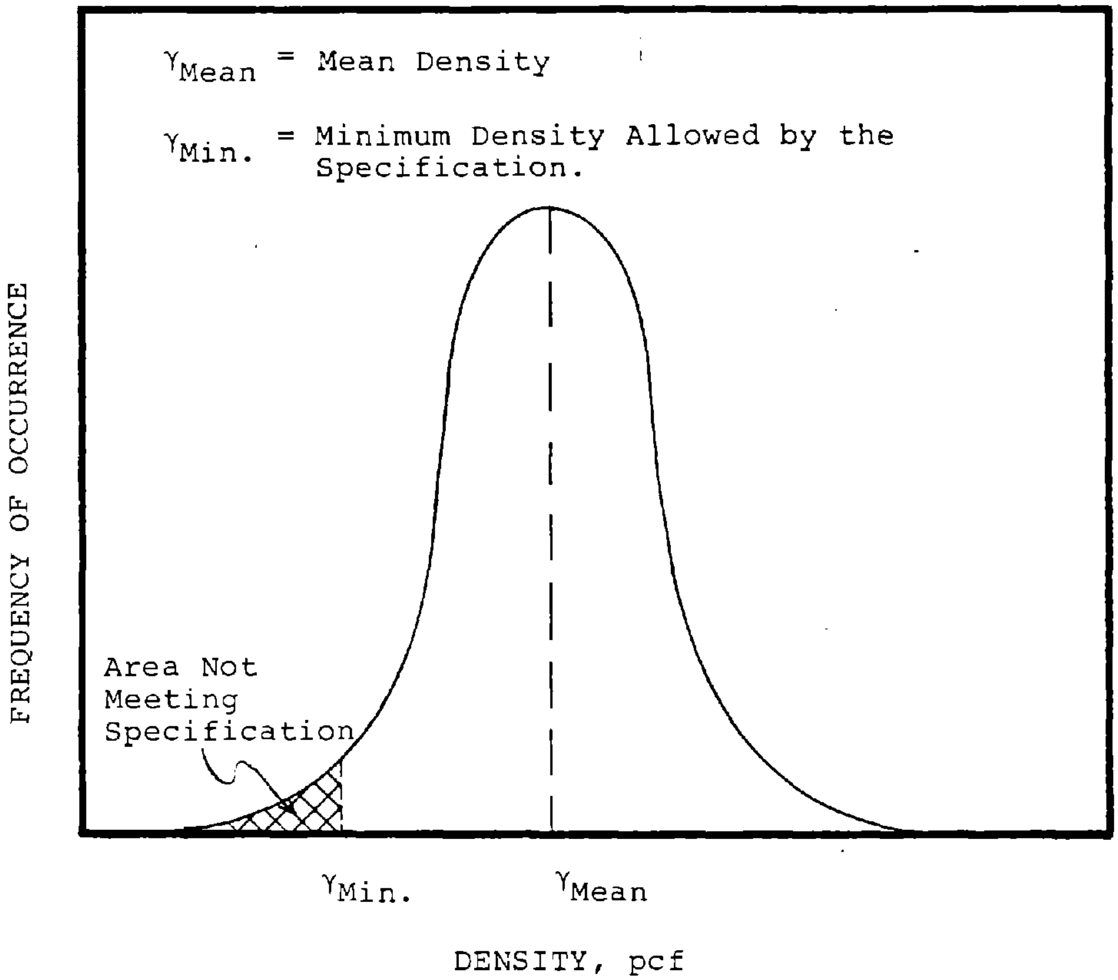


Figure 4. Frequency Distribution of Hot Mix Asphalt Concrete (HMAC) Density Along A Roadway Section

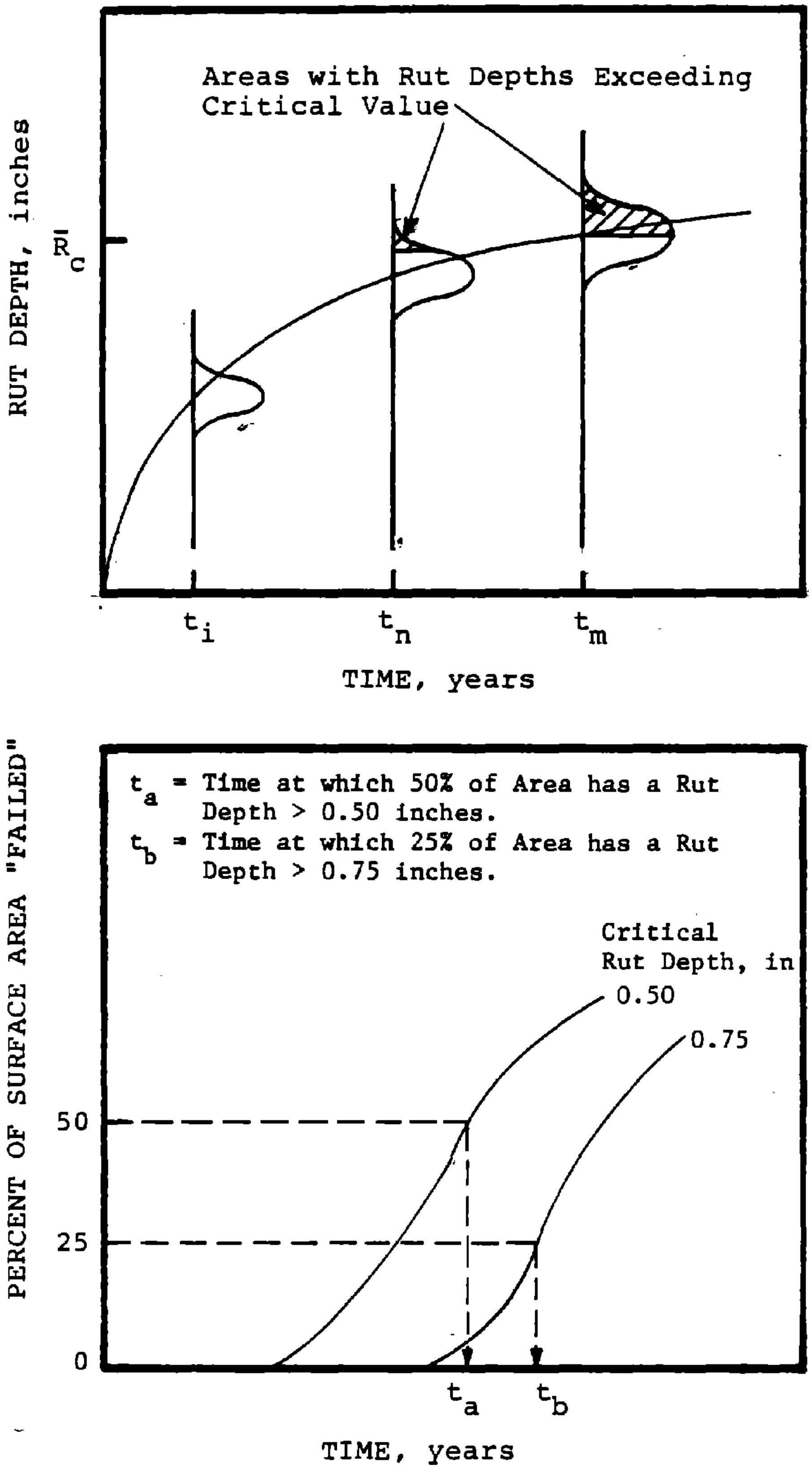


Figure 5. Illustration Showing an Increase in "Failed" Areas with Time for Different Critical Rut Depths Along a Roadway Section Based on HMAC Density Variations

1. Inherent variation in the naturally occurring or quarried material at the pickup location,
2. Process variation - additional variation produced by the handling and manipulation between the source of the material and the roadway (a function of the contractor and methods of production selected),
3. Testing variation introduced because the test procedure is not exact, and
4. Variation due to sampling location.

The importance of material variation depends on how the property affects material performance. For example, considering the relationship illustrated in Figure 3, further increases in asphalt concrete density above γ_B have little or no effect on pavement performance in the range designated as "B" because the critical level of rutting will not occur before other distresses take the pavement out of service. Therefore, it is not necessary to conduct numerous tests, once it is determined that the density is within this range of data. However, if the density is measured to be in the area designated as "A", more testing can likely be justified, because rutting or pavement performance is noticeably affected by small changes in density.

Another factor also confounds efforts to develop a methodology to determine cost effectiveness, and in particular, development of optimum sampling and testing frequencies. This factor is the effect of testing frequency and the enforcement program on a contractor (discussed conceptually in Chapter 2). Simply doing more testing will not improve pavement life nor increase the time to failure, unless the contractor is affected by the number of tests being performed. However, our knowledge about the pavement or product does increase with an increase in number of tests; therefore, an agency has a lower risk to accept a defective lot with increased testing frequency. This may or may not affect how the contractor performs.

The primary question to be answered is, "When does increased testing cease to be cost effective?" For example, in most cases it is not necessary for one to know the exact mean or the standard deviation of a particular lot or product. The factors that affect the number of tests to be taken are the cost of testing, the correlation of the test value to product performance, the expense of initial production or construction, the cost to replace or rehabilitate the material because of failed areas, and the normal or acceptable variation of the material test value. Of course, different properties have varying degrees of importance on pavement performance and the properties that have the greatest effect should be tested more to insure that the material or construction meets the desired performance standards. Figure 2 is a simplified flow chart illustrating the methodology for determining if a change in testing frequency is warranted.

As previously discussed, two questions must be addressed to define the relationship between test frequency and material quality for determining the cost effectiveness of a particular test and test program. These are:

1. Does the test frequency have some effect on the contractor's ability or intent to produce an acceptable product, and
2. How many tests are required to insure that the product is acceptable at some established confidence level?

Contractor Effect Approach

One of the most important factors affecting the number of tests that are cost effective has to do with how contractors perceive the acceptance and controls of an agency's enforcement program. This is a very difficult question to answer and the answer would vary from contractor to contractor and State to State. In order to try to establish a relationship to be used in defining cost effectiveness, one must first define the variables that would have an effect on this relationship. These variables have been identified as follows:

1. State enforcement programs and how contractors interpret these programs.
2. The contractor's motivation to produce an acceptable product.
3. Allowable tolerance in test results from construction.
4. Inherent variation of the material, test procedure, and sampling techniques.

Without doubt, items 1 and 2 are difficult, if not impossible, to explain or predict without the investigators being intimately familiar with physical conditions and contractors on a project-by-project basis.

One might expect that the relation between material variability and number of tests would begin at some level corresponding to little or no testing and approach an asymptotic minimum value of variability for large N, corresponding to the inherent material variation and test procedure inaccuracy. One equation which follows this behavior is:

$$COV = COV_M \; [1 + C_o(N+1)^{D_o}] \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

A similar equation form might also be assumed for the mean value (which may increase or decrease with testing frequency):

$$\mu = X_T\,[1 + A_o(N+1)^{B_o}] \quad\text{.............................}(2)$$

where:

A_o, B_o, C_o, D_o = regression constants that have to do with the SHA enforcement of its quality control program, the contractors intent to produce a good product, production processes, and the allowable construction tolerance or specification set by the State.

COV_M = the inherent coefficient of variation of the material, test procedure, sampling technique, or other variations not controllable by the contractor.

COV = the final coefficient of variation of the material "population" produced by the contractor, using N tests.

X_T = the target value set by the agency's minimum or maximum specification value for a particular test or derived from a job mix formula.

μ = the final mean value of the material "population" produced by the contractor, using N tests.

N = number of tests required by the agency to insure that the product meets the specified standards.

One of the efforts of this study was to generate relationships of the types given above. Data gathered during the State visits on this project were incorporated with numerous data accumulated from other projects (for example, Ref. 2). However, this effort did not result in usable information, because only sample means and standard deviations were available from project construction files and the literature reviewed. Population means and standard deviations were unavailable, and it would have taken an extremely large testing budget to measure the "true" mean and variation of the different tests used in each agency's quality control program, even for the few projects reviewed in this study.

To determine such relationships would require that a number of projects be built or material produced under a given testing and quality control program, and after construction the product tested extensively to define the "true" mean and variation. As this was well beyond the scope of this project, sample data, engineering experience and judgement were used to estimate what were viewed as reasonable values for the constants in the above equations. These values were applied for demonstration purposes and are summarized in Tables 1 and 2.

However, these constants can also be computed from real data if one can define the inherent variation, the maximum variation associated with no testing, and the variation associated with the current test program. For the condition of no testing (N = 0), equations (1) and (2) reduce to:

$$C_o = \frac{COV_o - COV_M}{COV_M} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

and

$$A_o = \frac{\mu_o - X_T}{X_T} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where: COV_o = The coefficient of variation associated with no testing

Table 1
Summary of Constants Selected For Predicting Material Variation As a Function of Testing Frequency

Type of Penalty Imposed By Agency	C_o	D_o
Very Strict and Rigidly Controlled - High Penalties	0.5	-2.5
Moderate Penalty and Control	0.75	-2.0
Low Penalty and Control	1.5	-1.0
No Penalties	3.0	0

Table 2
Summary of Constants Selected For Predicting the Material "Population" Mean As a Function of Testing Frequency

Type of Penalty Imposed By Agency	A_o*	B_o
Very Strict and Rigidly Controlled - High Penalties	1.0	-2.3
Moderate Penalty and Control	0.9	-1.3
Low Penalty and Control	0.7	- .5
No Penalties	0.5	- 0

*A_o can be (+) or (-) depending on from which direction the observed value approaches the target value.

μ_o = The "true" mean of the product associated with no testing. This value is generally not well defined and can be highly variable between contractors for the case of no testing.

The other constants, B_o and D_o, can be calculated using A_o and C_o, as well as values for the mean and coefficient of variation that are typical for the current test frequency used for control by the agency. For example, selected projects were used to compute the constants C_o and D_o (Equation 1) for bitumen content of dense graded hot mix asphalt concrete (HMAC). Materials testing data and other information were obtained from projects reviewed and studied by the authors in Reference 2.

The constants A_o and B_o (Equation 2) were not determined for the same projects, because the "true" or population mean was unknown and unavailable for the case of no testing. In many cases, it was suggested by State personnel that the true mean, μ, be set equal to the target value, X_T. Table 3 lists the constants calculated for each project. As shown, these constants do vary quite extensively and are dependent on the assumed inherent coefficient of variation. Table 3 also shows the ratio of the percent bitumen target value obtained from the Job Mix Formula in construction files to the sample mean measured from extraction tests summarized in daily testing reports. As noted, the sample mean (X_{EXTR}) was both greater than and less than the target value (X_T), but their ratio was approximately 1.0 for most projects.

It should be clearly understood that Table 3 has been prepared from limited data and required that the inherent coefficient of variation COV_M be assumed for each case. The assumed values of COV_M for each project varied with material type.

Table 3
Summary of the Variability Constants (Equation 1) and Error Terms Computed for Asphalt Contents (Extractions) Taken From Actual Project Testing Data Summarized in Reference 2

Test Section No.*	C_o	D_o	X_T/X EXTR	E**
TX15-410 (521A) Drum Mix Plant HMAC Surface	7.0	-6.4	1.0	.12
TX15-410 (521B) Batch Plant HMAC Surface	7.0	-2.2	1.0	.30
GA3-185 (147) Drum Mix Plant A-Binder HMAC	4.0	-0.74	1.0	.38
GA3-185 (147) Drum Mix Plant Asphalt Concrete Base	4.0	-2.0	1.0	.20
GA3-185 (92) Batch Plant A-Binder HMAC	4.0	-2.1	0.98	.20
GA5-95 (33) Drum Mix Plant Asphalt Concrete Base	5.0	-1.9	0.96	.52
GA5-95 (28) Batch Plant HMAC Surface	5.0	-2.5	1.03	.37
A25-40 (347) Drum Mix Plant HMAC Surface	7.3	-1.1	0.96	.39
A25-40 (338) Batch Plant HMAC Surface	7.3	-1.5	1.02	.30
A25-17 (253) Drum Mix Plant HMAC Surface	5.7	-1.0	1.0	.39
A25-17 (254) Batch Plant HMAC Surface	5.7	-1.3	0.98	.30
OR9-14 (8226) Drum Mix Plant HMAC Surface (Type E)	5.3	-0.62	1.30	.52
OR9-14 (8209) Batch Plant HMAC Surface (Type E)	5.3	-1.4	0.93	.36

Table 3
Summary of the Variability Constants (Equation 1) and Error Terms Computed for Asphalt Contents (Extractions) Taken From Actual Project Testing Data Summarized in Reference 2
(continued)

Test Section No.*	C_o	D_o	X_T/X EXTR	E**
UT2-173 (132) Drum Mix Plant HMAC Surface	4.0	-0.51	1.07	.85
UT2-171 (018) Batch Plant HMAC Surface	4.0	-1.4	1.06	.53
MI8-52 (11039) Drum Mix Plant HMAC Overlay	5.3	-0.20	1.0	1.40
MI8-106 (11040) Batch Plant HMAC Overlay	5.3	-3.6	1.0	.29

*Projects selected from Reference 2.

**Value that corresponds to a 95% Confidence Level.

These examples were calculated simply to indicate the variability that may be expected in the assumed relationship to represent contractor effects.

Each user should conduct his own investigation to define these constants or develop an appropriate relationship. In addition, if the production processes change (as illustrated in Figure 6), or the specifications are revised, or there is a time effect (as illustrated by Figure 7), the constants will also change and must be redetermined. Figure 8 shows the flow chart for including consideration of effect of testing frequency on material quality and consequent effects on performance.

Statistical Approach

The second approach taken for this project considers the "allowable risk" (that an agency is willing to take) of accepting inferior or defective material. This approach has been studied previously; some earlier and more current results are documented by McMahon, Ruth and others (Refs. 3 - 10). Here suggested test result values are not provided, as in the "contractor effect" approach, but rather estimates are given of the range in which the true mean for a quantity might lie, given a limited sample of values for that quantity.

This range is defined both by the variation in the sample values and by the confidence to be placed in the limits on the true mean of the population from which the samples were drawn. The greater the confidence level, the wider the range must be. The confidence level, in percent, corresponding to a

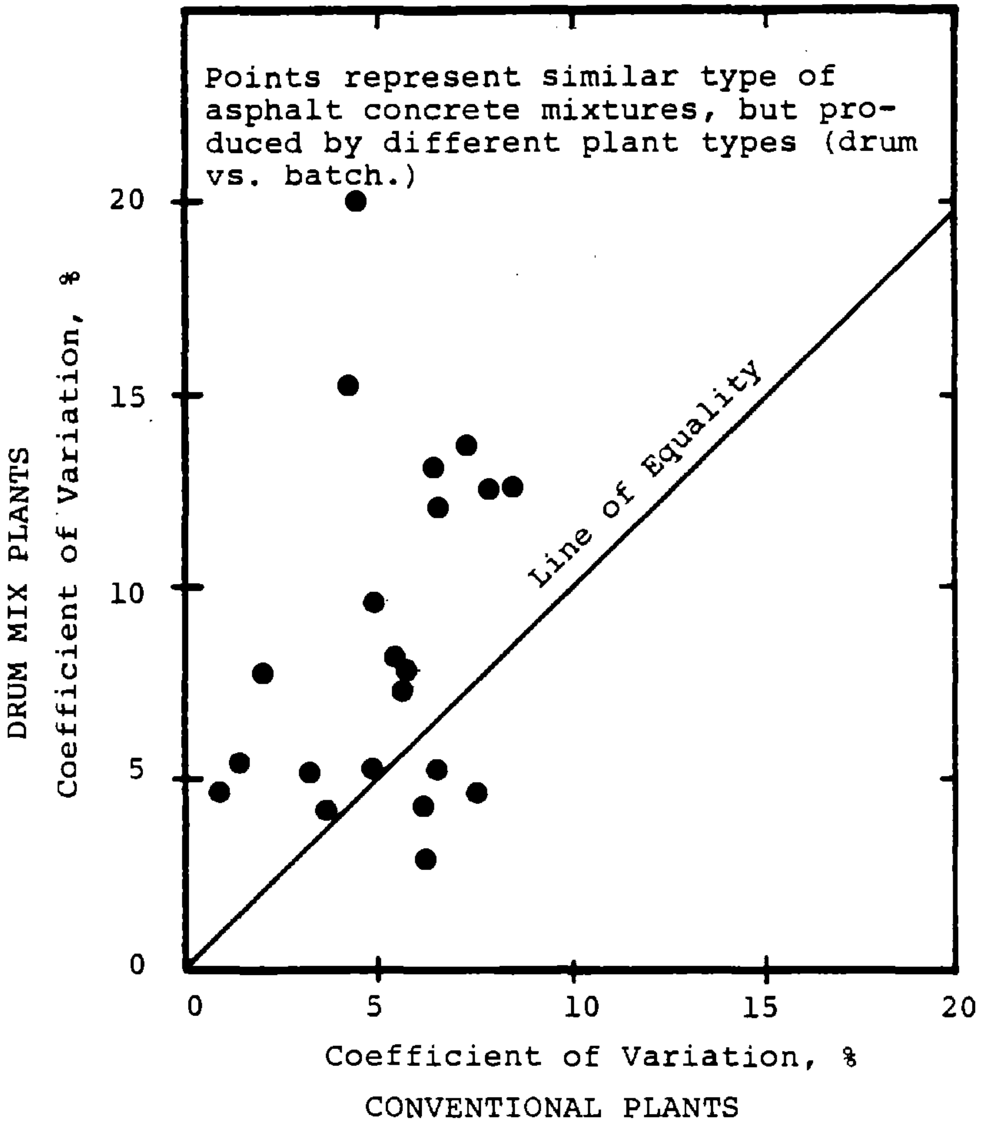


Figure 6. Comparisons of Coefficient of Variations Between Different Mixing Processes for Extracted Asphalt Content (Ref. 2)

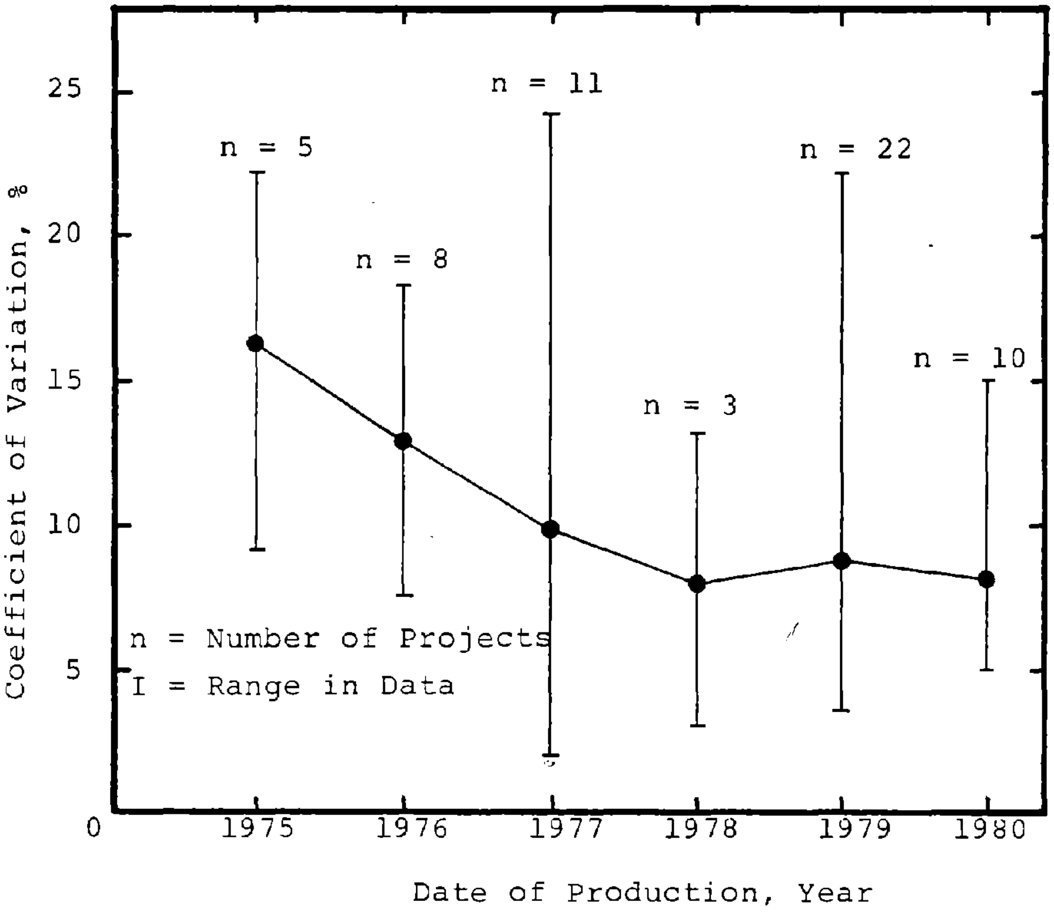


Figure 7. Decrease in Coefficient of Variation for Percent Passing the No. 4 Sieve with Time (Ref. 2)

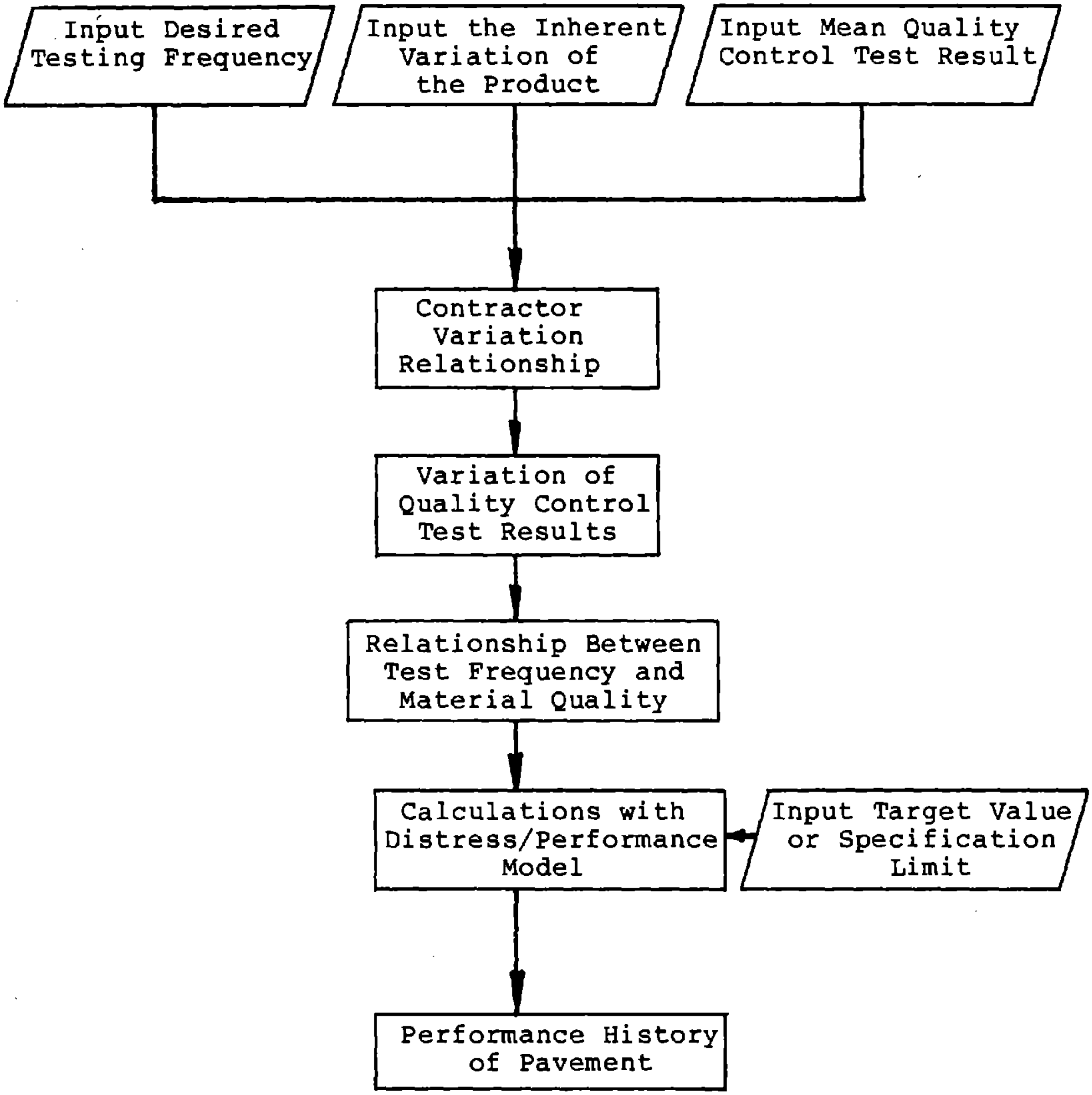


Figure 8. Analysis Using Contractor Variation and Stochastic Performance Model for Cost Effectiveness Methodology

certain range about the mean of a population, is the percentage of samples drawn from that population which fall within that range. A confidence level may be one-sided or two-sided. A one-sided level refers to all values either below or above a certain limit, whereas, a two-sided confidence level refers to a symmetrical range about the mean.

To quantify this relationship, the statistical distribution which describes the population must be determined or assumed. Studies by Kennedy and others (Refs. 11 - 15) have shown that a normal distribution is an excellent approximation for the distribution of results for most common test types. The assumption is therefore made that the normal distribution is appropriate for the populations considered.

It can be shown that if a population has a normal distribution with mean μ and standard deviation σ, then the distribution of the means $\bar{x}$ of samples of size N from that population approaches a normal distribution with mean μ and standard deviation $\sigma/\sqrt{N}$ as the sample size N increases. The term $\sigma/\sqrt{N}$ is also called the standard error of the mean. The distribution of sample means can be standardized by the following transformation:

$$Z = \frac{\bar{x} - \mu}{\sigma/\sqrt{N}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where: Z = standardized statistic with a mean of zero and standard deviation of one,
$\bar{x}$ = sample mean,
μ = population mean,
σ = population standard deviation, and
N = number of samples.

For our purposes this equation can be rewritten as:

$$E = \bar{x} - \mu = Z\sigma / \sqrt{N} \qquad (6)$$

Assuming that the population standard deviation equals the sample standard deviation σ, then for a given number of tests N and a Z-value corresponding to a desired confidence level, an error term E can be computed. When the error term E is added to and subtracted from the sample mean, a confidence interval is defined within which the population mean μ will exist at the chosen level of confidence. This error term E was computed for bitumen content for a 95 percent confidence level using the same projects listed in Table 3. The asphalt content construction tolerance for most of the projects listed in Table 3 is (+) or (-) 0.4 or 0.5 percent. As shown the E-value exceeds the tolerance on some of the projects.

The assumption of a normal distribution for sample means from a normal parent population does not hold for small N; these obey a distribution called a "Student's t-distribution." Small N here might be considered to be N less than 20. The methodology does make this distinction in actual practice, using the t-statistic rather than Z-statistic discussed above. The Z-statistic was retained in the present discussion to simplify the explanation.

In terms of this analysis, a confidence level is selected and a standard deviation is assumed based on experience or historical data. Various N-values are then inserted into the above equation to arrive at error terms. Next, the worst case, in terms of performance, is determined and the error term is either added to or subtracted from an assumed sample mean.

Figure 9 shows the flow chart for estimating the relationship between test frequency and an estimate of material quality based on statistical concepts.

For example, if an error term of 10 pounds per cubic foot were computed for asphalt concrete density, it would be subtracted from an assumed sample mean since a reduced density is considered detrimental to performance. In other cases, it will be necessary to consider the two-tailed case whereby both finite test values resulting from $\bar{x} \pm E$ are considered. For example, if an error term of 0.5 percent were computed for asphalt content, detrimental effects in terms of performance could result from both adding and subtracting this E from an assumed mean value.

Assumed material test results equal to the confidence limits for assumed values of N are entered as mean values for the tested parameter, and used to evaluate the performance functions. Thus, cost calculations can be performed for any testing frequency and the most cost effective frequency can be identified. This type of analysis defines the relative risks involved when the test frequency is altered. In economic terms, the analysis defines the relative costs associated with the uncertainty that results from performing fewer tests. This same approach can be used to compare different types of tests.

PROCEDURE FOR DETERMINING REPAIR REQUIREMENTS

One of the factors that affect the overall cost and resulting cost effectiveness of a particular test has to do with how an agency manages the product under evaluation. In other words, what are the critical factors that affect when and how the

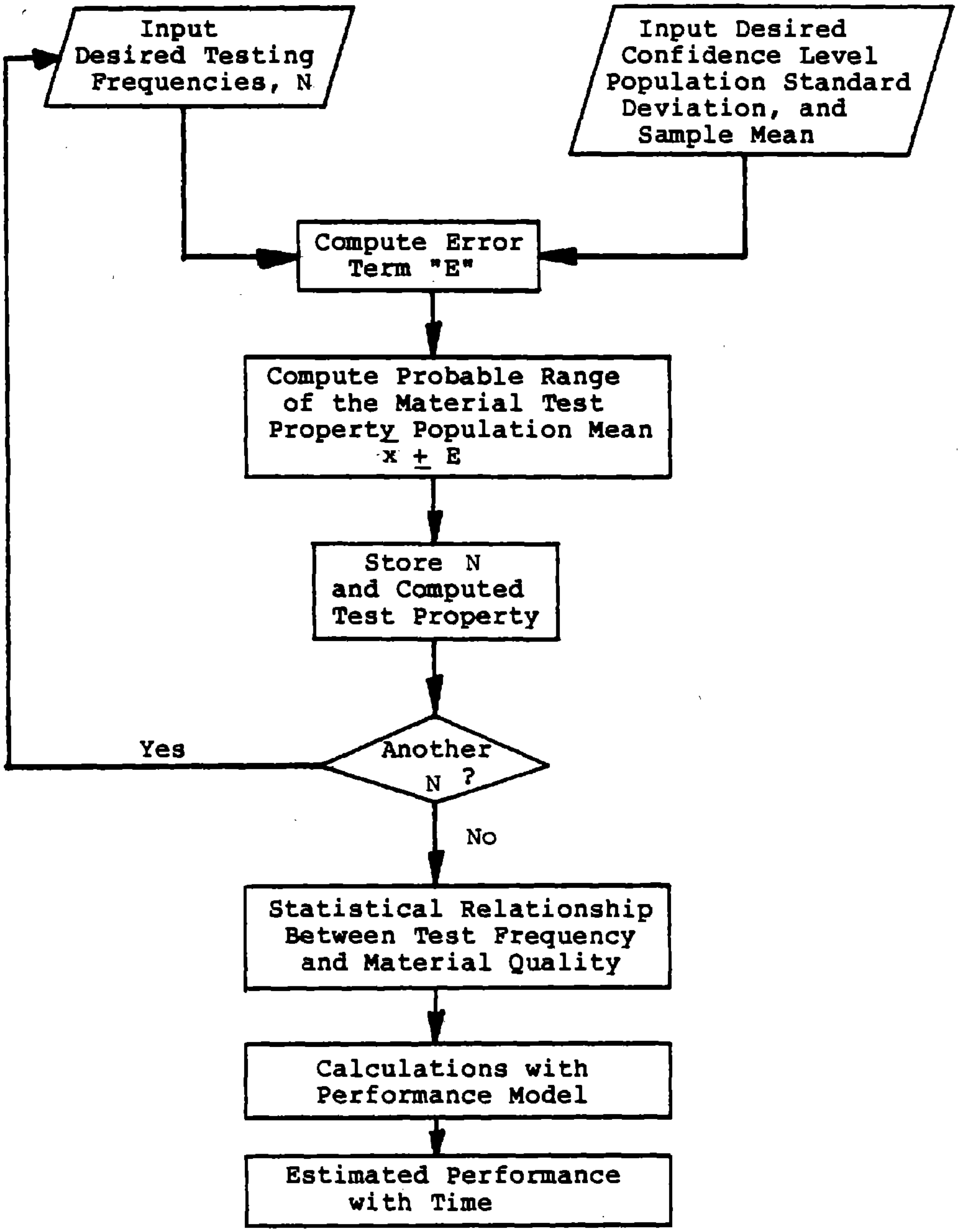


Figure 9. Analysis Using Confidence Interval Estimation for Cost Effectiveness Methodology

product is repaired. Every agency has decision criteria and/or functions (even though they may be subjective) that are used to define the type of repair.

In addition, the cost to repair defective material is highly dependent on the type and amount of distress or combination of distresses. (For example: the use of seal coats to repair reduced skid resistance as opposed to the use of overlays to repair fatigue cracks). Therefore, decision criteria are applied to select a type of repair option appropriate to the predicted physical condition of the pavement or other product at time t. Time t is defined as the time at which the calculated distress value exceeds the critical level (amount and/or area) that causes the pavement or other product to be repaired or maintained. Selèction of a repair option implicitly establishes a repair cost at time t. As an example, the following distress or performance measures were considered for use in the methodology, because these constitute the criteria most often used to determine maintenance or repair needs for asphalt concrete roadways:

(1) alligator cracking,
(2) rutting,
(3) loss of pavement serviceability (or alternatively roughness), and
(4) loss of skid resistance

Most SHA's utilize a set of maintenance guidelines based on the above list of distress or performance measures. Some States may use all four types, while others may use only a few, or even some not listed. In addition, different SHA's specify different levels of distress or performance as critical levels for "triggering" maintenance or repair.

There are cost functions that can be used to predict the probable repair costs of a flexible or rigid pavement as a function of age (Refs. 15 - 17). Both techniques (repair cost equations or the approach described above) are approximate and use simplifying assumptions. However, as the technique based on predictions of the physical condition of the construction allow universal application to a range of materials, it was selected instead of the equations relating maintenance cost to age.

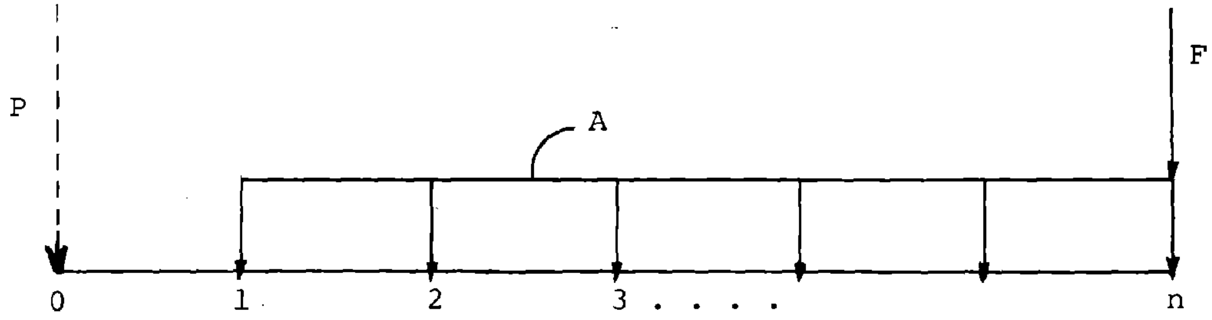
PROCEDURE FOR COMPARING TOTAL COSTS

In judging the attractiveness of alternative testing programs, it is necessary to recognize the time value of money. Because capital may be loaned at interest, the value of a monetary unit is greater at present than the same unit at a later date. Two methods were considered for evaluating, on an economic basis, multiple alternatives: present worth and equivalent uniform annual costs.

Using the concept of equivalence and by taking into account the interest rate and number of compounding periods, it can be stated that any future payment or series of payments can be represented by a single, equivalent present worth. Conversely, an actual present worth or a future payment can be represented by an equivalent uniform annual cost. Figures 10 and 11 illustrate the concepts of present worth and equivalent uniform annual cost using standard cash flow diagrams. The factors in parenthesis, e.g., (P/A,i,n) are compound interest factors which are tabulated in most engineering economy texts. Table 4 identifies these factors and lists formulae for their computation.

Present Worth Analysis

Present Worth Analysis is currently a widely accepted method because future expenditures or receipts are transformed into



$$P = A(\frac{P}{A},i,n) + F(\frac{P}{F},i,n)$$

P = equivalent present worth

A = actual series of payments

F = actual future payment

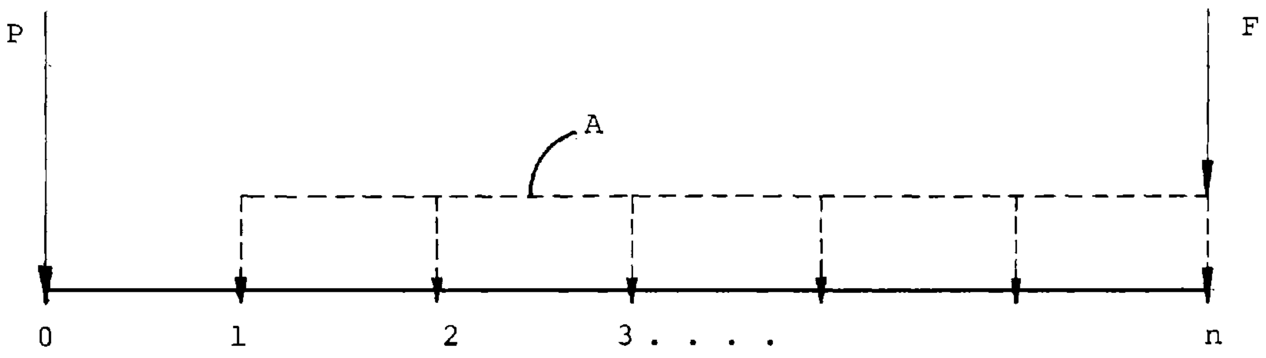
n = number of compounding periods

i = interest rate per period

$(\frac{P}{A},i,n)$ = uniform series, present worth factor

$(\frac{P}{F},i,n)$ = single payment, present worth factor

Figure 10. Equivalent Present Worth of Actual Future Series of Payments



$$A = P(\frac{A}{P},i,n) + F(\frac{A}{F},i,n)$$

A = equivalent uniform cost

P = actual present worth

F = actual future payment

n = number of compounding periods

i = interest rate

$(\frac{A}{P},i,n)$ = uniform series capital recovery factor

$(\frac{A}{F},i,n)$ = uniform series sinking fund factor

Figure 11. Actual Present Worth Represented by Equivalent Uniform Annual Cost

Table 4
Compound Interest Factors

Payment Type	Factor	Symbol	Formula
Single Payment	Compound Amount	$(\frac{F}{P},i,n)$	$(1+i)^n$
	Present Worth	$(\frac{P}{F},i,n)$	$\frac{1}{(1+i)^n}$
Uniform Series	Sinking Fund	$(\frac{A}{F},i,n)$	$\frac{i}{(1+i)^n-1}$
	Capital Recovery	$(\frac{A}{P},i,n)$	$\frac{i(1+i)^n}{(1+i)^n-1}$
	Compound Amount	$(\frac{F}{A},i,n)$	$\frac{(1+i)^n-1}{i}$
	Present Worth	$(\frac{P}{A},i,n)$	$\frac{(1+i)^n-1}{i(1+i)^n}$

i = interest rate

n = number of compounding periods

present equivalent dollars. In comparing two or more alternatives, future payments or series of payments for each case are converted to present values. The alternative which has the lowest present value is considered (at least from an economic standpoint) the most attractive.

As an example, two pavement structures are to be compared. The first structure (A) initially costs $100,000/mile and requires $2000 per mile per year for routine maintenance and $40,000 per mile for rehabilitation at the end of eight years. The second structure (B) initially costs $75,000 per mile and requires $4000 per mile per year and $30,000 per mile for rehabilitation at the end of eight years. An interest rate of ten percent is assumed. The present worth analysis is as follows:

$$\begin{aligned}\text{Present Worth of A} &= 100{,}000+2000(\tfrac{P}{A},10\%,8\text{yrs})+40{,}000(\tfrac{P}{F},10\%,8\text{yrs})\\ &= 100{,}000 + 2000(5.335) + 40{,}000(.4665)\\ &= 100{,}000 + 10{,}670 + 18{,}660\\ &= \$129{,}330\end{aligned}$$

$$\begin{aligned}\text{Present Worth of B} &= 75{,}000+4000(\tfrac{P}{A},10\%,8\text{yrs})+30{,}000(\tfrac{P}{F},10\%,8\text{yrs})\\ &= 75{,}000 + 4000(5.335) + 30{,}000(.4665)\\ &= 75{,}000 + 21{,}340 + 13{,}995\\ &= \$110{,}335\end{aligned}$$

Based on the present worth analysis, pavement structure B should be chosen.

In the preceding analysis the most important assumption was that the alternatives were equal in all respects except cost. However, in most cases, alternatives under consideration have different potential service lives. Techniques have been devised to overcome this difficulty; the most common method is to assume that an alternative can be considered a sequence of identical alternatives. That is, each alternative will be replaced with an "identical successor" at the end of its service life, and this process will continue until all alternatives reach the end of their service lives at the same time.

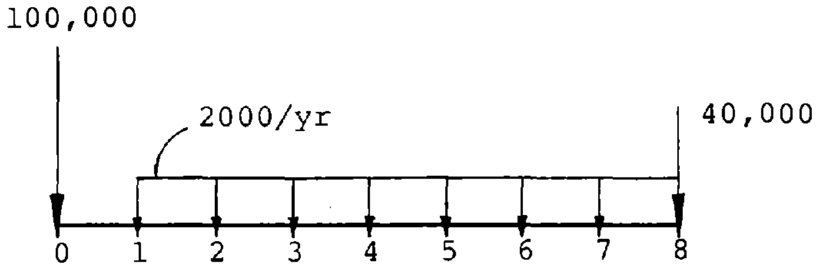
As an example, assume that pavement structures A and B are the same as before but that another pavement structure (C) costs \$50,000 per mile initially, requires \$1750 per mile per year for routine maintenance, and \$18,000 per mile for rehabilitation after four years. Figure 12 illustrates the cash flow for the three alternatives. The present worth for structure C is computed by:

$$\begin{aligned}
\text{Present Worth of C} &= 50{,}000+1750(\tfrac{P}{A},10\%,8\text{yrs})+18{,}000(\tfrac{P}{F},10\%,4) \\
&\quad + 50{,}000(\tfrac{P}{F},10,4)+18{,}000(\tfrac{P}{F},10\%,8) \\
&= 50{,}000 + 1750(5.335) + 18{,}000(.6830) \\
&\quad + 50{,}000(.6830) + 18{,}000\ (.4665) \\
&= 50{,}000 + 9{,}336 + 12{,}294 + 34{,}150 + 8{,}397 \\
&= \$114{,}177
\end{aligned}$$

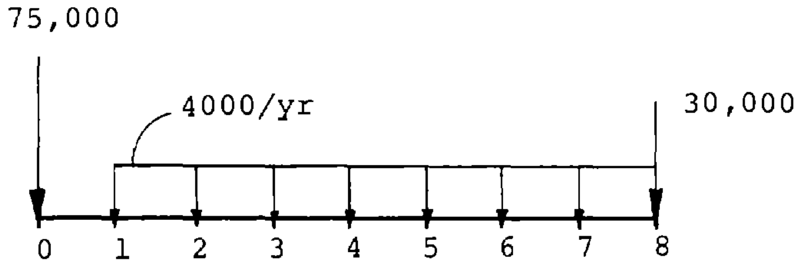
Therefore, pavement structure B remains the most economic choice.

Equivalent Annual Cost Analysis

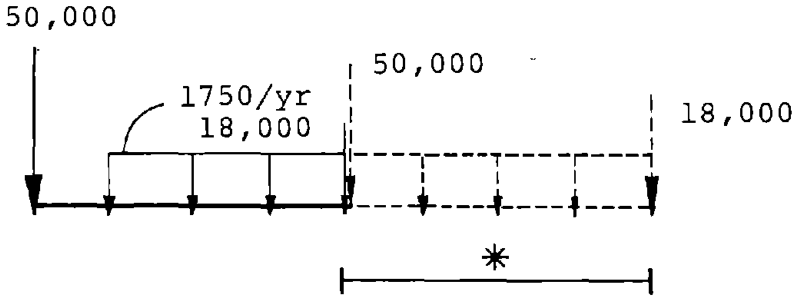
In this method of comparing multiple alternatives, all present and future values are converted to equivalent uniform annual



Structure A



Structure B



Structure C

*Repeated for Present Worth Analysis

Figure 12. Cash Flow Diagrams for Present Worth Analysis Example

costs (simply termed annual cost). In comparing multiple alternatives, that which has the lowest annual cost is the most attractive.

As an example, the previously mentioned pavement structures are to be compared on an annual cost basis.

$$\text{Ann. Cost of A} = 100{,}000\ (\tfrac{A}{P},10\%,8)+2{,}000+40{,}000(\tfrac{A}{F},10\%,8)$$

$$= 100{,}000(.18744)+2{,}000+40{,}000(.08744)$$

$$= 18{,}744 + 2{,}000+ 3498$$

$$= \$24{,}242$$

$$\text{Ann. Cost of B} = 75{,}000\ (\tfrac{A}{P},10\%,8)+4{,}000+30{,}000(\tfrac{A}{F},10\%,8)$$

$$= 75{,}000(.18744)+4{,}000+30{,}000(.08744)$$

$$= 14{,}058 + 4{,}000 + 2623$$

$$= \$20{,}681$$

$$\text{Ann. Cost of C} = 50{,}000\ (\tfrac{A}{P},10\%,4)+1{,}750+18{,}000(\tfrac{A}{F},10\%,4)$$

$$= 50{,}000(.31547)+1{,}750+18{,}000(.21547)$$

$$= 15{,}774 + 1{,}750 + 3878$$

$$= \$21{,}402$$

As previously determined, pavement structure B is still the most attractive.

It is of interest to note that for the annual cost comparison, no assumption is made concerning equal service lives. That is, alternatives may be directly compared with no sequential repetition of alternatives.

Present Worth Analysis Versus Equivalent Annual Cost Analysis

The obvious difference between the two methods is that the present worth analysis requires equal service lives of alternatives for direct comparison; unequal service lives require special treatment. The special treatment requires sequential repetition of alternatives until all alternatives reach the end of their service life at the same time. It should be noted that from a mathematical standpoint, both methods are exact and thus, always predict the same alternative as most attractive. In fact, if the sequential alternative repetition technique is used, the computed present values can be converted into annual costs that are numerically equal to those obtained from a conventional annual cost comparison. This can be illustrated by converting the present costs of pavement structure C, derived using the sequential repetition technique, to an equivalent annual cost:

$$\begin{aligned}\text{Annual Cost of C} &= 114{,}177\ (\tfrac{A}{P}, 10\%, 8)\\ &= 114{,}177(.18744)\\ &= \$21{,}402\end{aligned}$$

Note that this number is equal to the value previously computed for pavement structure C.

In general, the present worth of an alternative that requires an investment I, service life n, and interest rate i, with k equal to the number of sequences, can be expressed in terms of the single payment present worth factor (see Table 4):

$$\text{Present Worth} = I[1+\frac{1}{(1+i)^{n}}+\frac{1}{(1+i)^{2n}}+\ldots+\frac{1}{(1+i)^{(k-1)n}}] \ldots\ldots(7)$$

This expression is the sum of k terms in a geometric series which can be reduced to:

$$\text{Present Worth} = I\frac{[1-\frac{1}{(1+i)^{kn}}]}{[1-\frac{1}{(1+i)^{n}}]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

$$= I\frac{[1-(1+i)^{kn}][1+i]^{n}}{[1-(1+i)^{n}][1+i]^{kn}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

To convert this present worth to an equivalent annual cost, multiply by the uniform series capital recovery factor (see Table 4) expressed in terms of k:

$$\text{Annual Cost} = I\,\frac{[1-(1+i)^{kn}][1+i]^{n}}{[1-(1+i)^{n}][1+i]^{kn}} \times \frac{i(1+i)^{kn}}{(1+i)^{kn}-1} \ldots\ldots\ldots (10)$$

$$\text{Annual Cost} = I\,\frac{i(1+i)^{n}}{(1+i)^{n}-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

This expression is simply the equivalent annual cost of the alternative, which could have been computed directly by using an annual cost analysis.

Procedure for Determining Cost Effectiveness

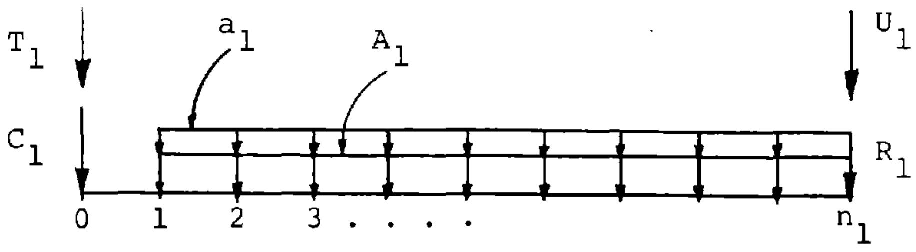
The basis for determining cost effectiveness is an incremental benefit-cost analysis. This is a widely accepted method of comparing multiple alternatives while ensuring that a change from the existing (i.e., do nothing) situation is warranted.

Based on the comments presented in the previous section, a procedure to determine cost effectiveness is herein presented. It is recommended that annual cost be used as a basis for computing benefits and costs. This circumvents the previously discussed difficulties encountered using a present value analysis to compare alternatives with different lives.

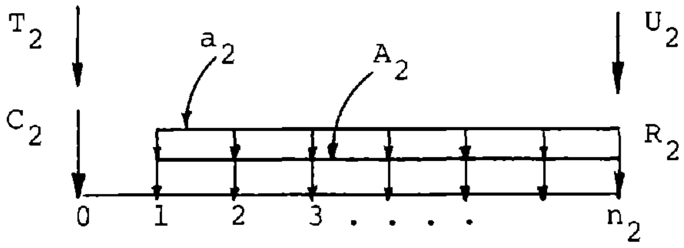
User costs should also be considered because under certain circumstances these costs tend to dominate the analysis. These user costs fall into two categories: First, there are user costs associated with major rehabilitation activities. These costs would include the extra time expended by the traveling public while traversing an area of pavement undergoing major rehabilitation. Second, there are user costs (time, gas, oil, tires, etc.) associated with minor rehabilitation activities as well as simply traversing rough roads. These costs occur on a day-to-day basis.

The benefits and costs associated with two example alternatives should be computed as shown in Figure 13. All costs are converted to equivalent uniform annual costs using the compound interest factors previously discussed. For multiple (i.e., three or more) alternatives, the incremental benefit-cost analysis should be performed using a challenger/defender approach (Figure 14). In this approach, alternatives are arranged in order of increasing testing cost. The first defender should be the do-nothing (i.e., minimal testing) condition with the least expensive alternative the challenger.

Incremental benefit is the reduction between defender and challenger in uniform annual cost to build, maintain, and rehabilitate the road. Incremental cost is the increase in testing cost between defender and challenger. An incremental



Alternative 1



Alternative 2

T = testing costs
C = construction costs
a = annual user costs
A = annual maintenance costs
U = user costs associated with rehabilitation
R = rehabilitation costs
A_{si} = total annual cost of alternative i (excluding testing costs)
A_{ti} = annual cost of testing for alternative i

$$A_{s1} = C_1 \left(\frac{A}{P}, i, n_1\right) + a_1 + A_1 + (U_1 + R_1)\left(\frac{A}{F}, i, n_1\right)$$

$$A_{s2} = C_2 \left(\frac{A}{P}, i, n_2\right) + a_2 + A_2 + (U_2 + R_2)\left(\frac{A}{F}, i, n_2\right)$$

$$A_{t1} = T_1 \left(\frac{A}{P}, i, n_1\right)$$

$$A_{t2} = T_2 \left(\frac{A}{P}, i, n_2\right)$$

The terms in parentheses are taken from Table 4.

$$B/C = \text{incremental benefit-cost ratio} = \frac{A_{s1} - A_{s2}}{A_{t2} - A_{t1}}$$

Figure 13. Benefit-Cost Analysis for Two Alternatives Resulting from Different Testing Schemes

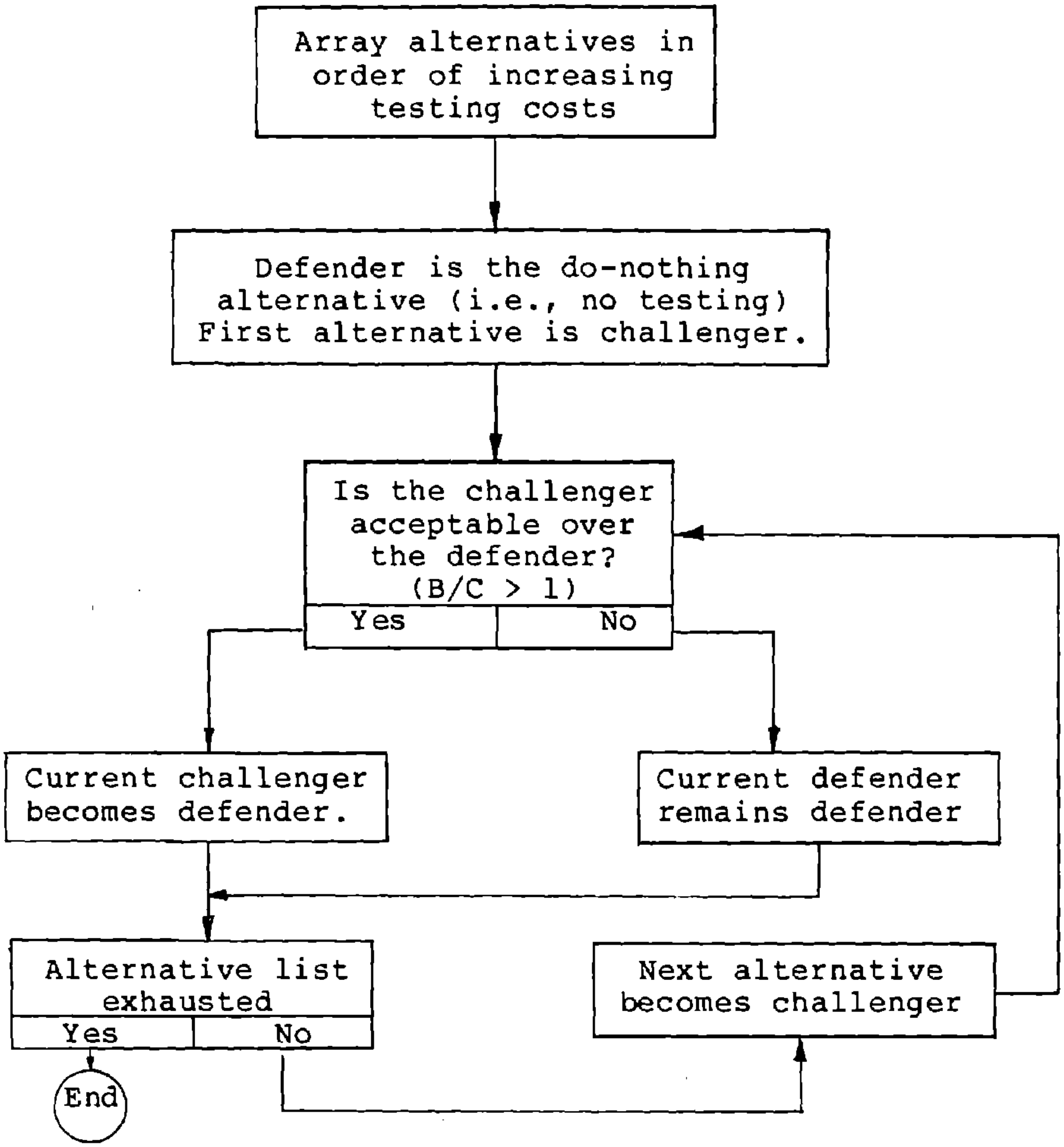


Figure 14. Flow Diagram of the Challenger/Defender Procedure for Analysis of Multiple Alternatives

benefit-cost ratio greater than one indicates that more benefit is received from increased testing than that increased testing costs. If this is the case, the challenger then becomes the defender to the next alternative, otherwise the original defender remains the defender to the next challenger.

CHAPTER 4

TESTING COST EVALUATION FOR SELECTED CURRENT PROGRAMS

Three States were selected to evaluate the costs of different sampling and testing programs. To ensure diversity between the testing and sampling programs studied, one of the States selected was to rely primarily on the use of end-result type specifications and one on the traditional or "cookbook" approach. In addition, one State Highway Agency (SHA) was to be a large agency and one a small agency. States that agreed to participate were Arizona, Illinois, and West Virginia. The types and frequencies of tests performed in each of these States are listed in Appendix A, and were obtained from the appropriate sampling guides and/or project procedures guides of each SHA. As expected, there are significant differences among the three agency programs.

Figure 15 shows a typical organizational structure of a State Department and Transportation Materials and Tests Division, with sub-units indicated for the Asphalt Concrete Section.

EVALUATION OF SHA TESTING COSTS

Based on interviews with several officials in each agency, it was quickly determined that testing costs are not well defined and are evaluated differently by different SHA's. For example, the Illinois DOT (IDOT) computes testing costs in terms of dollars expended per unit of paving material. The West Virginia Department of Highways (WVDOH), which uses end-result specifications, lists costs for several tests; however, these costs are only for extra tests requested by a contractor faced with a sublot of failing material. Thus, these costs

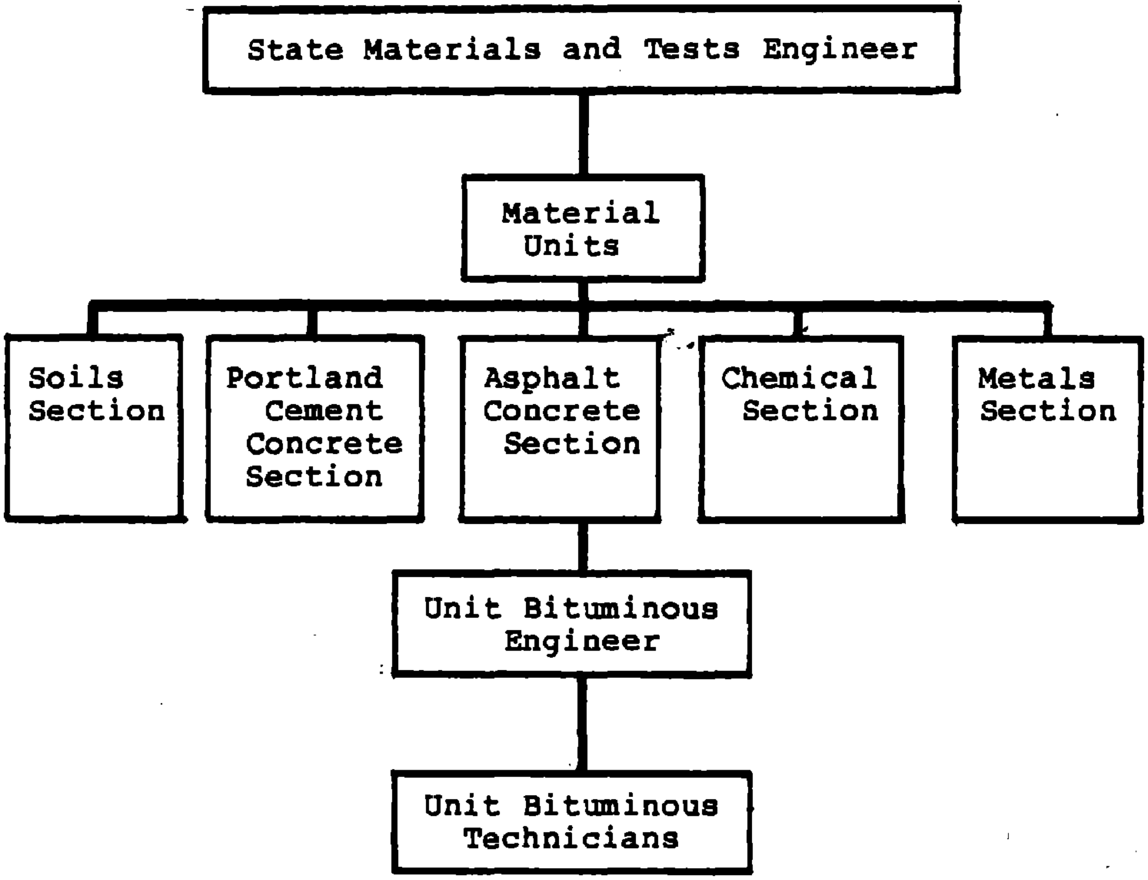


Figure 15. Typical Organizational Structure of a State DOT Materials and Tests Division for the Purpose of Computing Testing Costs

are for tests not performed on a routine basis. The Arizona Department of Transportation (ADOT) computes costs on a per test basis. However, these costs do not include some of the indirect cost items and are not updated each year.

It is believed that any unit test cost should include at least the following:

1. Direct Labor Costs - Technician and supervisor salaries
2. Testing Equipment Costs - Nonexpendable equipment depreciation
3. Travel Costs and Vehicle Costs - Vehicle and equipment rental, subsistence, mileage and maintenance costs
4. Administrative Overhead and engineering costs

These costs are explained in detail subsequently.

Information on testing costs was obtained and evaluated in an attempt to determine the total cost associated with each SHA testing program. However, a detailed cost breakdown by equipment costs, depreciation, travel costs, supplies, other indirect cost items and number of tests performed for a fiscal year was unavailable.

All States did have a cost or price schedule for the tests that are performed on a routine basis. These price schedules (cost per test) were obtained and are provided in Appendix B. It should be understood that the unit costs listed do not include all of the indirect cost items listed above. As shown, the unit price schedules vary quite substantially among the SHA's.

An attempt was initially made to compute overall testing cost for each test performed in the asphalt concrete material section of each State. However, it was quickly determined that numerous items were not recorded, or were available only through extensive study of accounting procedures and records. Therefore, it was decided that a reasonable cost to perform a particular test would have to be established by increasing each unit cost on the price schedule according to what items were omitted in determining those costs.

Figure 16 shows a limited comparison between contract size (bid price) and total amount of testing charged to the project. The testing costs plotted on Figure 16 represent the total costs of labor, laboratory, overhead, travel, equipment and supplies charged to a particular construction project and includes the central, district and/or residency charges. It is interesting to note that this limited comparison from one State, indicates that total testing costs (using the traditional type of specifications) generally represent eight to twelve percent of the total construction costs. Total testing cost data were not readily available for the condition where the contractors are responsible for quality control.

Direct Labor Cost

Direct Labor Cost for each test includes the amount of salaried time (both testing and supervisory) required to prepare, perform and report the test. The actual times to perform each of the tests listed in Appendix A were generally available from each State. However, the amount of time (or cost) required for sampling and transporting the material was not readily available. In addition, the unit costs given in

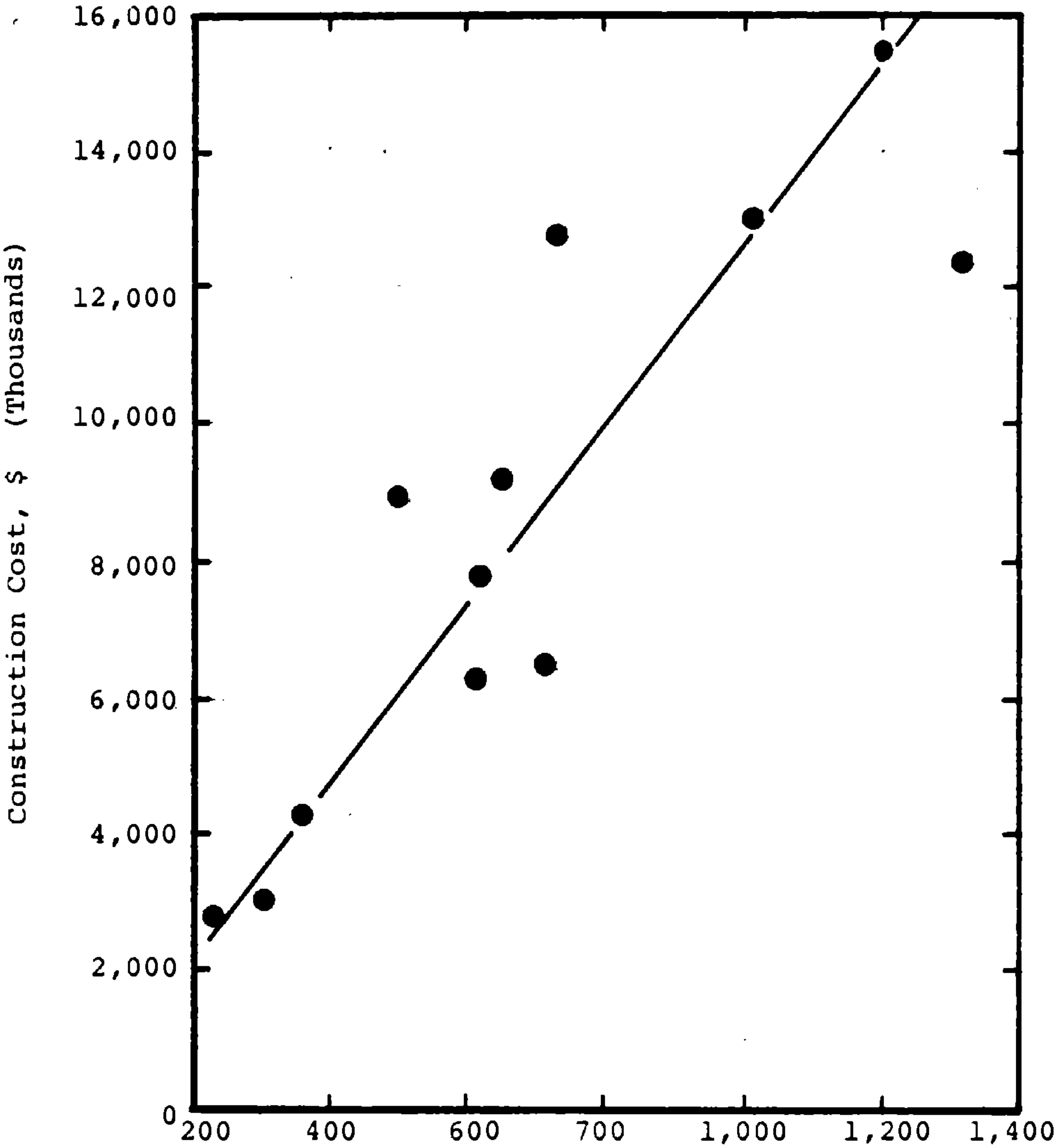


Figure 16. Comparison of Total Construction Cost to Total Testing Cost

Appendix B generally represent the central laboratory and not field laboratory costs.

All SHA's interviewed have detailed cost accounting procedures that record and document all charges to a particular construction project or account. However, the specific details and type of accounts in each procedure vary quite substantially between SHA's, and were even found to vary with time within a SHA. This time variation greatly complicates the problem of trying to compute unit testing costs, especially if a detailed cross-reference is unavailable between similar accounts with time.

Another complicating factor is time charged to incorrect account numbers. One SHA had conducted a recent audit and found that approximately 25 percent of the laboratory labor time had been charged to a special administration number entitled "General Design." During the audit it was determined that 50 percent of those hours should have been charged to particular construction projects. Therefore, much of the information available from historical records does not necessarily reflect the "true" direct labor costs associated with a particular testing program for construction projects.

Testing Equipment Cost

Testing equipment costs include a proration of the equipment cost by year so that this cost may be included in the total cost of testing. Annual depreciation cost of testing equipment is a measure of the "annual consumption of value" throughout its useful life. Depreciation should be considered for equipment until the time when the equipment can no longer be maintained. For most equipment, the depreciation time is generally a "best guess" of a materials engineer experienced in using the equipment.

The types of equipment in use and identity of individual equipment items can generally be obtained from an inventory of equipment in each laboratory, if these inventories are periodically updated. Equipment depreciation costs were generally omitted from the evaluation of unit testing costs, with the exception of West Virginia. For this State, unit costs were obtained from a contractor responsible for quality control testing and do include equipment depreciation costs.

Transportation Cost

In most cases, transportation costs are considered minimal and are omitted from cost computations. However, transportation or shipment of samples will vary with the distance they are to be shipped. For example, one would expect greater transportation costs for larger states which routinely ship samples to a central laboratory, such as Arizona and Texas.

Administrative and Overhead Costs

Administration and Overhead Costs represent the indirect labor costs; they generally include vacation, holiday, sick leave, and other benefits provided by the State agency. These costs are normally included by a SHA in establishing the unit cost of a test, because these costs do not change extensively with time. However, other overhead costs, such as supplies and equipment maintenance required to conduct a test are not usually included.

PROCEDURE FOR CALCULATING TESTING COSTS

The evaluation of cost effectiveness for particular tests requires that unit costs be determined for each test. The following describes a standard procedure for determining the unit cost of a quality control or acceptance test. The procedure is a modification of a method devised by the Louisiana Department of Transportation and Development (LDOTD). Application of the LDOTD method to the other SHA's proved impractical within the limited time available, due to the fact that the method relies heavily on special accounting procedures and data used by LDOTD. However, the procedure is logical and does consider many of the variables and factors that affect overall costs, and was therefore selected for use in this study.

The procedure consists of identifying and adding together four separate costs that generally comprise the total cost of a test. These costs are 1) salary costs, 2) equipment costs, 3) travel costs, and 4) administrative and overhead costs. It is recommended that the source of such data be the most recent fiscal year for which complete information is available.

It is convenient to group testing costs according to material type as tests on a particular material are performed by the group of individuals in that material unit. A tabular solution is advised. Separate tables should be filled out for each material. The format in Table 5 is recommended to facilitate this approach. Each column in the table is numbered and has an explanatory title. More detailed explanations for each column are provided below:

Table 5
Table for Calculation of Testing Costs
SUMMARY OF TESTING COSTS FOR ASPHALT LABORATORY

1 Test	2 Test Time	3 Number of Tests Per Year	4 Weighted Time Factor	5 Salary Time %	6 Salary $/Year	7 Salary $/Test
Pen.	5	400	2000	27	39,108	97.77
Visc.	5	300	1500	20	28,969	96.56
Solub.	5	300	1500	20	28,969	96.56
Duct.	5	300	1500	20	28,969	96.56
Flash	5	100	500	6.5	9,415	94.15
R & B	5	100	500	6.5	9,415	94.15
		1500	7500	100%	144,845	

1 Test	8 Equipment Deprecia-tion $/Test	9 Vehicle and Equipment Rental $/Test	10 Travel $/Test	11 Supply $/Test	12 Admn. Overhead $/Test	13 Admn. Eng. $/Test	14 Total Annual $/Test
Pen.	1.14	3.60	4.80	4.00	12.00	6.67	129.88
Visc.	1.14	3.60	4.80	4.00	12.00	6.67	128.77
Solub.	1.14	3.60	4.80	4.00	12.00	6.67	128.77
Duct.	1.14	3.60	4.80	4.00	12.00	6.67	128.77
Flash	1.14	3.60	4.80	4.00	12.00	6.67	126.36
R & B	1.14	3.60	4.80	4.00	12.00	6.67	126.36

1. Test - This includes any independent routine or activity which is performed to determine the quality or acceptability of a material. Again, all tests on a particular table must pertain to a particular material type and be performed by a particular material unit.

2. Test Time- This number is the amount of salaried time expended while performing the test. For this procedure, man-hours should be used as the basic unit and should include time spent by all personnel involved from start to finish and should include time attributed to planning, travelling, sampling, testing, inspection, and reporting.

3. Number of Tests Per Year - This number is the actual number of times the particular test under consideration was performed during the fiscal year for which data is extracted.

4. Weighted Time Factor - This number is the product of the test time and the number of tests per year. This represents the total time spent conducting that test during the year for the material under consideration by the appropriate material unit.

5. Salary Time (%) - This number, expressed as a percent, is equal to the individual weighted time factors divided by the total of the weighted time factors. This represents the proportion of the annual salary of those performing all listed tests that is allocated to any particular test.

6. Salary Cost Per Year - This number is the product of the salaried time (expressed as a decimal) and the total salaried cost per year (defined below).

   The total salaried cost per year is the sum of the annual salaries for all personnel who routinely contribute to all of the tests for a material unit, with the annual salaries increased to reflect the agency's benefit payroll additive and any validated overtime costs and reduced to reflect part-time participation in other activities. For instance, if a supervisor performs duties for more than one material unit, an appropriate portion of his salary should be allocated to each unit.

   As indicated above, the salary of the Materials Engineer is generally to be distributed to the various material units, but some appropriate portion (perhaps 40 percent) should be omitted due to other staff duties not related directly to the testing. Perhaps 75 percent of the salary for his assistants should be proportionately allocated down to the appropriate material units (i.e., 25 percent of their time is spent on administrative duties not directly associated with tests). For lower levels of management, 100 percent of salaries can reasonably be proportionately allocated to the individual units in which they participate.

7. Salary Cost Per Test - This number is the quotient of the salaried cost per year and the number of tests per year.

8. Equipment Depreciation Costs Per Test - Depreciation costs may be determined by summing the depreciation costs for all equipment used by a material unit and allocating an equal value to all tests. This simplified procedure may not be totally realistic since not all tests require every piece of equipment; however, this cost is usually not significant enough to warrant a more sophisticated procedure. Depreciation costs may also be computed on an annual basis using a tabular approach (Table 6). The annual depreciation cost for an item of equipment is taken as the inverse of the service life plus an appropriate inflation rate and then multiplied by the initial cost. It should be understood that depreciation costs should not exceed the value of the equipment. After the total annual depreciation cost is computed, it is divided by the total number of tests per year.

9. Vehicle and Equipment Rental Cost Per Test - The total vehicle and equipment rental costs for a material unit are summed for the fiscal year, and divided by the total number of tests conducted per year. This estimate could be refined by applying weighting factors reflecting test dependence on vehicles or rented equipment, but this is probably not justified.

10. Travel Costs Per Test - This number reflects the annual cost of travel, meals, lodging, etc. for field travel, exclusive of the vehicle costs (Item 9 above). In addition, these costs do not include conference and convention travel expenses. The total travel costs for a material unit are summed for the

Table 6
Method of Computing Equipment Depreciation Cost Per Test

Equipment Item	Initial Cost	Estimated Service Life	$\frac{1}{S.L.} + I$	Annual Depreciation
Oven	700	10	.20	140
Ductility Unit	2000	15	.17	340
Balance	200	7	.24	192
Balance	1000	7	.24	240
Splitter	200	15	.17	34
Penetrometer	800	5	.30	240
Flash Tester	600	7	.24	144
Water Bath	500	7	.24	120
Oven	1000	8	.23	230
Desk	200	20	.15	30
			TOTAL =	1710

I = assumed rate of inflation

$$\text{Equipment Depreciation Cost/Test} = \frac{\text{Total}}{\text{No. of Tests Per Year}}$$

$$= \frac{1710}{1500} = \$1.14\text{/Year/Test}$$

fiscal year and divided by the number of tests per year.

11. Supply Costs Per Test - This number reflects the annual cost of all expendable supplies and non-expendable repair parts used for the test. The total supply costs for a material unit are summed for the fiscal year and divided by the number of tests per year.

12. Administrative Overhead Cost Per Test - This number includes clerical support, building maintenance, freight, repair and service, and other miscellaneous operating expenses. For an agency material test division, these are summed for the fiscal year and apportioned to various material units (Figure 15). For a particular material unit, this apportioned annual cost is divided by the total number of tests per year to arrive at the administrative overhead cost for each test per year.

13. Administrative Engineering Cost Per Test - This number includes costs relating to policy formulation, management, and professional activities. Again, this number is computed for the entire material division and apportioned to the various material units. For a particular material unit, this apportioned annual cost is divided by the total tests per year to arrive at the administrative engineering cost for each test per year.

14. Total Cost Per Test - This number is the sum of Items 7 through 13.

EXAMPLE PROBLEM

The costs of tests performed in a State asphalt laboratory are to be computed. A salary benefit adjustment of 25 percent is assumed. For purposes of calculating depreciation costs, 10 percent inflation is assumed. For the fiscal year under consideration, the following tests were performed:

1. penetration (400 tests)
2. viscosity (300)
3. solubility (300)
4. ductility (300)
5. flash point (100)
6. ring and ball softening point (100)

Table 7 lists the applicable personnel and associated salaries. The salaries are adjusted for benefits. It is assumed that 25 percent of the time spent by the State asphalt engineer is devoted to administrative duties not directly associated with testing. In addition, this engineer is also responsible for the paint section, which consumes 25 percent of his total time. Interviews with laboratory personnel indicate that five man-hours are expended on each test. With this data, Columns 1 through 7 of Table 5 may be filled in. As a check, the total of column 6, salary cost per year, should be equal to that calculated in Table 7.

Table 6 lists all associated equipment initial costs, estimated service lives, and calculation of depreciation per test. This value is considered to be constant for all tests and is entered under Column 8 of Table 5.

Table 7

Annual Salaries of Asphalt Laboratory Personnel

Personnel	Annual Salary, $	Adjusted Annual Salary, $
State Asphalt Engineer*	30,000	37,500
Engr. Tech. III	24,000	30,000
Lab. Tech. III	20,5000	25,625
Lab. Aide II	16,000	20,000
Lab. Aide I	15,000	18,750
Engr. Student Trainee	3,000	3,750

Total Salary Cost/Year = (.75) (37,500 x .75)* + 30,000
+ 25,625 + ... + 3,750 = $144,845

*Also responsible for paint section which consumes 25 percent of time.

From records for the fiscal year under consideration, 18,000 miles were directly expended on testing. Departmental records indicated a rate of $ .30 per mile was charged. These values were apportioned to each test as follows and entered under Column 9 in Table 5.

$$\frac{(18{,}000 \text{ miles})\ (\$.30/\text{mile})}{1500 \text{ tests}} = \$3.60/\text{test}$$

Travel cost records also indicated that 120 days were expended traveling at a per diem rate of $60 per day. This was used as follows to calculate the travel cost per test and entered under Column 10 in Table 5.

$$\frac{\$60/\text{day} \times 120 \text{ days}}{1500 \text{ tests}} = \$4.80/\text{test}$$

Purchasing records indicated $6000 was spent on expendable supplies. This amount is apportioned on a per test basis as follows and entered under Column 11 in Table 5.

$$\frac{\$6000}{1500 \text{ tests}} = \$4.00/\text{test}$$

Financial records were consulted and it was determined that $18,000 was spent on clerical support, freight, building maintenance, etc., for the asphalt laboratory. This value was apportioned as follows to all tests and entered under Column 12 of Table 5.

$$\frac{\$18{,}000}{1500 \text{ tests}} = \$12.00/\text{test}$$

The State materials and tests engineer estimated that the asphalt laboratory consumed 25 percent of the $40,000 reserved for policy formulation, management, and professional activities. This amount was also apportioned on a per test basis and entered under Column 13 of Table 5.

$$\frac{\$40{,}000 \times .25}{1500 \text{ tests}} = \$6.67/\text{test}$$

Columns 7-13 are added for each test and the total is entered in Column 14 of Table 5. The amounts in this column represent the total cost per test.

CHAPTER 5

PERFORMANCE MODELS

LITERATURE REVIEW

The results of a Transportation Research Information Service (TRIS) literature search, of communication with engineers for various State agencies, and of communication with researchers throughout the United States led to the conclusion that few, if any, models are available which relate distress or performance to quality control test results. More than thirty reports were reviewed (Refs. 18 through 26 are typical of the sources and reports that were reviewed) for relating quality control tests to pavement performance. Most of the models that are available were eliminated for one or both of the following reasons:

1. Model did not adequately explain much of the observed data from which it was developed,
2. Model did not predict performance as a function of test parameters commonly measured for quality control.

In addition to these limitations, only the Madjizadeh (Ref. 1) and Arizona DOT (Ref. 25) models included variation of a test property (either standard deviation or coefficient of variation) as an independent variable. All other models were deterministic rather than stochastic in that they predicted a mean value of distress or performance based on a mean value of a test parameter. A stochastic model would predict distress or performance as a function not only of the mean test value, but also of the variation in the test value. The most desirable model would be of the form:

$$D = f(\bar{x},\sigma^2) \quad \text{..} \quad (12)$$

where, D = distress or performance measure,
$\bar{x}$ = mean quality control test results, and
σ^2 = variance of quality control test results.

Most of the models that have been developed to predict distress or performance are either "mechanistic" or "empirical." The mechanistic approach applies "pure" theories such as the theory of elasticity to model some type of physical occurrence. Empirical modeling uses actual data from real pavements to develop relationships which minimize the differences between observed and predicted values (i.e., regression techniques). For this type of project, only empirical models could be expected to have direct application as the independent variables for mechanistic models are not obtainable from standard quality control testing.

As an example of empirical modeling, McHattie, et. al. (Ref. 27), conducted a study to determine which variables were important on Alaska highways using regression techniques. In this study, variables were identified that had the greatest effect on performance (see Table 8) and on engineering properties (see Table 9). No similar studies were found for the 3 States used in this study. McHattie concluded that long-term performance is obtained from asphalt concrete which retains softness and low tensile strength. However, he also cautions the reader to guard against the temptation to use formulae generated from regression techniques outside the data boundaries.

There also have been laboratory studies to measure the relative effects of changes in material properties on engineering

Table 8
Results of Stepwise Regression Analysis For Correlation of Pavement Distress with Material Properties (Ref. 27)

Dependent Variable	Independent Variable (In order of regression inclusion)	Coefficient	Multiple "R"
Average Rut Depth	absolute viscosity (wheelpath)	3.4 E-06	.41
	bitumen content (wheelpath)	3.9 E-02	.51
	% - 3/8" aggregate	-3.7 E-03	.53
	% - #200 aggregate	1.0 E-02	
	saturated tensile strength	9.0 E-04	.57
	penetration at 77°F (wheelpath)	5.9 E-04	.59
	constant	5.8 E-02	
Regular Longitudinal Cracks	% - #40 aggregate	3.2 E+01	.45
	% - #10 aggregate	3.7 E+01	.52
	absolute viscosity (wheelpath)	2.1 E-04	.56
	bitumen content (non-wheelpath)	-6.7 E-01	.58
	absolute viscosity (non-wheelpath)	-1.6 E-04	.60
	% voids (non-wheelpath)	2.7 E-01	.62
	constant	-16.2	
Edge Longitudinal Cracking	penetration at 39°F (non-wheelpath)	-2.4 E-01	.36
	% - #10 aggregate	2.9 E-01	.36
	top layer pvmt. thickness (wheelpath)	-2.3	.62
	bitumen content (wheelpath)	-1.0	.68
	constant	2.0	

Table 8
Results of Stepwise Regression Analysis For Correlation of Pavement Distress with Material Properties (Ref. 27)
(continued)

Dependent Variable	Independent Variable (In order of regression inclusion)	Coefficient	Multiple "R"
Miscellaneous Thermal Cracks (across transverse grid lines)	% - #40 aggregate	3.9 E-01	.28
	% #200 aggregate	-7.1 E-01	.34
	bitumen content (non-wheelpath)	-7.1 E-01	.37
	top layer pvmt. thickness (non-wheelpath)		.39
	total pavement thickness (wheelpath)	5.1	.41
	% voids (non-wheelpath)	2.8 E-01	.42
	constant	9.1	
Miscellaneous Thermal Cracks (across longitudinal grid lines)	% - #40 aggregate	6.5 E-01	.46
	absolute viscosity (non-wheelpath)	-3.4 E-04	.48
	dry tensile strength	9.4 E-02	.53
	% - #200 aggregate	-9.0 E-01	.55
	top layer pvmt. thickness (non-wheelpath)	-4.8	.57
	saturated tensile strength	6.8 E-02	.58
	constant	2.3	

Table 8
Results of Stepwise Regression Analysis For Correlation of Pavement Distress with Material Properties (Ref. 27)
(continued)

Dependent Variable	Independent Variable (In order of regression inclusion)	Coefficient	Multiple "R"
Sum of Alligator Cracking in Both Wheelpaths	dry tensile strength	1.3	.59
	% - #200 aggregate	11.7	.71
	absolute viscosity (non-wheelpath)	1.3 E-03	.73
	bitumen content (non-wheelpath)	7.0	.74
	% - #40 aggregate	-1.0	.75
	top layer pvmt. thickness (non-wheelpath)	14.7	.76
	constant	-180.9	
Major Transverse Cracks	bitumen content (wheelpath)	-7.4	.39
	% - 3/8" aggregate	6.5 E-01	.46
	% - #10 aggregate	-2.4	.49
	% - #4 aggregate	1.8	.51
	% - #200 aggregate	-2.1	.53
	penetration at 77°F (non-wheelpath)	-1.9 E-01	.54
	constant	57.3	
Full Width Patching	% - #200 aggregate	169.2	.41
	penetration at 77°F (non-wheelpath)	-5.9	.48
	% - 3/8" aggregate	-18.0	.49
	total pvmt. thickness (non-wheelpath)	200.5	.51
	dry tensile strength	3.7	.52
	penetration at 39.2°F (wheelpath)	10.0	.53
	constant	-29.1	.53

Table 9

Results of Regression Analysis For Correlation of Asphalt Tensile Strength with Material Properties (Ref. 27)

Dependent Variable	Independent Variable (In order of regression inclusion)	Coefficient	Multiple "R"
Saturated Tensile Strength	absolute viscosity (wheelpath)	1.3 E-03	.61
	penetration at 39.2°F (non-wheelpath)	-1.6	.68
	maximum density	-1.2	.70
	bitumen content (non-wheelpath)	-1.8	.71
	absolute viscosity (non-wheelpath)	-3.9 E-04	.71
	penetration at 77°F (wheelpath)	6.7 E-02	.71
	constant	262.0	
Dry Tensile Strength	absolute viscosity (wheelpath)	9.9 E-04	.58
	penetration at 39.2°F (non-wheelpath)	-7.3 E-01	.62
	bitumen content (wheelpath)	6.8	.68
	bitumen content (non-wheelpath	-3.1	.70
	maximum density	-1.0	.71
	penetration at 77°F (non-wheelpath)	-2.4 E-01	.72
	constant	198.0	

properties. Walter, et al. (Ref. 28) performed a laboratory study at Oregon State University in conjunction with the Oregon DOT to determine the effect of variations in material properties on asphalt pavement life. Figures 17 through 20 are examples of the results of the laboratory testing. Although these data or tests are extremely useful for estimating the relative effects on pavement performance for a particular material or environmental area, they are less applicable on a universal basis for predicting pavement performance with time. Also, the measured test results can be related to pavement performance, only through data collection efforts.

SIGNIFICANT DISTRESSES, PERFORMANCE MEASURES, AND MATERIAL PROPERTIES

In the present study, a concentrated effort was placed on the distress types and performance measures that are typically found in asphalt concrete pavements in most of the geographical areas or environmental regions according to Rauhut et al., (Ref. 24). These are:

1. alligator cracking,
2. rutting,
3. loss of skid resistance, and
4. loss of present serviceability index (Roughness).

Other distress types such as block cracking, bleeding/flushing, raveling, and roughness from expansive clays can also be found in many areas across the country. However, their importance or occurrence is primarily dependent on the environment. Table 10 lists those distresses that are considered to be the most important by agency personnel in the three States interviewed in this study.

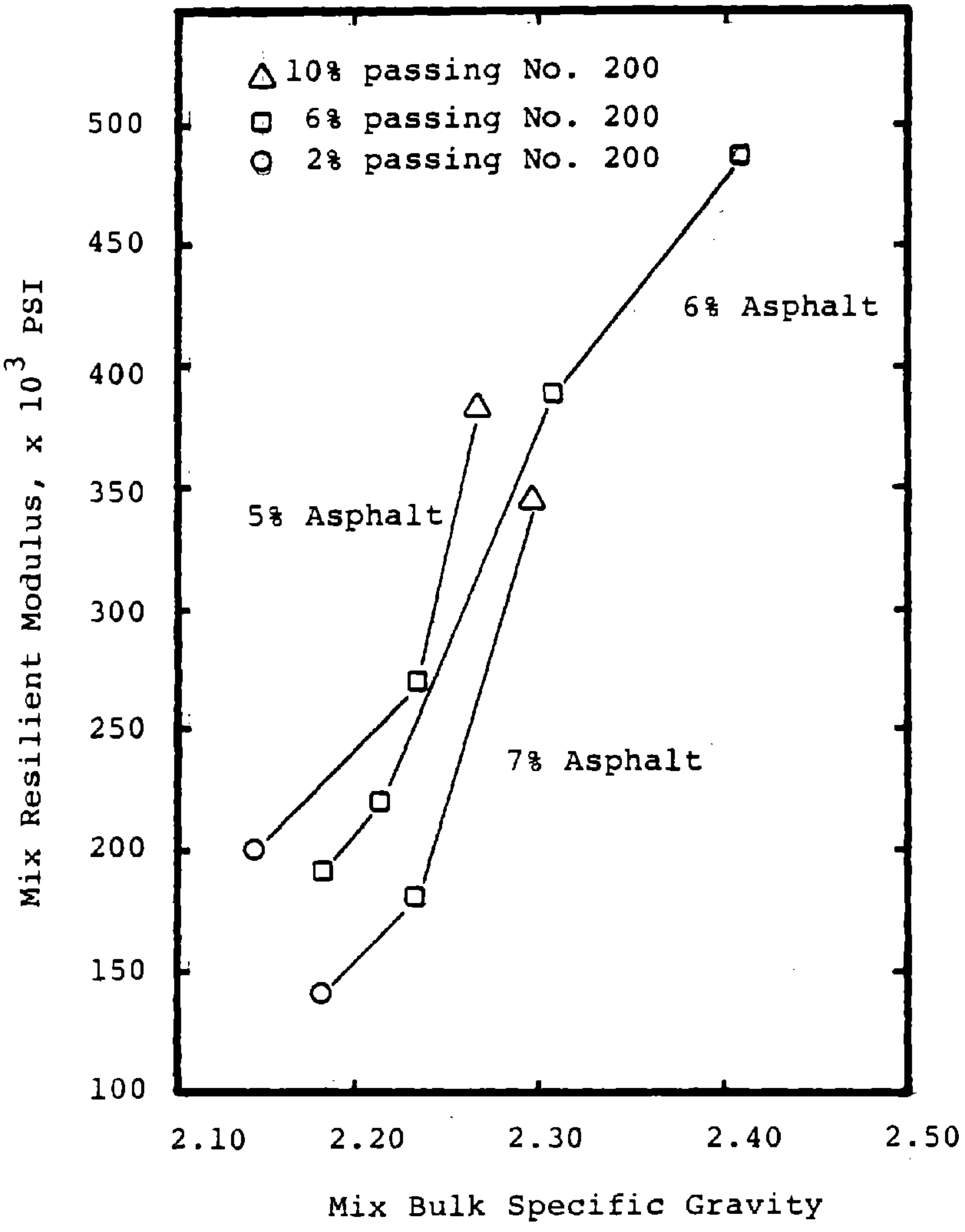


Figure 17. Influence of Bulk Specific Gravity on Resilient Modulus - As Compacted Samples (Ref. 28)

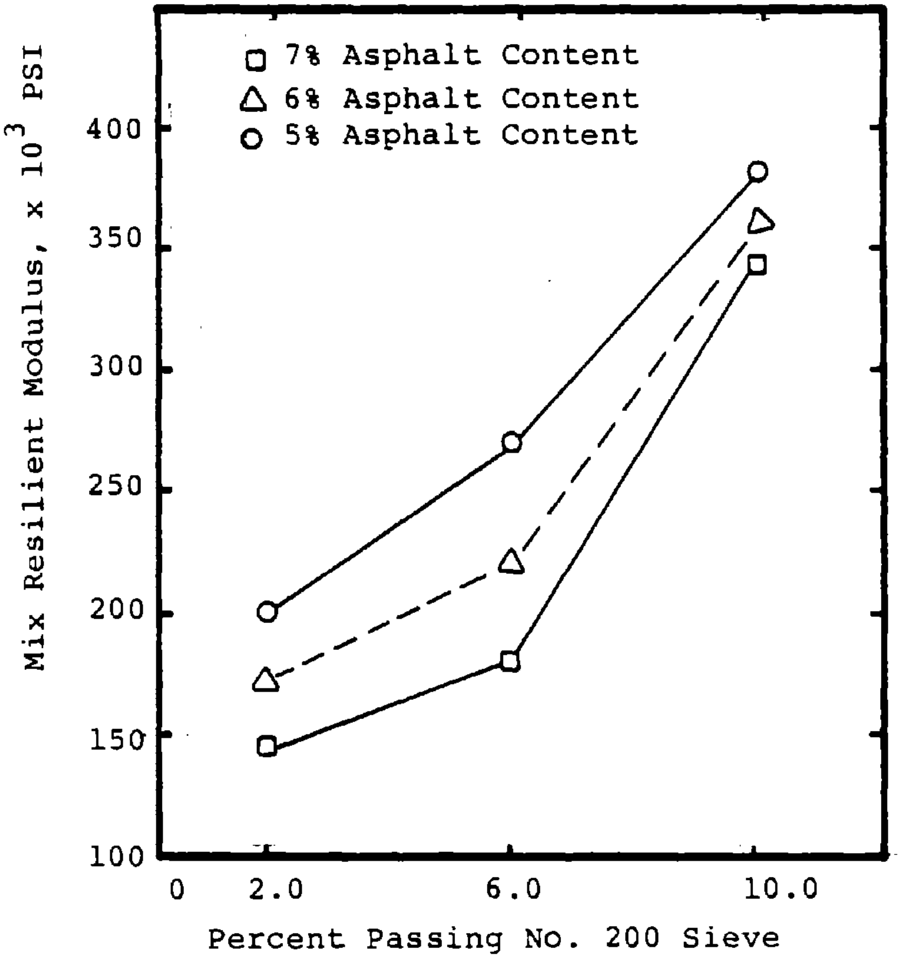


Figure 18. Influence of Amount of Fines on Resilient Modulus - As Compacted Samples (Ref. 28)

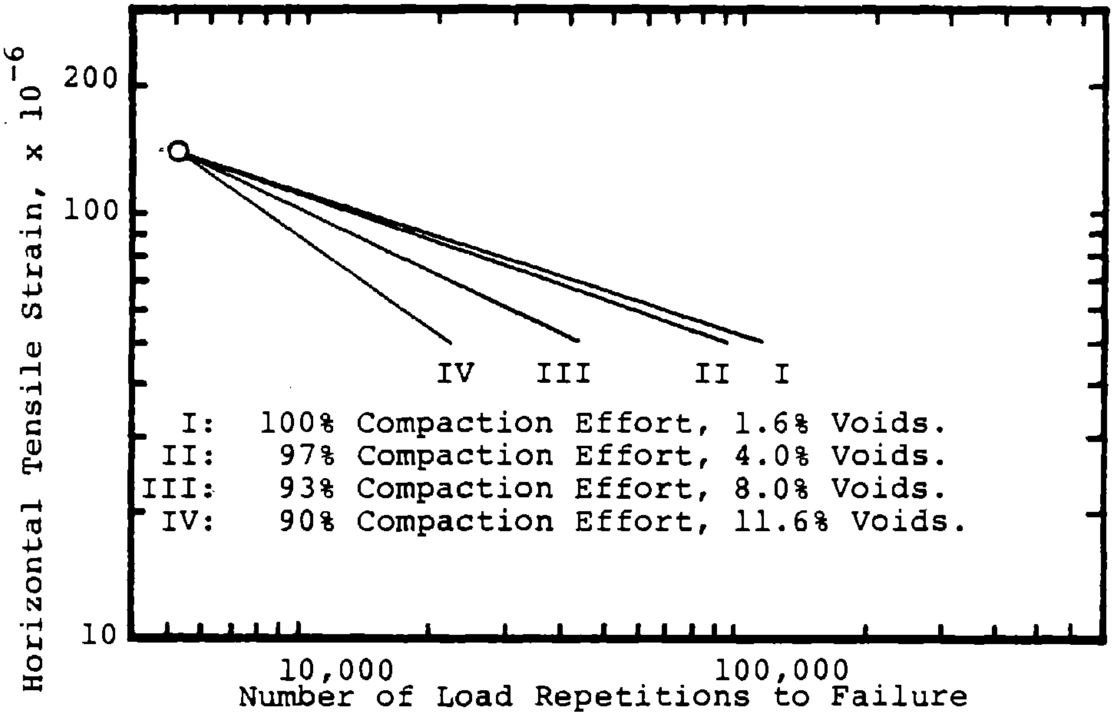


Figure 19. Influence of Mix Density on Fatigue Life, As Compacted Samples; 6% Passing No. 200 - 25% Passing No. 10 - 5.5% Asphalt (Ref. 28)

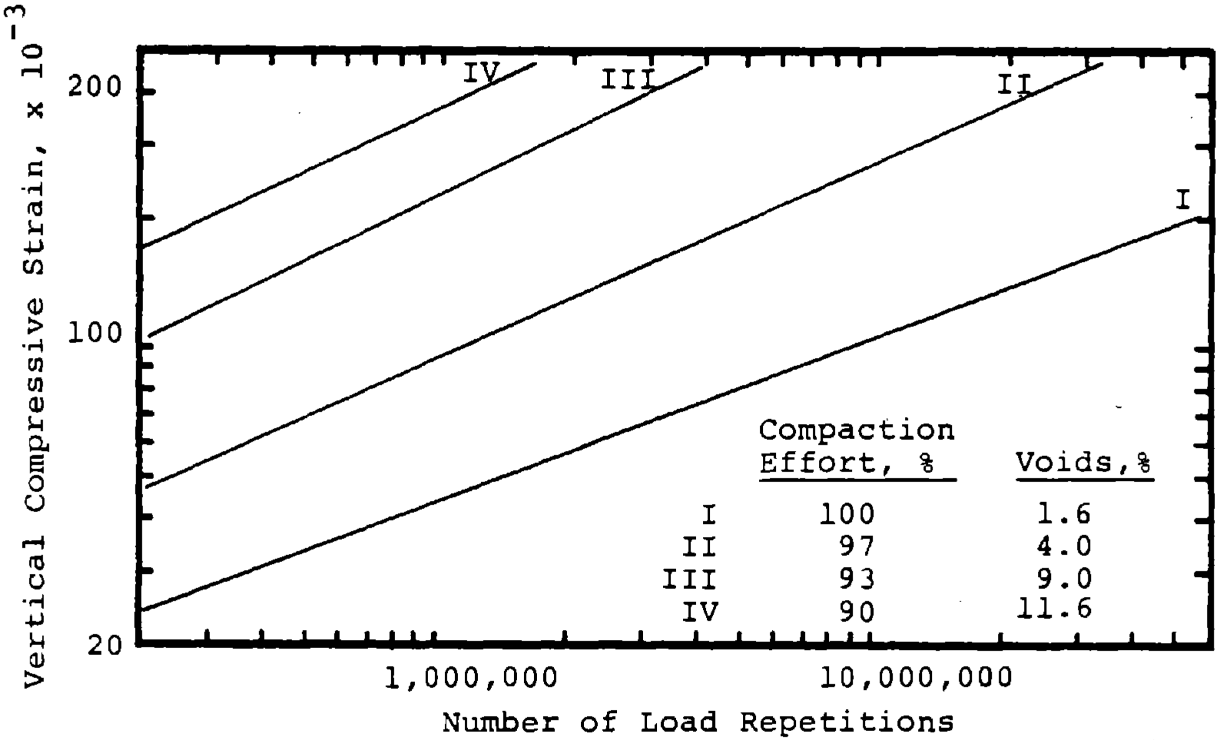


Figure 20. Influence of Mix Density on Permanent Deformation As Compacted Samples; 6% Passing No. 200 - 25% Passing No. 10 - 5.5% Asphalt (Ref. 28)

Table 10

Critical Distresses in the Three States Participating in the Study

Pavement Type	Order of Importance*	State Agency		
		A	B	C
Asphalt Concrete	1	Alligator Cracking	Rutting	Transverse Cracking
	2	Roughness	Shoving	Edge & Base Failures
	3	Rutting		
	4	Skid Resistance		
	5	Bleeding/Flushing		
Portland Cement Concrete	1		D-Cracking	Joint Failure
	2		Faulting	Bridge Deck Deterioration

*1 - Designates the most significant distress.

Although there is some agreement found in the literature on which distresses are important in a particular climate, there is much less agreement on what properties or tests correlate with these distresses or performance measures. For example, McHattie (Ref. 27) found that void content was not a good predictor of any performance measure on Alaskan highways, which is contrary to the findings by Kandhal (Ref. 29), who related void content to raveling severity. McHattie theorized that "weathering potential" under Alaskan climatic conditions is not high, and therefore mixtures with relatively high voids are not as strongly oxidized by the environment. Thus, those tests that are good predictors of pavement performance or of the occurrence of distresses will vary from State to State and even district to district (for example: West Texas, a hot-dry climate, versus East Texas, a hot-wet climate). Table 11 lists those material properties that are considered by agency personnel to have the greatest effect on performance in the three States included in this study. Ideally, the performance models should include these material properties as independent variables. These type models, however, were unavailable in each State.

MODELS SELECTED FOR USE IN THIS STUDY

The shortage of models to predict pavement distress or performance in terms of material properties measured by standard quality control or acceptance tests has been discussed previously. As discussed, it was necessary to utilize limited models and, in most cases, to couple two models, one to predict an engineering property in terms of measured material properties and the other to predict distress or performance from the engineering properties.

The models selected for use include:

Table 11
Material Properties that are Considered Critical to Asphalt Concrete Pavement Performance in Each State Interviewed

Order of Importance*	State Agency		
	A	B	C
1	Effective Voids	Asphalt Content	Density
2	Asphalt Content	Marshall Stability	Asphalt Content
3	Voids in Mineral Aggregate	Density	Gradation
4	Gradation	Gradation	
5	Stability		

*1 - Designates the most important material property.

1. The asphalt concrete mixture stiffness model developed by Witczak, et. al. (Ref. 30). This model is used to predict stiffness as an input variable for other models. Stiffness is predicted as a function of asphalt and mixture properties.
2. The Arizona Model for Roughness (Ref. 25), which is used to predict roughness indirectly from the asphalt content and the gradation of the aggregate in an asphalt concrete mixture.
3. The Waterloo Models (Ref. 31), which are used to predict rutting and strain at the bottom of the asphalt concrete from the asphalt concrete stiffness, pavement structure, stiffness of the subgrade, and traffic.
4. Algorithms from VESYS IV-B for predicting present serviceability index and fatigue cracking as a function of asphalt mixture stiffness and other engineering properties.
5. A skid resistance model, developed by Roberts and Jordahl (Ref. 32), which predicts skid resistance as a function of aggregate properties.

The models listed above were used generally in combinations to predict the distresses or performance measures considered. These models are described in more detail below.

Witczak Model for Stiffness of Asphalt Concrete Mixtures

The engineering property most commonly used in distress or performance models is the stiffness of the various material layers, so models were sought that would predict stiffnesses as functions of material properties derived from standard quality control or acceptance tests. The model developed at The Asphalt Institute and The University of Maryland to predict the dynamic modulus (or stiffness) of an asphalt mixture as a function of commonly determined mixture properties was selected for this purpose. The original equation resulted from work by Shook and Kallas (Ref. 33) and was modified by Witczak (Ref. 34) and, most recently by Witczak, Uzan, and Miller (Ref. 30).

Although the original model considered only dense graded mixtures with a fairly small variation in asphalt content, the most recent equations contain a correction term (α) to account for a wider range of mixture types and asphalt contents. The correction factors were developed using regression techniques designed to minimize the mean square error (MSE), which is a measure of the difference between the measured and predicted dynamic modulus. The resulting equation has a coefficient of determination (R^2) ranging from 0.739 to 0.939 for gravel and sand mixtures, respectively (Table 12).

$$\log_{10} E_A^* = A + B\,(P_{ac} - \alpha)^{0.5} \quad \ldots\ldots\ldots\ldots\ldots (13)$$

where:

$$A = 0.553833 + 0.028829\left[\frac{P_{200}}{f^{0.17033}}\right] - 0.03476P_v + 0.070377\,(\eta_{10^6,70}) + \frac{0.931757}{f^{0.02774}} \quad \ldots\ldots\ldots\ldots\ldots (14)$$

$$B = 0.000005T^{(1.3 + 0.49825 \log_{10} f)} - \frac{0.00189T^{(1.3 + 0.49825 \log_{10} f)}}{f^{1.1}} \quad \ldots\ldots\ldots\ldots\ldots (15)$$

E_A^* = Dynamic modulus, 10^5 psi

P_{200} = Percent passing No. 200 sieve

P_v = Volume of voids, %

$(\eta_{10^6,70})$ = Viscosity of asphalt cement at 70°F, 10^6 poise

Table 12
Correlation Terms for Predicting Dynamic Modulus of Various Types of Asphalt Mixtures Using the Witczak, et. al. Model (Ref. 30)

Mix Type	Number of Data Points	Corrected* Asphalt Content, %	R^2
Crushed Stone	162	4.0	0.917
Gravel	162	4.0	0.739
Slag	162	4.0	0.887
Sand - Low P_{200}	162	3.0 - 5.0	0.939
Sand - High P_{200}	162	3.0 - 5.0	0.796

*Corrected Asphalt Content for Use in Equation

(P_{ac}) = Actual Asphalt Content - Optimum + 4.0

f = Loading frequency, Hz

T = Pavement temperature, °F

P_{ac} = Asphalt content, % by weight of mixture

α = Correction factor based on mixture
= $P_{opt} - 4.0$

P_{opt} = Optimum asphalt content, % by weight of mixture

This model thus provides a relationship of stiffness (dynamic modulus) to asphalt and asphalt concrete mixture properties. It will be used subsequently with the Waterloo and VESYS models to predict rutting, fatigue cracking and PSI as a function of stiffness.

Arizona Model for Roughness

This study, performed by Way and Jones of the Arizona DOT (Ref. 25), resulted in several equations to predict roughness (as measured by the Mays ride meter), as a function of variation from the job mix formula. This variation was quantified by a parameter termed "Core Total Variance" (CTV) and was determined by the following procedure.

Fifteen projects were sampled to collect data. Following construction, a number of cores were taken and extractions performed. Based on all the cores taken, a mean and standard deviation were calculated for asphalt content and for the material retained on each sieve size. The standard deviation values were squared and summed for all sieve sizes and the asphalt content, resulting in a variance term. In addition, the difference between the means and target values were squared for all sieve sizes and summed, resulting in another variance term. The two variance terms were then added to obtain the Core Total Variance (CTV). Table 13 shows a sample calculation of Core Total Variance.

Data from the fifteen projects were then used to develop two roughness models. The first model predicted the slope of ride roughness per 18-kip ESAL as a function of CTV. This linear regression model had a coefficient of determination (R^2) of 0.41 and was expressed as:

$$Y = b + m(CTV) \qquad (16)$$

where: Y = slope of ride roughness per 18 kip load,
b = 0.0000266,
m = 0.00000044, and
CTV = Core Total Variance.

This model, in effect, predicts the rate of increase in roughness taking into account the character of traffic using the road. The second model predicted initial roughness after construction as a function of CTV. This linear regression model had a coefficient of determination of 0.44 and was expressed as:

$$Y = b + m(CTV) \qquad (17)$$

where: Y = ride roughness after construction,
b = 34.42,
m = 0.1610, and
CTV = Core Total Variance.

Therefore, by combining these two models, roughness can be predicted at any time by knowing the core total variance and the predicted number of 18 kip ESAL's applied. These were really the only models that considered quality control test results directly and took material variation into account. The Arizona roughness model essentially provides a relationship

Table 13
Sample Calculations of Core Total Variance for the Arizona Study (Ref. 25)

Sieve Size	Target Value*	Core Values		Target Average^2	Standard Deviation^2
		Average*	Standard Deviation		
1"	100	100	0.0	0.0	0.0
3/4"	97	99	0.7	4.0	0.49
1/2"	83	83	3.1	0.0	9.61
3/8"	72	70	3.7	4.0	13.69
#4	53	53	4.6	0.0	21.16
#8	40	41	3.4	1.0	11.56
#40	13	14	1.9	1.0	3.61
-#200	4	3.7	1.3	.09	1.69
Percent Asphalt	5	5.2	.3	.04	0.09
				10.13	61.90

*Values shown are percent passing

Core Total Variance = 10.13 + 61.90 = 72.03

between roughness and variations of aggregate gradation and asphalt content from an established job mix formula.

Waterloo Model for Rutting

This model, abbreviated WATMODE, was developed for the Province of Ontario by Meyer, et al. at the University of Waterloo (Ref. 31). WATMODE is based on a statistical analysis that relates laboratory tests on the Brampton and St. Anne's Road Tests in Ontario to measured roadway responses: rutting, fatigue cracking, and low temperature cracking. The elastic layer model BISAR was used as a structural model to introduce the pavement responses. For rut depth, the resulting equation is:

$$\text{Rut Depth} = R_1 + R_2 n + R_3 \ln n \quad \text{.........................} (18)$$

where: $R_1 = -1.0318 + 1.2067 t_e + (1.1639 E_A - 2.1788) \ln t_e$.(19)

$R_2 = (0.0456 E_s - 0.4114 E_A) \ln t_e - 0.0216 E_s + 0.0803$ ..(20)

$R_3 = 0.1896$

t_e = equivalent pavement thickness

$= (t_A + 0.5 t_{base} + 0.3333 t_{subbase})/10$ ....(21)

t = thickness of layers, inches

E_A = elastic modulus, psi/10^6

E_s = resilient subgrade modulus, psi/10^4

n = number of 18-kip equivalent axle loads/10^5

The primary advantage of WATMODE is its simplicity. In addition, the equation has a coefficient of determination (R^2) of 0.996, and thus provides reasonably reliable predictions of rut depth for the Ontario data base from which it was derived. Although extrapolation to areas very far south of Ontario would likely result in erroneous predictions as there are no environmental terms in the equations, this model was selected, because it is the only feasible model available for prediction of rut depth in terms of material properties.

Waterloo Model for Horizontal Strain at the Bottom of the Asphalt Concrete

This model is also a portion of WATMODE, but was developed through multiple regression on a very large factorial of flexible pavement analyses using the elastic layer model BISAR. The resulting equation is:

$$\begin{aligned} \ln\varepsilon_R = {} & 0.2395 - 0.1413t_A - 0.5476 \ln E_C \\ & -0.0024E_s (\ln t_A) - 0.0585E_A (\ln t_A) \\ & -0.0168\, t_B (E_C) + 0.0305t_A (\ln E_C) \quad \cdots\cdots\cdots\cdots (22) \end{aligned}$$

where:

t_A = asphalt concrete thickness, inches,

t_B = combined granular base thickness, inches/10,

E_C = resilient modulus of combined base, psi/10^4,

E_A = elastic modulus for asphalt concrete, psi/10^5,

E_s = resilient subgrade modulus, psi/10^3, and

ε_R = radial tensile strain at bottom of asphalt concrete (in /in x 10^{-3}) for an 18-kip single axle load.

This model has a standard error of estimate (in ln ε_R) of 0.0026 and coefficient of determination of 0.99. Unlike the model for rutting, this model is not specific to a particular environmental zone and can be used for any zone to provide a relationship between layer stiffnesses and thicknesses and asphalt concrete tensile strain.

VESYS IVB - Fatigue Cracking and PSI Loss

This distress model was originally developed using viscoelasticity at the Massachusetts Institute of Technology for the Federal Highway Administration (Ref. 35), but had poor predictive capability. An entirely different model for permanent deformation of materials was introduced by Brademeyer and others at the FHWA and has been discussed in great detail in the literature. Since the original development of the model, a number of revisions have been developed by others to provide for additional layers in the pavement structure and to account for factors such as seasonal variation in material properties and low temperature cracking, much better characterizations of axle loads, etc. VESYS IV-B (Ref. 36) is the most recent version and has the broadest capabilities.

The model requires numerous control and independent variables describing the flexible pavement structure, traffic loading, pavement temperatures, and material properties. Based on this information, the model predicts fatigue cracking, rut depth, slope variance, and present serviceability index as functions of time.

VESYS predicts fatigue cracking using the classical "linear summation of cycle ratios" damage approach (Miner's Hypothesis) to model the fatigue damage at any time due to an established axle load distribution and traffic rate. In addition, VESYS utilizes probability theory to account for variability of the input parameters.

VESYS is perhaps the most complete flexible pavement model available, in that it considers a broad range of material properties in its distress subsystems. However, it had little direct use for this study, because most of the input material variables, such as those for the permanent deformation characteristics of materials, are derived from sophisticated test procedures not used for quality control. Only material stiffness that is required by the model could be related to common test values through equation (13).

However, several algorithms from subroutines in VESYS IV-B were utilized to predict the damage index and present serviceability index (PSI). One algorithm combines rut depth and its variance in an asphalt layer with other layer data to estimate loss in present serviceability index (PSI). Using this algorithm, the rut depth determined from WATMODE was used to predict PSI loss.

The AASHO Equation for PSI as a function of slope variance, rut depth, and cracking and patching, (based on studies of data from the AASHO Road test) is:

$$PSI = 5.03 - 1.91 \log_{10} (1+SV) - 1.38R^2 - .01 (C+P)^{1/2} \text{.(23)}$$

where: SV = slope variance in 10^{-6} radians
R = rut depth in inches
$C+P$ = cracking and patching, in square yards per 1000 sq. yards.

The rut depth R in equation (23) is obtained from the WATMODE regression equation. The procedure for obtaining slope variance is adapted from VESYS IV-B as follows:

$$SV' = C_1 * \text{var}(R) = C_1 * C_2 * (R)^2 \quad \text{........................(24)}$$

$$SV' = 556 * \eta * R^2 \quad \text{..(25)}$$

where: η = coefficient of variation (C.V.) of vertical displacement under load

$$\simeq \quad C_3 * C.V. \ (E_A)$$

C_1, C_2, C_3 = Correlation Coefficients

E_A = the modulus of the asphaltic concrete obtained from equation (13).

The correlation coefficient C_3 was determined from several VESYS runs and is approximately 1.2. However, the coefficient, C_3 can vary with pavement structure; so this approximation should <u>not</u> be used elsewhere without further verification. Thus,

$$SV' \simeq 800 * R^2$$

It is known that a pavement is not perfectly smooth when opened to traffic; it is also known that PSI at that time is more often about 4.2 than anywhere near 5.0. Hence, we approximate SV in the AASHO regression equation (23) by:

$$SV = SV_o + SV' \quad \text{.......................................(26)}$$

where: SV' = the slope variance calculated from equation (25).

SV_o = SV (t=o) is the slope variance which, when substituted into the regression equation with R and C+P = 0, yields the given initial PSI. For PSI = 4.2, SV_o = 1.72.

For the purposes of the COSTOP example runs, the small correction to PSI from the effects of C+P was ignored; cracking was never a major factor in any of the examples, and no model for patching is available.

For fatigue cracking, the Waterloo model described above is used to predict initial horizontal strain at the bottom of the asphalt concrete. Damage Index (D.I.) is obtained from initial strain and number of 18-kip equivalent single axle loads (ESAL) in the usual manner:

$$\text{D.I.} = n/n_A \quad \text{(27)}$$

where: n = 18-kip ESAL applied

n_A = 18-kip ESAL allowable before visible cracking, or failure, results

$$= K_1 \, (\varepsilon_R)^{-K_2} \quad \text{(28)}$$

ε_R = tensile or radial strain at the bottom of the asphalt concrete layer, in./in.

$$K_1 = K_{1_R} \left[\frac{E_A}{E_R} \right]^{-4} \quad \text{(29)}$$

$$K_2 = 1.75 - .252 \log_{10} (K_1) \quad \text{(30)}$$

E_R, K_{1_R} = 500000 psi and 7.87×10^{-7}, respectively.

The reference values E_R and K_{1_R} are specific to a particular type of asphalt and are obtained at 70°F; E_A is the asphalt modulus at the pavement temperature under consideration. These relations are described in Ref. 37.

Area cracked was obtained from the Damage Index by assuming that the distribution of damage index over the area of the pavement is normal, and that a Damage Index of 1.0 corresponds to initiation of visible cracking on the pavement surface. Therefore, the area under the normal curve for which Damage Index is greater than 1.0 corresponds to the area of pavement surface expected to show cracking. The variance of the normal distribution of damage index is obtained from the variance of the initial strain by the usual procedure of propagation of variance; this variance is due to the variance of the moduli and thicknesses which enter the regression equation for initial strain. The effect of variation of asphalt modulus on K_1 and K_2 was ignored for this demonstration.

Skid Model

A comprehensive review of published skid models was conducted. Roberts and Jordahl (Ref. 32) conducted a regression analysis of skid resistance data from a number of sources. Twelve equations were available from the literature for predicting skid number (SN_{40}) for different types of aggregate ranging from a rapidly polishing soft limestone to a group of relatively nonpolishing materials. Of these twelve, nine equations, converted to a single standard form, are given in Table 14. None of these models are immediately suitable as given for use on this project, because material properties are excluded from the independent variables, except for aggregate type or classification.

As models are required to determine the effect material variation has on pavement performance, these equations were coupled with additional data (Ref. 43) and all available data was evaluated roughly. This was done to determine if skid number could be correlated to some material property.

Table 14

Equations for Skid Number SN_{40}

Aggregate Type	Description	Recast Equation
soft	Texas Georgetown Limestone	$SN = 34.6\ (N/10^6)^{-0.136}$
soft	Central and Northern Florida	$SN = 45.4\ (N/10^6)^{-0.222}$
soft	Virginia Limestone	$SN = 44.7\ (N/10^6)^{0.1964}$
soft	Texas Burnett Dolomite	$SN = 40.4\ (N/10^6)^{-0.121}$
soft	Kentucky Limestone	(Not convertible; $SN = 46.9$ at $N = 10^6$)
soft	Wisconsin Dolomite	(Not convertible; $SN = 43.1$ at $N = 10^6$)
soft	Georgia Limestone	$SN = 72.5\ (N/10^6)^{-0.128}$
hard	Texas Trap Rock	$SN = 43.5\ (N/10^6)^{-0.096}$
hard	Wisconsin Igneous Rock	(Not convertible; $SN = 49.5$ at $N = 10^6$)
hard	Texas Iron Slag	$SN = 46.4\ (N/10^6)^{-0.063}$
hard	Virginia S4, S5 non-polishing aggregate	$SN = 52.1\ (N/10^6)^{-0.058}$
hard	Georgia Siliceous aggregate	$SN = 54.8\ (N/10^6)^{-0.044}$

N = Number of Repetitions of equivalent truck axles.

For preliminary evaluation, it was decided to use the form:

$$SN = C_4(n_T/10^6)^{C_5} \qquad (31)$$

where: n_T = The number of truck axles applied to the pavement.

First, the coefficients C_4 and C_5 of the 9 equations listed in Table 14 were plotted to determine if a correlation existed between the two (Figure 21). As shown in Figure 21, there does appear to be a relationship between C_4 and C_5 for both hard and soft aggregates. For preliminary evaluations, it was assumed that the soft aggregates used in Figure 21 have a Mohs Hardness equal to 4.0 and the value for hard aggregates was assumed to be 6.5. These values were selected based on test results presented in Reference 43 of Mohs Hardness for aggregates very similar to the ones plotted in Figure 21. Using the assumed values of Mohs hardness, a relationship can be represented by the following equation:

$$C_5 = (-0.00034+0.00076H)C_4 - 0.38 + 0.014H \qquad (32)$$

where: H = Mohs Hardness

Taking the additional data provided in References 32 and 43, other material values were examined to determine their possible correlation to C_4 and C_5. The only other correlation found was Los Angeles abrasion loss as related to C_4, shown in Figure 22. This correlation can be represented by the following equation:

$$C_4 = 0.52\ (LA) + 27.13 \qquad (33)$$

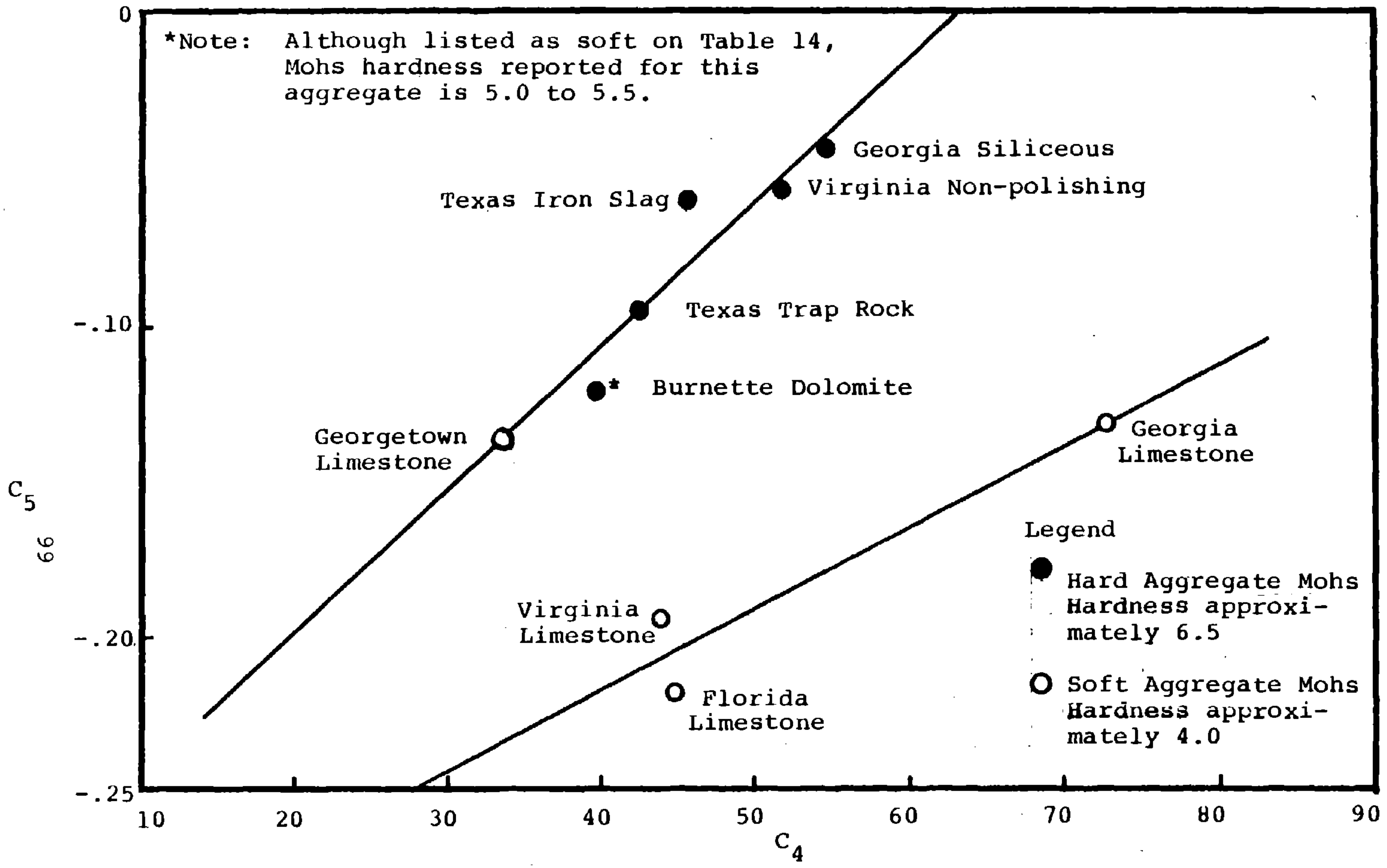
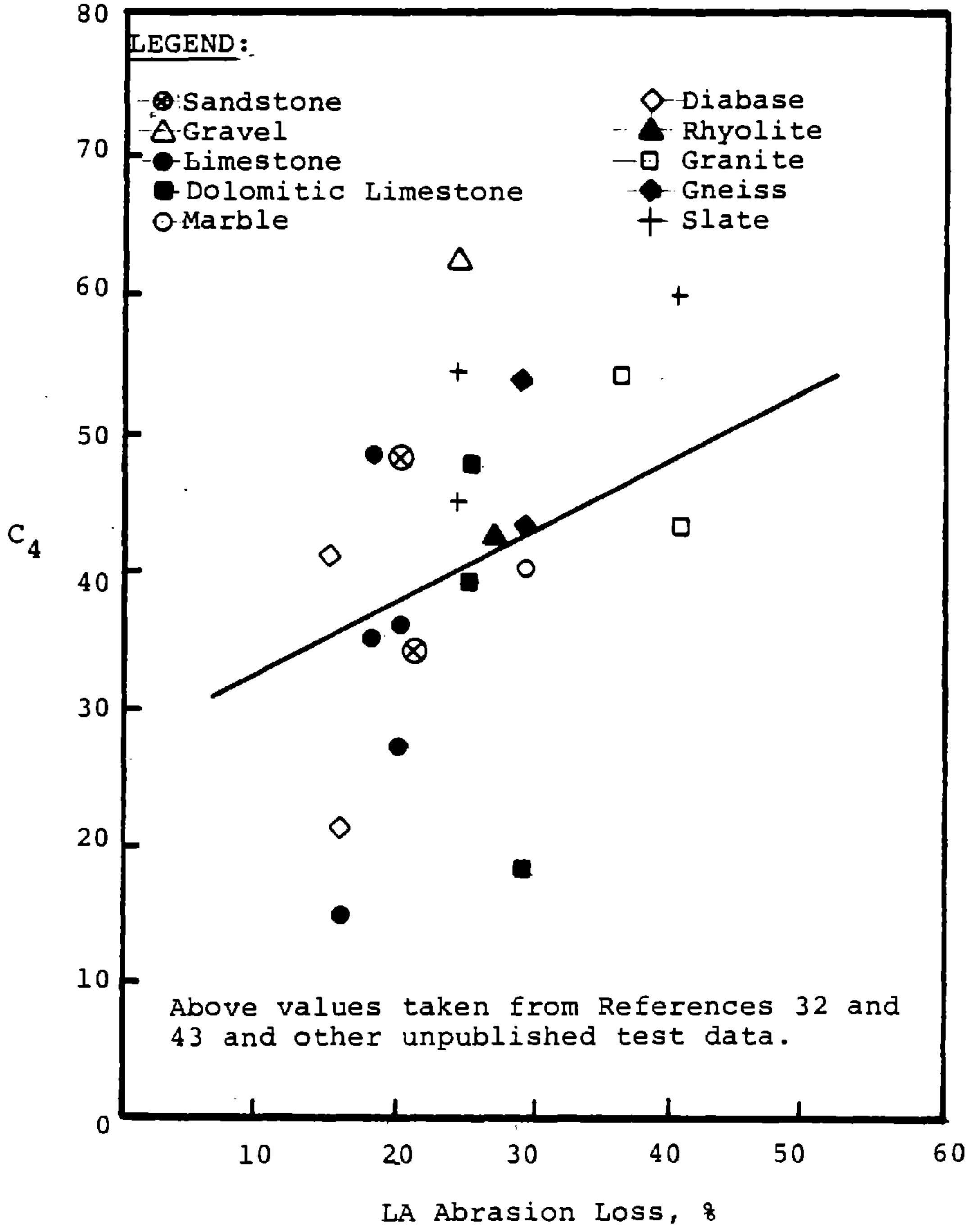


Figure 21. Illustration Showing Possible Correlation Between C_4 and C_5 for Aggregates with Different Hardness



Above values taken from References 32 and 43 and other unpublished test data.

Figure 22. Illustration Showing Possible Correlation Between C_4 and LA Abrasion Loss for Different Aggregate Types

where: LA = Los Angeles Abrasion Loss in percent.

However, the data are very scattered (Figure 22), and this may indicate that another material property not considered affects the results. It should be noted and understood that these equations are based on limited data and a very rough analysis, and have not been verified to an acceptable accuracy. Therefore, they are used in this report for illustrative purposes only and demonstration of the methodology.

PROCEDURE FOR CONSIDERING MATERIAL VARIANCE IN PAVEMENT PERFORMANCE PREDICTIONS

One overall limitation of the models discussed above is that most are deterministic rather than stochastic. The models generally predict a mean value of a dependent variance based on single values of the independent variables, which usually are themselves mean values of a set of test results assumed to be representative of a population. Therefore, material variability is not taken into account. This limitation can be partially overcome through Taylor series expansions of deterministic models to obtain equations that contain material variance. These equations result in prediction of the mean and the variance of distress and performance, and allow variation in material properties to be partially taken into account. An example is provided below for converting two deterministic multiple regression equations to stochastic form for use together in predicting rutting as a function of various material properties commonly measured for acceptance and quality control of an asphalt mixture in place.

In addition to being deterministic, there is associated with any empirical regression model an unknown prediction error (e) due to lack of fit, generally from two sources: 1) variability in nature; and 2) use of a mathematical form which does not include all factors that affect performance. Although the value of e is unknown for any specific combination of values for the quantities x_i, its variance is known from the regression analysis.

One may take the regression model (for example: $y = f(x_i)+e$, $i = 1,n$) and expand it in a Taylor series about the n mean values of the parameters x_i to predict the behavior of the dependent variable y when one or more parameters are varied from their mean values:

$$y = \bar{y} + \Delta y$$

$$= f(\bar{x}_i + \Delta x_i) + e \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (34)$$

$$\simeq f(\bar{x}_i) + \sum_{i=1}^{n} \frac{\partial f}{\partial x_i} \Delta x_i + \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{\partial^2 f}{\partial x_i \partial x_j} \left[\frac{\Delta x_i \Delta x_j}{2} \right] + e \quad \ldots\ldots (35)$$

where: $\bar{x}_i$ = is the mean value of the parameter x_i

$\bar{y}$ = the predicted value with all the x_i at their mean values.

It can be shown that if the integrals for the mean and variance of a continuous function are applied to the above equation, one obtains:

$$\sigma^2(y) = \sum_{i=1}^{n} \left[\frac{\partial f}{\partial x_i}^2 \right] \sigma^2(x_i) + \sigma^2(e) \ldots\ldots\ldots\ldots\ldots\ldots (36)$$

and

$$E(y) = \bar{y} + 0.5 \sum_{i=1}^{n} \frac{\partial^2 f}{\partial x_i^2} \left[\frac{\sigma^2(x_i)}{2} \right] \ldots\ldots\ldots\ldots\ldots\ldots (37)$$

where E(y) is the "expected value" of y in the presence of the variances $\sigma^2(x_i)$; to first order $E(y) = \bar{y}$.

The above relations assume that the x_i are uncorrelated, which is not the case in many regression models; if the approximate correlation coefficients are known between pairs of x_i, the equation can be modified appropriately.

Using these equations, one can employ a model that was originally deterministic and determine the approximate effect of changing one or several parameters, or their variances. Since a "system" fails normally due to the failure of its weakest component, a knowledge of the distribution as well as the mean value of a major component of a system model will greatly enhance the capability of that model to predict failure.

An example of the above is the use of asphalt concrete modulus from Witczak's regression equation (13) for predicting distress in asphalt pavements. Although the original model upon which equation (13) was based had an excellent coefficient of determination ($R^2 = 0.97$), one should note that the associated standard error of the fit, $\sigma(e)$, of .0887 in the $\log_{10}E_A$ corresponds to an uncertainty of 23% in the predicted value of E_A.

This equation can be differentiated analytically or numerically; the analytic derivatives are instructive in terms of the interplay of some of the independent variables, so they are given below. Let the equation be re-written as:

$$\mathrm{Log}_{10}\, E_A = C_o' + C_1' P_{200} f^{e_1} + C_2' P_v + C_3' \eta + C_6' f^{e_6} + (C_4' + C_5' f^{e_5}) T^{(e_2 + e_3 \,\mathrm{Log}\, f)} (P_{ac} - \alpha)^{e_4} \quad \text{........(38)}$$

where: $C_0' = 0.553833$ $\quad$ $e_1 = -0.17033$

$C_1' = 0.028829$ $\quad$ $e_2 = 1.3$

$C_2' = -0.03476$ $\quad$ $e_3 = 0.49825$

$C_3' = 0.070377$ $\quad$ $e_4 = 0.5$

$C_4' = 0.000005$ $\quad$ $e_5 = -1.1$

$C_5' = -0.00189$ $\quad$ $e_6 = -0.02774$

$C_6' = 0.931757$

Then:

$$d\mathrm{Log}E_A = q_1 df + q_2 dT + q_3 d\, P_{ac} + q_4 d\, P_{200} + q_5 dP_v + q_6 d\,\eta \quad \text{.......................................(39)}$$

where:

$$q_i = \frac{\partial \mathrm{Log}\, E_A}{\partial\, x_i}$$

$$x_i = \{f, T, P_{ac}, P_{200}, P_v, \eta\}$$

$$q_1 = C_1' e_1 \left[P_{200}\, f^{e_1 - 1}\right] + C_6' e_6 f^{e_6 - 1} + C_5' e_5 f^{e_5 - 1} \left[(P_{ac} - \alpha)^{e_4}\, T^{(e_2 + e_3 \log f)}\right]$$

$$+ (C_4' + C_5' f^{e_5}) e_3 \log T f^{-1} P_{ac}^{e_4} T (e_2 + e_3 \log f) \quad ..(40)$$

$$q_2 = (e_2 + e_3 \log f) T^{(e_2 + e_3 \log f - 1)} (C_4' + C_5' f^{e_5}) \quad .(41)$$

$$q_3 = (C_4' + C_5' f^{e_5}) T^{(e_2 + e_3 \log f)} e_4 (P_{ac} - \alpha)^{(e_4 - 1)} \quad ..(42)$$

$$q_4 = C_1' f^{e_1} \quad \ldots\ldots(43)$$

$$q_5 = C_2'$$

$$q_6 = C_3'$$

These quantities can be evaluated for a common set of conditions, for example, AC20 with a Penetration Index (PI) = -1, giving $\eta = 3.2$, and

$f = 10\text{Hz}$

$T = 70°F$

$P_{ac} = 5.5\%$

$P_{200} = 5.0\%$

$P_v = 5.0\%$

Substitution of these quantities into Equation (13) and the equations for q_i above yields: $E_A = 740{,}000$ psi

$$q_1 = \frac{\partial \text{Log } E_A}{\partial f} = 0.01139 \qquad q_4 = \frac{\partial \text{Log } E_A}{\partial P_{200}} = 0.01948$$

$$q_2 = \frac{\partial \text{Log } E_A}{\partial T} = 0.01818 \qquad q_5 = \frac{\partial \text{Log } E_A}{\partial P_v} = 0.03476$$

$$q_3 = \frac{\partial \text{Log } E_A}{\partial P_{ac}} = 0.0643 \qquad q_6 = \frac{\partial \text{Log } E_A}{\partial \eta} = 0.07038$$

To consider the effects on stiffness of varying temperature, substitute a 1°F increase in temperature into the above equation for q_2 while holding all the other values fixed as given. It can be seen that a 1°F increase in temperature reduces the modulus by approximately 4.3%, or 30,000 psi. The <u>fractional</u> change in E is given by $10^{q_2} \Delta T$. Now, as a second example, if a test procedure yields a measure of viscosity, say with a standard deviation of 0.2×10^6 poise, and the user wants to see the effect on the variance of modulus of improving the test so that a standard deviation of 0.1×10^6 poise is obtained, the above equations permit this to be done. Thus, the effects of variation in material test values can be evaluated as to their effect on engineering properties.

WATMODE (Waterloo Model of Distress Estimation) has within it several regression equations. The one to predict rutting (equation 18) is based on comparisons between measured rut depths as functions of pavement structure and traffic variables. Rut depth is measured in inches, averaged over both wheelpaths, and is predicted with a standard error of 0.11 inches. Corrections for large n and for $t_e < 1.2$ are given in the WATMODE program. These corrections are used in the program COSTOP1, but are not necessary for this example.

To obtain the variance in rut depth "R" from input variances of moduli and thicknesses, one has:

$$\frac{\partial R}{\partial x} = \frac{\partial R_1}{\partial x} + n \frac{\partial R_2}{\partial x} + \text{Log } n \frac{\partial R_3}{\partial x} \quad \ldots\ldots\ldots\ldots\ldots\ldots (44)$$

$$\frac{\partial R_1}{\partial t_e} = 1.2067 - \frac{2.1788}{t_e}$$

$$\frac{\partial R_2}{\partial t_e} = \frac{(.0456E_s - .4114\ E_A)}{t_e}$$

$$\frac{\partial R_3}{\partial t_e} = 0$$

$$\frac{\partial R_1}{\partial E_A} = 1.1639\ \ln t_e$$

$$\frac{\partial R_2}{\partial E_A} = -0.4114\ \ln t_e$$

$$\frac{\partial R_3}{\partial E_A} = 0$$

$$\frac{\partial t_e}{\partial t_A} = \frac{1}{10}$$

$$\frac{\partial t_e}{\partial t_{base}} = \frac{1}{20}$$

$$\frac{\partial t_e}{\partial t_{subbase}} = \frac{1}{30}$$

Hence:

$$\frac{\partial R}{\partial t_A} = 0.1 \left[1.2067 - \frac{2.1788}{t_e} + n \frac{(.0456E_s - .4114\ E_A)}{t_e} \right]$$

and

$$\frac{\partial R}{\partial E_A} = 1.1639\ \ln t_e - .4114\ n\ \ln t_e$$

Assuming: $E_A = 5 \times 10^5$ psi

$E_s = 10{,}000$ psi

$t_A = 4$ inches

$t_{base} = 8$ inches

$t_{subbase} = 12$ inches

$n = 5 \times 10^5$

Then, $t_e = 1.2$ and

$$\frac{\partial R}{\partial t_A} = -.1276$$

$$\frac{\partial R}{\partial E_c} = -.1628$$

Substitutions into the two equations just above indicate that changing the asphalt concrete modulus by 100,000 has 1.28 times the effect on rut depth as changing the asphalt concrete thickness by one inch. If one knows the variances of thickness and moduli, then at any value of n, the variance of rut depth is (approximately):

$$\sigma^2_{Rut} = \left[\frac{\partial R}{\partial t_A}\right]^2 (\sigma t_A)^2 + \left[\frac{\partial R}{\partial t_{base}}\right]^2 (\sigma t_{base})^2 + \left[\frac{\partial R}{\partial t_{subbase}}\right]^2 (\sigma t_{subbase})^2 + \left[\frac{\partial R}{\partial E_A}\right]^2 (\sigma E_A)^2 + \left[\frac{\partial R}{\partial E_s}\right]^2 (\sigma E_s)^2 \quad \text{..........................(45)}$$

This allows the methodology to compute both the mean value and variance of a particular distress caused by the variation of a material property. This becomes important when Y percent of the pavement's area exceeds a critical value and defines the pavement to be in a failed condition or in need of repair.

RUTTING AND PSI LOSS DEMONSTRATION MODELS

As discussed previously, the approach adopted for demonstrating the methodology was to combine models that predict engineering properties and others that predict distress or performance measures. Figure 23 summarizes the required inputs and models used for loss of Present Serviceability Index. As discussed above, appropriate material test values are input into a version of Witczak's model modified by Taylor series expansion to predict the mean and variance of asphalt concrete stiffness. This mean stiffness and its variance is then input, along with layer thicknesses and stiffnesses and load data, into the WATMODE rutting model to obtain a prediction of rut depth. Variance of rut depth is computed and is a function of mean rut depth and coefficient of variation of deflection (approximated as mentioned earlier, by a constant times the coefficient of variation of A.C. modulus). Finally, slope variance is also computed, which in turn is used to calculate loss of PSI. Thus, if material test results are varied due to a change in testing strategy, a change in PSI will result.

SUMMARY

Many of the tests that are commonly performed by most State agencies (See Table 15) are not considered in the models previously selected for demonstration of the methodology. These models are very limited in their derivation and should not be

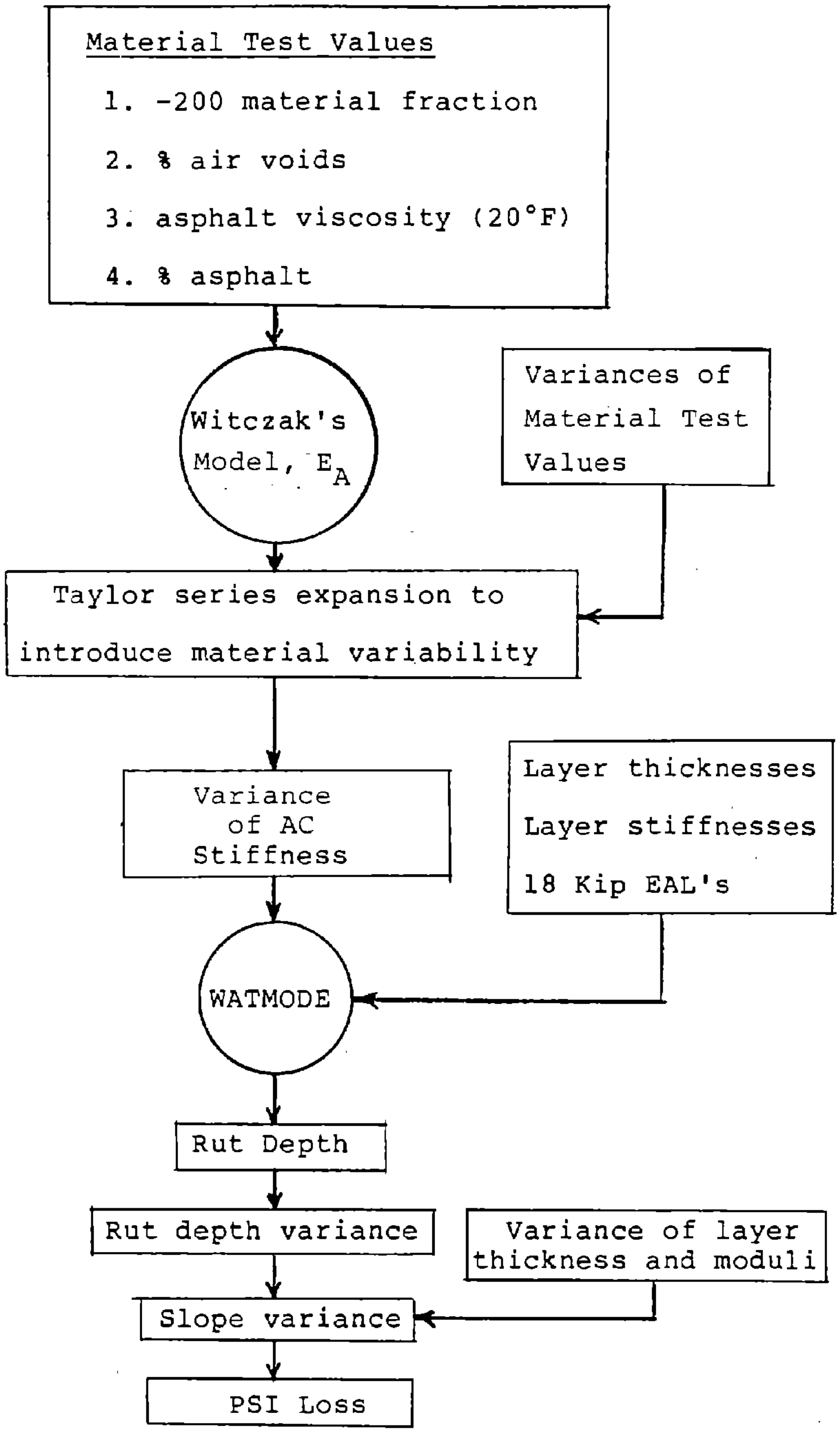


Figure 23. Algorithm Used for Computing PSI as a Function of Quality Control Test Results

Table 15
Tests that are Commonly Performed During or At Completion of Construction

	Type of Test		Considered in Models
1.	Thickness		✓
2.	Smoothness (As measured by a straight edge, or road meter. The straight edge is used by most State DOT's).		✓
3.	Compaction (As measured by the nuclear gauge-AASHTO T-238, pavement cores - AASHTO T-230, maximum specific gravity - AASHTO T-209, bulk specific gravity - AASHTO T-166. The nuclear gauge is used by the majority of the State DOT's).		*
4.	Asphalt Content (As measured by extractions, AASHTO T-164, and tank stripping.)		✓
5.	Asphalt Properties (As measured by the following tests and specifications):		
	AASHTO T-40	Sampling of Bituminous Materials	X
	AASHTO T-44	Solubility of Bituminous Materials in Organic Solvents	X
	AASHTO T-48	Flash and Fire Points by Cleveland Open Cup	X
	AASHTO T-49	Penetration of Bituminous Materials	*
	AASHTO T-51	Ductility of Bituminous Materials	X

✓ - Directly considered by the Models
* - Indirectly considered by the Models
X - Not considered by the Models

Table 15
Tests that are Commonly Performed During or At Completion of Construction (continued)

Type of Test		Considered in Models
AASHTO T-73	Flash Point by Pensky-Martens Closed Tester	X
AASHTO T-179	Effect of Heat and Air on Asphalt Materials - Thin Film Oven Test	X
AASHTO T-201	Kinematic Viscosity of Asphalts	*
AASHTO T-202	Absolute Viscosity of Asphalts	√
AASHTO M-20	Penetration Graded Asphalt Cement	X
AASHTO M-226	Viscosity Graded Asphalt Cement	X
6. Aggregate Quality (as measured by the following test methods):		
AASHTO T-27	Sieve Analysis of Fine and Course Aggregates	X
AASHTO T-84	Specific Gravity of Absorption of Fine Aggregates	X
AASHTO T-89	Determining Liquid Limit of Soils	X
AASHTO T-90	Determining Plastic Limit and Plastic Index of Soils	X
AASHTO T-103	Soundness of Aggregates by Freezing and Thawing	X
AASHTO T-104	Soundness of Aggregate by Use of Sodium Sulfate of Magnesium Sulfate	X

Table 15
Tests that are Commonly Performed During or At Completion of Construction

Type of Test			Considered in Models
	AASHTO T-176	Plastic Fines in Graded Aggregate by Use of Sand Equivalent Test	X
	AASHTO T-182	Coating and Stripping of Bitumen-Aggregate Mixtures	X
	AASHTO T-210	Production of Plastic Fines in Aggregates	X
	AASHTO T-96	Los Angeles Abrasion Test	✓
	AASHTO M-226	Viscosity Graded Asphalt Cement	X
7.	Mix Moisture Content as Measured by AASHTO T-110		X
8.	Mix Gradation (As measured by the following Test Methods):		
	AASHTO T-11	Amount of Material Finer than 0.075mm Sieve in Aggregate	X
	AASHTO T-27	Sieve Analysis of Fine and Coarse Aggregate	*
	AASHTO T-30	Mechanical Analysis of Extracted Aggregate	X
	AASHTO T-37	Sieve Analysis of Mineral Filler	X
	AASHTO T-164	Quantitative Extraction of Bitumen from Bituminous Paving Mixtures	✓

Of less critical importance but still necessary information is the lot or sample size for each of the above tests. Very few agencies will use the same lot size.

used by anyone for serious cost-effective studies. It will be necessary for any SHA wishing to use the methodology to develop suitable relationships, perhaps similar to those developed in Arizona and Alaska. These relationships would provide more accurate performance predictions for local materials and are relatively easy to develop. If the models developed incorporate variances of test results directly, then the Taylor series expansion will not be needed.

CHAPTER 6

COMPUTER PROGRAM "COSTOP1"

The basic project strategy was to develop a computerized alqorithm that was both general and modular in nature. A general program was desired to accept and process certain similar types of information expressed in a variety of ways. The form this information takes may be expected to vary among the State agencies. A good example of this is maintenance decision criteria. Most agencies utilize a set of maintenance guidelines based on the occurrence and/or level of severity of various distress or performance measures. Some SHA's use up to seven types of distress, while others may only use a few. In addition, different SHA's probably specify different levels of distress or performance. Thus, the program needs to have the capability of handling SHA-specific maintenance decision criteria.

The program also needs to be modular, because SHA's may develop their own relationships that take into account materials and environments inherent to their area. The program must have the capability of accepting these in-house relationships and merging them with other portions of the program.

PROGRAM DESCRIPTION

"COSTOP1" is a computer program which simulates the appearance and growth of pavement distress with age and number of vehicles, determines a time at which one or more failure criteria are exceeded, and evaluates the economic consequences of such functional failures. The calculated results are tied to a testing program for materials used in construction by varying the values, standard deviations, or both for test results as functions of the number of tests performed. The program can analyze a large number of "testing programs" and perform a differential benefit/cost analysis on the results to indicate to the user the most beneficial test program, subject to the assumptions and distress models used.

COSTOP1 uses distress models provided by the user in the form of FORTRAN function subprograms, examples of which will be given later. Each function has a name FUNCnn, where nn is an integer. This enables the program to select and evaluate this correct function based on the input data.

The program requires the following types of information to perform the simulations and the associated economic analyses. The exact combination needed for any particular analysis depends on the specific distresses being modeled. As an example, the inputs required for the evaluation of tests related to asphalt concrete paving materials are listed after the general category.

1. Traffic variables: ADT, percent trucks, 18-kip ESAL per truck, rate of growth - to provide quantities (like total vehicles to date, total ESAL to date) which are often used in distress models.

2. Materials variables: Asphalt concrete variables (e.g., percent asphalt, percent voids); base and subgrade variables (density, moisture content, gradation).

3. Models (as needed): A - relations among material variables and inputs to distress models; B - Distress

models (Relationships that describe distress/ performance as a function of material properties).

4. Testing Program variables: Identification of the material parameters under test, the cost of such testing, the numbers of tests to be performed under different testing programs, and information relating the material parameter to the numbers of tests.

5. Economic variables: The cost of initial construction and of annual maintenance; the user costs associated with normal use and with rehabilitation; the interest rate to be used in the analysis; the width of the pavement.

6. Control variables: The maximum time a simulation can proceed, and the age at which detailed simulation should begin.

7. Rehabilitation variables: Types of rehabilitation to be considered, their cost in some convenient units, values of the different distress types which trigger rehabilitation, and information relating the type of rehabilitation selected to the levels of the various distresses present when rehabilitation is needed.

For a specific test program, COSTOP1 determines the adjusted values of the tested parameters based on the input values and the number of tests. For each year considered it then obtains the values and coefficients of variation for each function (some of which can depend on functions already evaluated; the order of evaluation is significant) and examines those results representing distress values to see if any limiting value has been attained or passed. If no distresses have occurred, it proceeds to the next year; if one or more, a more precise time of failure is determined by interpolation and a rehabilitation is prescribed.

Construction, maintenance, user, and rehabilitation costs are combined into an equivalent uniform annual cost over the service life of the pavement. Similarly, testing costs are converted to equivalent uniform annual costs. Alternatives are arrayed in order of increasing (annual) testing costs.

A challenger-defender approach is then used to directly compare two alternatives using a differential benefit-cost (B/C) ratio. If the B/C ratio is greater than one, the challenger becomes the defender to the next challenging alternative. Conversely, if its B/C ratio is less than one, the defender remains a defender to the next challenger. Up to fifty testing programs which have differential benefit/cost ratios greater than one (implying that an additional dollar of testing cost returns more than one dollar in economic benefit) may be presented for examination by the user.

The overall methodology is illustrated conceptually in Figure 24. The alqorithm shown is a simplistic representation of the general, modular nature of the methodology. Although COSTOP1 was initially evaluated on asphalt concrete surface materials, it can be used for a multitude of different highway materials (for example: paint, joint sealant materials, etc.) by simply changing the performance models.

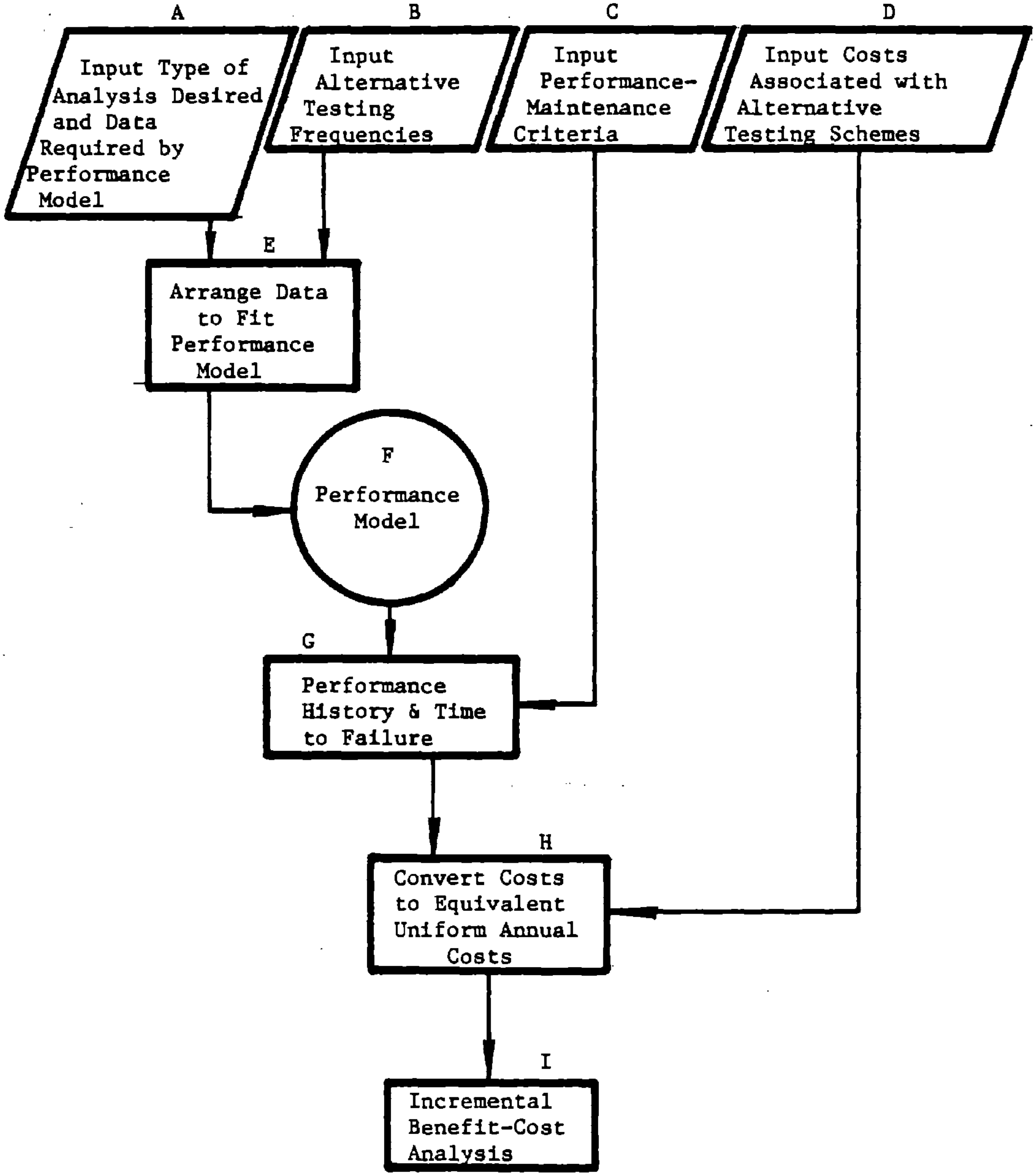


Figure 24. COSTOP1 Algorithm for Determining the Cost Effectiveness of Multiple Testing Schemes

INPUT VARIABLES

The amount of input data required to execute the COSTOP1 program depends on the performance functions selected and decision criteria established. As listed above, COSTOP1 has seven primary types of input variables. Appendix C is a detailed input guide of the COSTOP1 program for evaluating asphalt concrete materials. A more general discussion for each of the input variable types is provided in this section.

Performance Models

Performance models include the relationships between material test values and a measure of the performance. These models are included as subprograms to COSTOP1. This allows the models to be easily changed without having to rewrite the entire program. In fact, the program was specifically written so that SHA's may develop and use in-house performance relationships for asphalt concrete or other materials. Additional relationships can be used by simply removing the current performance function subprogram and replacing it with other equations or models in a similar format. The performance relation or relations can be replaced by any other desired relations in the following manner:

1. Determine all the input variables needed for the models and assign them identification numbers (1 through 10 if traffic related, 11 through 99 if not traffic related). These numbers are indices on the array X containing current values of these variables which is sent to each of the subprograms by the rest of the program. Write the performance equations in terms of these variables X(1) - X(99) and convert each resulting relation into a Fortran function with the name

FUNCTION FUNCnn, where nn is a number from 1 to 15. The output of each function must also be assigned a variable name and ID number, by the same rules as above. Compile these new subprograms and link them to the remainder of the program, in place of the old models.

2. Now, in setting up the input data, take the list of variables prepared above and assign ID numbers to the variables equal to the indices assigned above. The model results are also named and numbered in the same way, and these results can be inputs to a model with a larger ID number (which for any time is evaluated after the function with the smaller ID number). The value nn in the subprogram name FUNCnn must be given on the data input line varying the output of that function.

The input guide provides further information on the detailed preparation of the data.

Material Properties

Asphalt concrete paving materials were chosen for demonstration purposes, using combined models as previously discussed in Chapter 5. The first relationship used is that developed by Witczak, et al. (Ref. 30), which predicts asphalt concrete stiffness as a function of the following quality control parameters:

(1) asphalt content,
(2) air void content,
(3) amount of material passing the No. 200 sieve, and
(4) asphalt viscosity.

Both the sample mean and the coefficient of variation are required for each material variable. These values can be based on historical data and can be either material, area, or contractor dependent. Other quality control variables used include thickness of the asphalt concrete layer and LA Abrasion of the coarse aggregate. Input parameters not related to quality control include loading frequency and pavement temperature.

The Witczak regression model is deterministic rather than stochastic in that it predicts a mean stiffness value based on mean input values; however, variability of pavement materials on performance are considered as previously discussed in Chapter 5. To accomplish this, derivatives of the Witzcak equation were obtained with respect to all the input parameters, and these were combined with the variances of the parameters to obtain the variance of the predicted modulus. COSTOP1 performs the differentiation numerically; no analytic derivatives are needed. This does require, however, that the input functions be mathematically continuous with respect to the input variables. For example, a correction function in the rut depth model (see Chapter 5), originally expressed as a step function of the variable "equivalent asphalt thickness," was replaced with a smooth function closely approximating the original equation.

Asphalt concrete stiffness and its variance are then inserted into the rut depth prediction equation from the Waterloo Model of Distress Estimation (WATMODE - Ref 31). It should be noted that WATMODE also requires other inputs such as layer thicknesses and moduli for the lower layers. Variance in rut depth is then computed by taking the partial derivatives of the

WATMODE equation with respect to input parameters, which themselves have an associated variance.

Using rut depth and rut depth variance, slope variance is computed, which in turn can be used to compute loss of present serviceability index (PSI) at any point in time. Thus, a performance relationship was developed that predicts loss in pavement serviceability as a function of quality control parameters and time.

Traffic Variables

The traffic input variables are simply the independent variables or parameters required to exercise the performance functions. These are not necessarily agency dependent. Traffic was considered as a separate input variable, because almost all highway materials are affected to some degree by traffic. However, if the performance models or repair decision functions are not traffic dependent, then traffic would not be an input. Traffic inputs used by COSTOP1 for the example evaluation of asphalt concrete paving materials consisted of initial ADT, percent trucks, 18-kip ESAL's per truck, and traffic annual rate of growth anticipated over the next twenty years.

Testing Program Variables

The testing program input variables include the specific material tests that are being evaluated, the unit cost to perform each test, the testing frequency to be evaluated, and information relating the material mean value and variation to the number of tests. Of course, in order to evaluate a particular test, the parameter being tested must be an independent variable in the performance model, or it must be relatable to one of the independent variables considered in the model. The maximum number of test types that can be considered in any one problem is five; the maximum number of testing frequencies for any one test type is 10. The actual number of frequencies that can be considered in one problem depend on the number of tests being evaluated. Any combination of number of tests and testing frequencies for each test can be considered, subject to the above limits, as long as the total possible combinations does not exceed 250. For example, three different tests at four levels of testing frequency each would yield 64 possible testing combinations (4 x 4 x 4 = 64). This limit of 250 can be changed, however, by changing the dimensions on certain arrays within the program.

The cost to perform each test is determined external to the program, and only the unit cost is entered. Chapter 4 presented and discussed a procedure to calculate these unit costs in a materials laboratory.

Two techniques are used to relate the material mean and variation to the number of tests being performed. The first is based primarily on a statistical approach. This approach requires that the user select a confidence level on the probability that the population mean will differ from the sample mean by less than a value computed from the sample variance and the number of tests in the sample.

The other approach is based on the assumption that the quality of construction or production is affected by the level of testing (contractor's effect). Four coefficients are required to explain how the population mean and variation may vary depending on the number of tests being performed. These coefficients should be determined from experimental programs as discussed in Chapter 3. The two techniques should not be used simultaneously.

Economic Variables

The economic variables that are considered in the program include the cost of initial construction, the annual maintenance cost, the user cost associated with normal use and with rehabilitation, the interest rate that is used in the analysis, and the average width of one lane. The initial construction, annual maintenance and user cost are entered in dollars per lane mile. These costs are determined external to the program and should represent averages for a particular highway type (interstate, U.S. or State route) for an area within a State or district. The annual user cost can be omitted if it is impossible to establish. However, provision has been made in the program to permit its input, if values are available.

Control Variables

There are two control variables that are considered in the COSTOP1 program. These are: 1) the maximum time a simulation can proceed and 2) the age at which detailed simulation should begin. The maximum time is used to limit the number of computations in the absence of a simulated failure. If the maximum number of years is reached, then no rehabilitation is called for and no rehabilitation cost is obtained. The maximum number of years should exceed the expected maximum time to rehabilitation based on a review of historical records of product repair or replacement. The age at which detailed simulation should begin depends upon the model selected. Based on previous experience with some models, a lower limit on time to failure can be reasonably determined in some cases. For these, the first year of evaluation can be increased to that time to minimize the number of computations COSTOP1 must make.

Rehabilitation Variables

Rehabilitation variables include the different types of repair techniques considered by the agency, their costs in dollars per square yard (or in some other convenient units), values of distress that cause repairs to be performed, and information on how pavements are generally repaired with relation to their physical conditions. The problem is to map, in the most general way, the repair options onto the very numerous combinations of levels of distresses, so that for every combination an action is specified (even if it is a "do nothing" action). The problem is complicated by a desire to do this completely on the basis of data read into the program, rather than by hard-coding a decision tree (in which the decision levels might be input data, but not the direction of the decision based on those levels). A simple example of the latter would be a statement that if Y percent of the pavement has rutting greater than R inches, then place a one-inch overlay on the pavement; Y and R can be read in as variables, but the choice of rehabilitation is fixed within the program. The former is characterized by the ability to specify externally the number and direction of the branches in the decision tree, and, in our simple example above, to specify the type and details of the rehabilitation option selected.

A procedure has been developed which, on the basis of extensive testing, satisfies the above requirements, and in addition has the advantage of relative simplicity for the user. The procedure itself is not simple in practice, but its complexities are in the programming, not the required input. This procedure is discussed in more detail in the Input Guide (Appendix C), and an example of this procedure is provided in Appendix E.

PROGRAM OUTPUT AND INTERPRETATION

COSTOP1 calculates equivalent annual pavement and testing costs for each test frequency or test program. All costs are based on a unit of dollars per lane mile. In addition, for each test program the age at failure (the time at which one of the distress values has exceeded the critical value established by the agency), the type of failure (the specific distress type requiring maintenance or rehabilitation), and the type of repair technique selected from the decision tree are all determined for the user. No computations are made beyond the predicted time of rehabilitation.

The program also prints the differential benefit/cost ratio for the fifty best testing alternatives considered. The differential benefit is the decrease in equivalent annual pavement costs because of an increase in the testing program, and the differential cost is the increase in testing costs between two test programs. All possible combinations of testing frequencies are not printed, but only those alternatives with a differential benefit/cost ratio greater than one.

Selection of the testing alternate should be based on the test program with the highest testing cost that has a differential benefit/cost ratio greater than one. A differential benefit/cost ratio greater than one means that for every dollar spent in increased testing cost, more than a dollar is returned in lower pavement costs.

PROGRAM ASSUMPTIONS

The following assumptions have been made in program COSTOP1 which have not been discussed in detail in the description of the methodology:

1. The method used for propagation of variance assumes that the coefficients of variation are small with respect to 1, so that only the second derivative terms need to be included. Given the approximations involved elsewhere, this is probably not a problem.

2. A possibly more limiting assumption applies to the financial analysis. When the statistical approach is used, one specifies a confidence level CL, such that CL percent of the time the material mean value will fall above or below (whichever is the direction for longer pavement life) a value V. This implies that there is a (100 - CL) percent chance that the mean value will fall outside the limiting value V. Presumably this will cause the pavement to fail at an earlier time than calculated by the program, which uses V as the mean in its computations. Thus in the case where CL is 95 percent, we have a 5 percent chance that the pavement will fail before the calculated time associated with a specific test program. We are, however, associating 100 percent of the equivalent annual cost of the pavement with that time of failure. The correctness of this assumption depends on the meaning of the confidence level. If the confidence level is associated with a percent

area of pavement, and assume (in our example) 95 percent of the pavement, if tested (or 95 percent of the pavement material), would yield values on the high-performance side of the limit V, then 5 percent (100 - CL) will fall on the other side of V. Thus by the time functional failure is calculated (using V as a mean value), 5 percent of the pavement will have already failed. If in general when (100 - CL) percent of the pavement has failed, the entire pavement must be rehabilitated, then the assumption is correct; otherwise, an alternative procedure must be devised.

CHAPTER 7

EVALUATION OF TESTING PROGRAMS

Computer program COSTOP1 was used to determine the cost effectiveness of selected asphalt concrete tests, using data obtained from the three States visited. These tests are listed below and include most of the tests commonly performed by State agencies, as summarized in Table 16.

Mix Gradation (Percent Passing No. 200 Sieve)
Asphalt Concrete Thickness
Percent Air Voids (or Compaction)
Asphalt Content
Asphalt Viscosity (or Penetration)
Los Angeles Abrasion

This limited study of asphalt concrete tests was conducted to demonstrate the use of COSTOP1 in evaluating test frequency and overall test programs. An evaluation of all tests performed in the central, district, and residency asphalt laboratories was impossible, because performance functions relating each test to pavement performance (either directly or indirectly) were unavailable. However, the techniques presented can be used for any test or combination of tests or with any other construction material provided performance models and testing cost data are available or can be determined.

In addition, it should be clearly understood that the results and discussions to follow are limited and based primarily on our interpretation of the interviews conducted within each State, and are highly dependent upon the distress/performance models used in the evaluation (see Chapter 5). These performance models are limited, and are not applicable to all situations and physical conditions encountered in each State, and do not even consider the distress manifestations caused by

Table 16

Number of Agencies That Test Properties; Methods Used and Basis for Pay Factors (Ref. 38)

Property	Agencies That Test Property	Dominant Test Method Used and Number of Agencies	Dominant Basis for Pay Factor Used and Number of Agencies
Thickness	31	Cores 23	Statistical 5 Guide in Spec. 7 None [1] 14
Smoothness	37	Straight-edge 26	Statistical 6 Guide in Spec. 6 None [1] 18
Compaction	43	Nuclear Gage 26	Statistical 11 Guide in Spec. 11 None [2] 16
Asphalt Content	43	Extraction 32	Statistical 17 Guide in Spec. 6 None [2] 15
Asphalt Properties	44	Agency Tests 31	Statistical 8 Guide in Spec. 13 None [2] [3] 16
Aggregate Quality	39	Approved Source 9 AASHTO 28	Statistical 3 Guide in Spec. 2 None [2] [3] 27
Mix Moisture Content	21	Standard or Modified Tests 18	None [2] [3] 15
Mix Gradation	45	AASHTO 35	Statistical 18 Guide in Spec. 8 None [2] [3] 14

Note: Table 15 in Chapter 5 gives a more detailed breakdown of the specific test types of the above properties.

[1] Do not accept work below Specification tolerance. Most agencies require overlay to correct deficiency at contractor's expense.

[2] Do not accept work below Specification.

[3] Usually a requirement is not necessary.

some material deficiencies (i.e., for example, low asphalt contents causing extensive ravelling or high asphalt contents causing flushing and reduced skid resistance). In fact, only the material test values that have an effect on the asphalt concrete stiffness and structural response of the pavement to imposed wheel loads are considered. Therefore, specific statements about revisions to current test programs cannot be provided; only general statements have been given.

TYPICAL PROJECT DATA SELECTED FOR STUDY

Specific data were established for each of the inputs briefly discussed in Chapter 6. The following provides a brief discussion on the inputs selected for each State.

Traffic

A two-lane rural highway was selected for project study in each of the three States. The number of traffic applications and the axle load distribution for the two-lane highway was assumed to be constant among the agencies. The traffic data used for most of the examples include:

One way - Initial ADT = 6,000
Percent Increase in Traffic Per Year = 5%
Percent Trucks = 10%
18-kip ESAL's per truck = 0.30

Pavement Cross Section

The pavement cross section selected for the examples was designed using the AASHTO interim design guide and traffic data presented above. Strength coefficients for the asphalt concrete surface, granular base and subbase layers were assumed to be constant for all States. The pavement cross section used in most of the examples is described below:

Dense graded asphalt concrete surface = 4.5 inches
Crushed stone base = 8.0 inches
Granular subbase = 12.0 inches

Pavement Cost

Annual maintenance and annual user cost and user cost of rehabilitation were unavailable from each State. Therefore, none of these cost items were considered in the examples. Initial construction costs were found to vary significantly among the States and within each State, depending on the physical, geological, and other site specific conditions. However, for simplicity and comparison, a constant value of $90,000 per lane mile was used for all examples.

Material Properties

Material test data for each of the independent variables considered in the performance/distress models were obtained from historical records and construction files and represent typical values found in each State. The specific values selected for these examples are listed in Table 17. Although the mean value selected for each data item varied among the SHA's, the coefficients of variation were assumed to be constant. All of the other material inputs were assumed to be constant between the problems.

SHA's Decision Functions

As stated previously, all the participating SHA's have some type of pavement management system that applies decision

Table 17
Summary of Typical Values Found from Historical Records Used in the Examples for Evaluating Test Programs

Test	State A	State B	State C	Coefficient of Variation, %
Percent Bitumen, %	6.0	5.0	6.0	6.0
Percent Air Voids, %	3.0	5.0	2.5	40.0
Percent Passing No. 200 Sieve, %	3.0	6.0	6.0	25.0
Viscosity @ 70°F 10^6 Poise	3.2	5.0	5.0	10.0
Average Asphalt Concrete Pavement Temperature, °F	85	75	75	10.0

criteria to identify when pavements should be repaired. During the State visits, interviews were conducted with pavement design and maintenance engineers to identify the factors which trigger maintenance and/or rehabilitation, when specific decision criteria were not available through published records. Interpreting the results of these interviews was quite difficult, but this information was collected from each SHA on a subjective basis and transformed into a decision tree based on our interpretation and understanding of the agency's normal practices. Tables 18 through 20 illustrate the decision trees established for each State visited. However, it should be understood that these decision functions are based upon our understanding and interpretation of the interviews and other data collected.

Testing Cost "Best Guess"

To evaluate the cost effectiveness of particular tests requires that a unit cost be determined for each test. Since the "true" unit costs were generally unknown, the costs listed in Appendix B were adjusted to account for those items that were omitted as discussed in Chapter 4. These revised unit costs were then compared to typical unit costs charged by commercial laboratories, for reasonableness. Those unit costs are shown in Table 21 for the asphalt concrete tests commonly performed in each State.

ANALYSIS OF SAMPLING AND TESTING FREQUENCIES FOR A PARTICULAR TEST

COSTOP1 was used to evaluate the optimum sampling and testing frequency for each individual test listed above, using the data obtained from each State. These results are summarized in Table 22. It is emphasized, however, that each test was

Table 18

Rehabilitation Requirements and Decision Criteria for State "A"

Primary Distress Criterion - Fatigue Cracking, C	Other Criterion			Rehabilitation Type and Avg. Cost, $/sq. yard
C > 20%				1. 4" Overlay - 6.00
1% < C < 20%	Roughness > 256 in./mi.			2. Mill 1" plus 2.0" Overlay - 4.50
	Rutting > 0.50			3. 1.5" Leveling Course plus 1.5" Overlay - 5.00
	Skid Resistance < 43			4. Membrane plus 1.5" Overlay - 4.75
C < 1%	Roughness > 256 in./mi.			5. Mill 1" plus 1.5" Overlay - 3.50
	Rutting >50%			6. 1" Leveling Course plus Overlay - 3.00
	Skid Resistance < 43	Roughness; 156-256 in./mi.		7. Mill 0.5" plus 1" Overlay - 2.50
		Roughness; < 156 in./mi.	ADT < 1000	8. Chip Seal - 1.25
			ADT > 1000	9. Asphalt Concrete Friction Course - 1.75

Table 19
Rehabilitation Requirements and Decision Criteria for State "B"

Primary Distress Criterion - Rutting, R	Other Criterion			Rehabilitation Type and Avg. Cost, $/sq. yard
R > 0.5 inches				1. 3" Overlay - 5.50
0.25" < R < 0.5"	PSI <2.0		ADT < 1000	2. Mill 1" plus 1" Overlay - 3.25
			1000 < ADT < 5000	3. Mill 1" plus 1.5" Overlay - 4.00
			ADT > 5000	4. Mill 1" plus 2.0" Overlay - 4.75
	PSI >2.0	Fatigue Cracking >50%	ADT < 1000	5. Seal Coat plus 1" Overlay - 3.50
			1000 < ADT > 5000	6. Membrane plus 1.5" Overlay - 4.50
			ADT > 5000	7. Membrane plus 2.0" Overlay - 5.25

Table 19
Rehabilitation Requirements and Decision Criteria for State "B"
(continued)

Primary Distress Criterion - Rutting, R	Other Criterion			Rehabilitation Type and Avg. Cost, $/sq. yard
R < 0.25"	PSI <2.0		ADT <1000	8. Mill 0.5" plus 1.0" Overlay - 3.00
			1000 < ADT < 5000	9. Mill 0.5" plus 1.5" Overlay - 3.75
			ADT > 5000	10. Mill 0.5" plus 2.0" Overlay - 4.50
	PSI > 2.0	Fatigue Cracking > 50%	ADT < 1000	11. Seal Coat - 1.50
			1000 < ADT < 5000	12. Seal Coat plus 1.0" Overlay - 3.50
			ADT > 5000	13. Seal Coat plus 1.5" Overlay - 4.25

Table 20
Rehabilitation Requirements and Decision Criteria for State "C"

Primary Distress Criterion - Fatigue Cracking, C	Other Criterion		Rehabilitation Type and Avg. Cost, $/sq. yard
C > 50%			1. Seal Coat plus 2.5" Overlay - 5.50
1% < C < 50%	Rutting >0.5"	ADT < 1000	2. Mill 1" plus Seal Coat and 1.5" Overlay - 4.75
		ADT > 1000	3. Mill 1" plus Seal Coat and 2.5" Overlay - 6.25
C < 1%	Rutting > 0.5"	ADT < 1000	4. Mill 0.5" plus 1.5" - Overlay - 3.50
		ADT > 1000	5. Mill 0.5" plus 2.5" Overlay - 5.00

Table 21
Summary of Unit Testing Costs That Were Used in the Evaluation of Test Programs (Dollars per Test)

Test	State A	State B	State C
Los Angeles Abrasion	120	125	150
Asphalt Viscosity	100	125	150
Percent Bitumen	90	80	80
Percent Air Voids	60	60	70
Gradation	85	90	100
In-Place Density	30	30	40
Cores-Thickness	80	105	105

Table 22
Summary of Optimum Sampling and Testing Frequency for Selected Asphalt Concrete Tests
(Asphalt Concrete Tonnage = 1750 tons per lane mile)

Type of Tests	Number of Tests per Lane Mile for Each State A	B	C
Asphalt Viscosity	12 (2)*	10 (1)*	12 (1)*
Percent Passing No. 200 Sieve	13 (8)	12 (6)	12 (6)
Percent Asphalt Content	14 (4)	12 (4)	12 (6)
Asphalt Concrete Thickness - Cores	16 (-)	12 (2)	15 (2)
Percent Air Voids or Density	20 (4)	20 (8)	15 (8)

*( ) Denotes the current testing frequency that would be used for control of the above example in each state. In some cases this value represents the minimum frequency specified.

evaluated independently of the other tests without considering the interrelationship between different test values. For example, if the bitumen content is increased for a particular sample, the percent air voids measured for that sample will likely decrease. Considering these effects would likely change the optimum number of test frequencies for each type of test. However, the optimum numbers of tests listed in Table 22 does indicate the relative importance of the test or sensitivity of the test result to pavement performance for the specific unit cost and other physical factors.

A review of Table 22 indicates that percent air voids (or density) is the critical test parameter (largest number of tests per lane mile). One possible explanation for this is the relatively larger coefficient of variation and smaller unit costs assigned for the example (see Table 17 and 21), as opposed to the variations and unit costs for the other test parameters. These values, however, are typical based on a review of material test reports from each State and from data accumulated by Kennedy (Refs. 11 and 12). The least critical test parameter is asphalt viscosity (or penetration).

The optimum number of tests was found to vary between States and can be expected to vary between districts in a particular State, depending on the environment, highway type, and other physical conditions. In every case, however, all optimum sampling and testing frequencies selected by COSTOP1 are much greater than the current frequencies specified within each State visited, as shown in Table 22.

The Arizona Department of Transportation roughness equation (Ref. 25) presented in Chapter 5 was used to demonstrate the sensitivity of selected values using the COSTOP1 computer program. The input data generated from State A was used for this brief sensitivity study to show the effect of coefficient of variation, mean core total variance, testing cost, and construction cost on optimum number of gradation (extractions) tests. The results are presented in chart form in Figure 25. As shown, the coefficient of variation has the largest effect on the optimum number of tests (11 to 24 tests per lane mile) to be performed over the expected range of each of these input variables. It is suggested that the user do similar type sensitivity studies to become familiar with the inputs and outputs of the program.

ANALYSIS OF MULTIPLE TESTS

In most cases, more than one quality characteristic or test value must be considered in defining the optimum test program. For example, asphalt concrete thickness alone is insufficient to assure the desired performance. To be durable, an asphalt concrete mixture must also have the necessary amount of bitumen and proper grading.

Information accumulated from each SHA was also used to identify the optimum testing programs for the six tests listed above. These results are summarized in Table 23 and examples of the output are included in Appendix F. For the output given in Appendix F, the first set of testing frequencies does not necessarily represent the current test frequencies of each State. The output provided for each problem is the end-result of an iterative process, because of the maximum number of possible test programs that can be considered in any one COSTOP1 run, as discussed in Chapter 6.

As shown in Table 23, there is a significant difference between results for the three SHA's. In all cases, however,

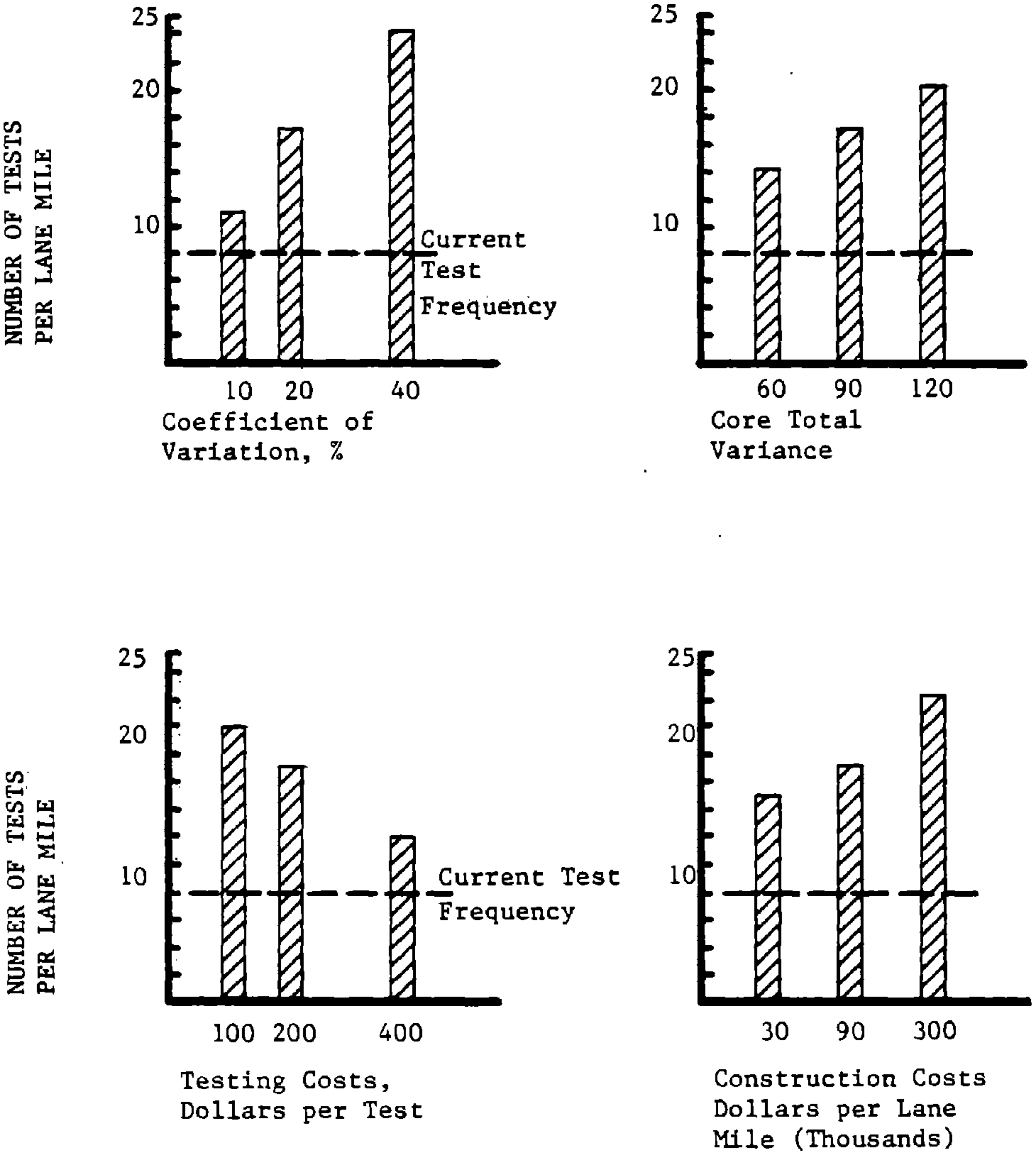


Figure 25. Graphical Presentation of the Effects of Different Factors on the Optimum Number of Tests per Lane Mile (Asphalt Concrete Tonnage=2500 Tons)

Table 23
Summary of the Optimum Testing Program for An Asphalt Laboratory, Number of Tests per Lane Mile (Asphalt Concrete Tonnage = 1750 tons)

Test	State		
	A	B	C
Bitumen Content	9	15	15
Percent Air Voids	6	21	18
Percent Passing 200 Sieve	3	15	18
Asphalt Viscosity	3	15	12
Asphalt Concrete Thickness	9	15	15

the limited models indicate that an increase in testing can be justified based on the economic benefits. For example, the cost computations for State A show that an increase in equivalent annual testing costs of approximately $300 per lane mile ($430 to $730) will result in a savings of approximately $1,000 per lane mile ($29,800 - $28,800) of equivalent annual pavement costs over the life cycle of the pavement. For State B, an increase in equivalent annual testing costs of approximately $1,000 per lane mile ($400 to $1,445) will save approximately $3,700 per lane mile ($24,000 - $20,300) of equivalent annual pavement costs. For State C, an increase in equivalent annual testing costs of approximately $750 per lane mile ($350 to $1,100) will save approximately $4,300 per lane mile ($23,600 - $19,300) of equivalent annual pavement costs. Without question, additional testing is justified based on the performance models and other data discussed in this report.

The Los Angeles abrasion test was considered in the computations of reduced skid resistance, but for all of the examples, the functional pavement failure requiring repairs were due to structural failures rather than loss of skid resistance. Therefore, the indication was that no tests are needed to control skid resistance, only the acceptance test for the material source is required (one per source). However, if the pavement would have required maintenance or repair because of reduced skid resistance prior to any other repairs, then COSTOP1 would have selected a specific number of tests to be performed per lane mile.

An evaluation was also conducted for only three of the tests listed above. These are percent air voids, asphalt viscosity, and asphalt concrete thickness. The reason for considering just three of the tests was to allow the use of more test frequencies (a maximum number of 250 possible combinations of test types and test frequencies has been established in the program, as discussed in Chapter 6). Table 24 summarizes the results of these analyses and the output has been included in Appendix F. The results for these examples are similar to those for the more inclusive test programs discussed above.

To determine if there is a difference between rural and urban areas (different traffic levels and corresponding pavement cross sections), input data for State A was used to compare the optimum testing programs for different highway types (State routes, US routes, and Interstate highways). These results are summarized in Table 25 and the output has been included in Appendix F. As shown, the optimum testing program varies depending on the type of highway. For the particular example evaluated, surface thickness is the critical test for low volume roads, and percent air voids is critical for high volume roadways. For the high volume roadway, the models indicate that an increase in equivalent annual testing costs of approximately $900 per lane mile ($900 to $1,800) will decrease the equivalent annual pavement costs by approximately $6,500 per lane mile ($104,000 - $97,500), a definite savings.

The decision criteria used by a State agency to manage its pavements will also have an effect on the selection of an optimum test program. Table 26 summarizes the results from analyses using different decision criteria related to rut depth for State B. As shown, if the critical rut depth that causes maintenance is changed from greater than or equal to 0.5 inches for 50 percent of the wheel path area to greater than or equal to 0.75 inches for only 25 percent of the wheel path area, the least critical test changes from asphalt viscosity to gradation.

Table 24
Summary of Testing Programs for Selected Tests per Lane Mile
(Asphalt Concrete Tonnage = 1750 tons)

Test	State		
	A	B	C
Percent Air Voids (Density)	6	24	18
Asphalt Viscosity	3	12	12
Asphalt Concrete Thickness (Cores)	9	15	15

Table 25
Summary of the Effect of Highway Type on Optimum Test Program
Using Data From State A

Test	Low Traffic	Moderate Traffic	High Traffic
Percent Air Voids (Density)	3	6	21
Asphalt Viscosity	3	3	18
Asphalt Concrete Thickness (Cores)	6	9	3

Table 26

Summary of the Effect of the Critical Distress Criteria on Optimum Test Program Using Data From State B

Type of Test	Rut Depth > 0.50 inches for 50% of Wheel Path HMAC t = 4.0 inches	Rut Depth > 0.75 inches for 25% of Wheel Path	
		HMAC Thickness	
		4.0 inches	1.5 inches
Bitumen Content	10	10	3
Percent Air Voids	10	10	3
Percent Passing 200 Sieve	10	3	3
Asphalt Viscosity	3	10	3
Asphalt Concrete Thickness	10	10	10
Failure Mode	Rut Depth	PSI	Damage Index
Asphalt Concrete Tonnage per lane mile	1600	1600	550

As for the other examples, the optimum testing program for a U.S. Highway and a State route were compared. These are also shown in Table 26. Although, the number of tests per lane mile are the same for the gradation and asphalt concrete thickness measurements, the volume of material on a per test basis is significantly different. For example, percent passing the Number 200 sieve for the 4-inch asphalt concrete layer should be taken every 530 tons, whereas, for the 1.5-inch asphalt concrete layer a test should be performed every 180 tons. In summary, although specific optimum test programs may vary from State to State, all analyses indicate that an increase in testing frequency and testing cost is justified and should decrease the life-cycle pavement costs by much more than the additional increase in testing cost.

ECONOMIC IMPACT

The COSTOP1 program offers a realistic, statistically based method for evaluating different testing strategies. For the conditions assumed in this report, the following two generalizations may be made concerning the economics of increased material testing. These are:

1. On the average, an additional $1, above present testing levels, spent on testing will decrease pavement cost by approximately $5. This ratio of increased testing cost to reduction in pavement cost was found to vary from 2.5 to 20.
2. For higher volume traffic levels (thicker pavements) such as Interstate highways, percent air voids (or density) is the critical test parameter whereas for lower volume traffic (rural roads), asphalt concrete thickness is the critical test parameter.

It must be remembered that the results discussed above are directly dependent on the performance models used and the materials tests considered in the evaluation. These limited results obtained from the COSTOP1 program strongly indicate that additional testing can be justified through a reduction in life-cycle pavement costs. Significant short and long-term effects on State, county or city budgets could be expected if these results were implemented. The short-term effects would generally be increased testing budget requirements, but the desirable long-term effect should be pavements that require less maintenance and repair over their design life.

CHAPTER 8

GUIDELINES FOR EVALUATING TEST PROGRAMS

This chapter provides specific guidelines for evaluating existing test programs and provides recommendations for revising those programs for both flexible and fixed testing budgets. In addition, possible use of the COSTOP1 program for other purposes is discussed. Other such uses include: 1) defining allowable (and reasonable) construction tolerances to improve specifications such that materials of inferior quality will not be used and 2) development of pay reduction schedules that are reasonable and equitable and can be used for enforcement to ensure adequate construction.

SELECTION OF OPTIMUM TEST PROGRAMS

State agencies are often asked by legislatures if the agency can decrease the amount of testing or costs for quality control programs. In some cases, such a requirement has been imposed on agencies due to decreases in operating budgets and state personnel set by the legislature (Ref. 39). The COSTOP1 program can provide a basic tool and methodology to assist the agency to predict the relative effects of changes in the expected quality of pavement construction due to decreases or increases in the amount of testing.

Results from the program can be used to establish the most cost-effective test program for a given budget such that the agency gets the highest return on every dollar spent for testing. For this specific use, a step-by-step procedure has been prepared to assist the user in generating the inputs for the program and using COSTOP1 to evaluate the current test program and for making changes to the program. The procedure listed below has been prepared for evaluating asphalt concrete tests; however, the same general steps can be applied to other materials for which suitable models exist.

1. Selection of details requiring consideration - The user should first select the typical details of the test program to be considered, the physical conditions of the pavement to be evaluated and the environment in which the pavement must function. Some such site details are site specific (expansive soils as compared to non-expansive soils), environment specific (wet-freeze as compared to dry-no freeze), material specific (crushed stone as compared to river gravels), production specific (drum mix plants as compared to batch plants), highway specific (Interstate highways as compared to State routes), or contractor specific variables. It is suggested that the agency break the State (or county, or city) into different areas with significantly different physical conditions. The optimum test program should be established separately for physical groups of highways having significant differences between them.

2. Define performance in terms of the material test under evaluation - The current version of COSTOP1 only considers six asphalt concrete tests. These are percent asphalt content, percent air voids, gradation, asphalt viscosity, asphalt concrete thicknesses, and Los Angeles abrasion. As discussed previously, performance is related to these material properties by limited models developed and/or applied only to demonstrate the methodology developed. Serious application of COSTOP1 will necessitate the development of

more reliable relationships as explained in Chapter 6. In fact, it is highly recommended that relationships be developed by each agency to reflect their own specific conditions.

To begin, the significant distresses or performance measurements that cause the pavements to be repaired should be established. An investigation should then be conducted to establish those properties or factors that affect each particular distress or performance measure. Standard regression techniques may then be used to define the correlation between various parameters and can be used to generate relationships between materials test results and distress and performance measures. (For examples, refer to Refs. 1, 25, 26, 27 and 28.)

3. Calculation of testing costs - Using the procedure described in Chapter 4, establish the unit cost for each test performed in the central and field laboratories. These unit costs should be representative of the most recent year for which data is available.

4. Selection of values of input variables for the performance models - The actual inputs to the program will vary depending on the independent variables included in the performance models. However, all inputs should represent average values typical for the specific problem under evaluation. For example, the mean asphalt content and its coefficient of variation should reflect average values established from construction records for a particular grading, aggregate type, and/or contractor.

5. Selection of the type of evaluation - There are two types of evaluation that can be used with the COSTOP1 program. These are: (1) the "contractor response approach," and (2) the "statistical approach." The contractor response approach should only be applied if changes in contractor performance with changes in testing program (as discussed in Chapter 3) have been established. In most cases, this relationship will be extremely difficult to establish. The statistical approach simply defines the range of the true population mean and standard deviation in terms of the sample mean and standard deviation at some confidence level. At the present time, the statistical approach is probably the only option available to most agencies.

6. Establish the decision criteria (critical values of distress or performance) that cause repair or maintenance to be performed - Based on agency practice or review of maintenance, repair, and rehabilitation projects, establish a "decision tree" of decision criteria as described in Chapter 6 and Appendix E. This "set of strategies" will function in COSTOP1 to decide when repair is required and what should be done. Appropriate unit costs should be established for each repair option included in the decision tree.

7. Select the types of tests and testing frequencies to be initially evaluated - As a first iteration, all tests should be considered at three different sampling frequencies, with the first representing the existing test program. Other appropriate

considerations may then be considered as suggested by the results obtained. The zero testing alternative can only be considered using the contractor effect approach.

8. COSTOP1 computations - The computer program COSTOP1 is then run to calculate the equivalent annual pavement and testing cost for each test program alternate. All alternates are arranged in order of increasing testing cost, and a differential benefit/cost ratio is calculated for each. All challenger options with ratios greater than 1.0 are printed out. In addition to the differential benefit/cost ratios, both the time to failure and selected rehabilitation option are printed as output. These values can be compared to the time to failure that is typical for the area in question to determine if the results are reasonably close to the performance of in-situ pavements.

9. Selection of testing program - The most cost effective testing program is the largest or most expensive test program with a differential benefit/cost ratio greater than or equal to 1.0. This implies that a dollar spent on expanding the test program over the next most expensive program returns at least an additional dollar in reduced equivalent annual costs. If a more precise solution is desired than for the first three sampling frequencies considered, the program is rerun with revised sampling frequencies based on the results obtained from the first iteration. This may be continued until the testing program is obtained with a differential benefit/cost ratio nearest 1.0.

However, if the agency has a specific testing budget for an asphalt concrete laboratory, then the combination of test types and associated sampling frequencies can be defined using the same steps as outlined above. The difference is that the current cost of all test programs evaluated should be equal to or less than that testing budget. The one to be selected is the one with the lowest sum of equivalent annual testing cost and equivalent annual pavement cost.

ESTABLISH REVISED CONSTRUCTION TOLERANCES OR CONSTRUCTION SPECIFICATIONS

COSTOP1 can also be used to determine the cost effectiveness of imposing higher standards for material production and construction. For example, the "tighter" the construction tolerances or the higher the standards of construction imposed by specifications on the contractor, the longer the pavement will be expected to perform, but, the more costly it will be to construct. Therefore, the question to be answered for a particular material test procedure and agency is how strict may the controls be before becoming impractical or too costly. To answer this question, the user must be able to answer two questions. These are:

1. How are production or construction costs affected by a change in construction tolerance or material specification, and
2. Will the material produced under the new specifications in fact produce a longer lasting pavement?

To use COSTOP1, first assume that the agency's enforcement policies are adequate, so that the material produced when the higher standards are imposed will be more uniform and of higher quality. To answer the first question, interviews can be conducted with area contractors to estimate the increase in construction or production cost caused by a change in a specification (i.e., an increase in density of a material in-place or a smaller construction tolerance for asphalt content). Once an estimate has been secured, COSTOP1 can be run to compute the total equivalent annual cost (equivalent annual pavement cost plus equivalent annual testing cost) using each specification. If use of the revised specification results in a smaller equivalent annual cost, then a specification change would appear to be justified.

ESTABLISHING PAY REDUCTION FACTORS

One of the most important parameters affecting quality of work is the enforcement program of the responsible agency. In most cases, one of two types of enforcement programs are applied. One is a pass/fail type approach and the other involves reductions in pay in event of marginal quality of construction as measured by one or a combination of control tests. These rules of pay reductions are commonly referred to as "pay reduction factors."

There are two types of pay reduction schedules, stepped and continuous. Stepped schedules establish intervals of construction or material quality and apply a single pay rate for each interval. Continuous schedules are functions relating the pay reduction to selected quality measures. The stepped reduction schedules are the most common in use today. Tables 27 through 29 show examples of pay adjustments for different test variables.

Construction and/or material production should be judged on the basis of quality that can normally be produced using acceptable care and effort. As stated by Elliott and Herrin

Table 27

Approaches Used By State Agencies to Determine Pay Adjustments For Non-Compliance with Compaction Requirements (Ref. 38)

Approaches	Number of Agencies
Percentage reduction in contract price computed by formula based on statistics	3
Pay factors for percentage of target density	7
Pay factors for percentage of control strip density	4
Pay factors for percentage of voidless density	1
Pay factors for daily mean air void content	1
Pay factors based on deviation of air void content	1
Price adjustment for percentage of deficiency	1
Pay factors based on computed quality level	2
Pay factors based on computed quality index	1
Pay factors for percentage within limits	2

Table 28
Approaches Used By State Agencies to Determine Pay Adjustments For Non-Compliance with Asphalt Content Requirements (Ref. 38)

Approaches	Number of Agencies
Percentage reduction in contract price computed by formula based on statistics	3
Pay reduction for percent out of tolerance	3
Pay factors for average deviation from job mix	13
Pay factors for deviation of sample average as percentage	1
Pay reduction for sample average as percentage	1
Pay factors based on deviation of mean above or below mix tolerances	1
Price adjustment computed by specific procedure based on percentage of asphalt above or below mix-design tolerance	1
Pay factors for degree of non-conformance of moving average	1

Table 29

Approaches Used By State Agencies to Determine Pay Adjustments For Non-Compliance with Mix Gradation Requirements (Ref. 38)

Approaches	Number of Agencies
Percent of reduction in contract price computed by formula based on statistics	4
Pay factors for deviation of the mean from job-mix formula	14
Pay reduction for percent within limits	1
Pay reduction for deviation of the sample average as a percent of mix tolerance	1
Pay reduction for the percent out of tolerance	3
Pay factors for the degree on non-conformance	1
Pay adjustment computed by a detailed procedure in this specification	1

(Ref. 10), "Good or Acceptable work should receive 100 percent pay, Superior should be rewarded and Inferior work should be penalized." Most conflicts for alleged failures to deliver what was contracted for arise from failure of some specification to be communicable. For evaluation using the COSTOP1 program, it must be assumed that the specifications are communicable and specific to site conditions. In addition, it is the responsibility of the materials engineer to consider the most important variables in the pay reduction factors in a way that is logical, equitable, and defensible.

To establish pay reduction factors, COSTOP1 can be used to estimate the change in pavement cost for a particular test program and quality of construction. COSTOP1 can be initially used to predict the equivalent annual pavement cost for a reasonable or expected quality of work (using a particular test program). Next, both the mean and standard deviation of the material property used to accept and control the work may be appropriately increased and decreased to illustrate the effect of superior and inferior work on the equivalent annual pavement cost. It is assumed that this test parameter is the most sensitive variable related to pavement performance. Different sample mean values and standard deviations are used to calculate a range of equivalent annual costs for each combination for different conditions. The pay adjustment factors or functions can then be based on the difference (in percent) between the equivalent annual costs for the expected quality of work and the quality actually obtained.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to develop a capability for determining the cost effectiveness of individual tests and associated sampling frequencies used in controlling the quality of pavement construction and materials as related to performance. This objective has been accomplished, but immediate implementation will be limited due to lack of models relating materials properties commonly measured to performance of a pavement or other product. Development of models was not a part of this project, but a few limited models for demonstration were developed. Conclusions and recommendations for further study are discussed below.

CONCLUSIONS

A methodology has been developed that provides the means for individual agencies to determine how frequently tests should be conducted, and to establish priorities among different tests to gain the greatest effect on pavement performance. In general, this project was dependent on availability of stochastic models relating quality control test results to distress or performance measures. As these did not exist, the computer program COSTOP1 (in which the methodology is implemented) was made modular so that models could be easily inserted as they become available. Input formats were also developed that allow maximum flexibility in defining decision criteria for maintenance, repair, or rehabilitation strategies and for structuring the studies.

A very serious conceptual problem was encountered in discrimination between the statistical concept of improving estimates of means and standard deviations as compared to actual (or "population") means and standard deviations and the actual effect of increased testing on a subsequent product to be produced later. There is no doubt that an increase in testing frequency offers a better opportunity for identifying and perhaps replacing deficient materials. It also appears logical that the contractor will respond by producing a better product on subsequent portions of the current project or other projects for which he expects high test frequencies. However, there is certainly no established relationships that indicate what a typical contractor response would be, let alone what a specific contractor might do under a specific set of conditions.

The approach taken was to include a very general model for contractor response, which can be easily modified by input to reflect the expectations for contractor response of the agency conducting the study. If this relationship can be established with reasonable confidence, this should be the primary approach adopted for any studies conducted. However, the statistical approach for considering the effects of better evaluating the material properties, due to increased frequency of testing, has been included as a useful alternative.

Based on the limited models available for demonstration, the methodology appears to consistently indicate that high testing frequencies are cost effective. This appears logical (almost obvious) in view of the relatively nominal cost of testing compared to costs for repair and rehabilitation. It generally requires very little improvement in the product, especially in reduction of variance, to increase the service life prior to required repair or rehabilitation.

Based on these limited studies, it appears on the average that doubling the test frequencies now commonly used would result in a savings of at least 150 percent of the additional testing cost. This finding is based on preliminary models whose limitations have been previously discussed. The authors consider this to be a significant finding of the study.

RECOMMENDATIONS FOR CONTINUED RESEARCH

The methodology developed and embodied in COSTOP1 accomplishes the objectives of this project. However, to apply this methodology to practice suitable performance models must be developed in terms of material properties commonly measured by quality control tests. Therefore, the emphasis for continued research should be toward development of stochastic models that will predict distress and performance measures directly in terms of the commonly measured material properties.

While it may be feasible to develop such models within SHA's to represent local materials and environments, this will undoubtedly prove to be a fairly expensive undertaking that may or may not gain support of legislative bodies. It appears very probable that empirical relationships developed from multiple regression analyses will provide the most practical and accurate models. Mechanistic models may be useful in combination with empirical data, but this appears to have less utility as an approach than long-term collection of data and the development of empirical models.

A strong initiative is underway by the FHWA, AASHTO, and the Transportation Research Board to build a national data bank and to ensure that it satisfies a number of data needs. It will be critical to ensure that the data collected during long-term monitoring of in-service highways now planned will include the results of quality control testing, including variance as well as mean values, that will be required to develop the desired models.

While the long-term data collection effort represents the best source for development of quality models for the long-term, it may be possible to develop useful models in the short-term using data obtained from mechanical testers. Tentative plans have been discussed for the establishment of a mechanical tester in a controlled environment at the Turner-Fairbank Highway Research Center at McLean, Virginia, and to later use mobile testing equipment on in-service highways. This equipment accelerates wheel-load applications such that failure may be obtained in reasonably short periods of time. While the results of accelerated testing are not as reliable as those under mixed traffic over the long-term, they might provide sufficient reliability to be useful for studies utilizing the capabilities of COSTOP1.

Despite the dearth of suitable models, it is likely that some benefit can be gained through limited implementation for one or more interested SHA's. Such an implementation effort could be expected to uncover problems in utilization of COSTOP1 by SHA's not anticipated by the authors of this report. Also, ideas for new applications and improvements would likely result.

In summary, it is recommended that a limited implementation study be initiated, and that any feasible initiatives be undertaken to produce the types of models required by COSTOP1. This should certainly include establishing congruity with the data collection activities planned for the long-term monitoring effort (Ref. 40) and the FHWA's Highway Condition and Quality of Highway Construction Survey Reports (Ref. 41) or any special studies that may be expected to offer useful models at an acceptable confidence level (for example, an analysis of the data stored in the COPES data base for rigid pavements, Ref. 42).

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APPENDIX A

SAMPLING AND TESTING FREQUENCIES FOR ACCEPTANCE AND CONTROL

This appendix provides recommended sampling and testing frequencies for Arizona, Illinois and West Virginia highway agencies in tabular form. Arizona practice appears in Tables 30 through 36, Illinois practice in Tables 37 through 43, and West Virginia practice in Tables 44 through 45. These tables have been included in this appendix to illustrate the extensive number of test types that are performed for different materials in each SHA for controlling paving construction and materials.

Table 30

Arizona Acceptance Sampling Guide For Soils

MATERIAL CODE, NAME AND TYPES	TYPE OF TEST(S) REQUIRED	SAMPLING POINT	MINIMUM SAMPLING FREQUENCY
SUBGRADE	PROCTOR DENSITY	ROADWAY	ONE PER SOIL TYPE
	COMPACTION	ROADWAY	ONE PER 1500'
	GRADATION, PI	ROADWAY	ONE PER 1500' OR CHANGE IN MATERIAL
EMBANKMENT	PROCTOR DENSITY	IN-PLACE	ONE PER SOIL TYPE
	COMPACTION	IN-PLACE	ONE PER 1500' PER LIFT
NATURAL GROUND	PROCTOR DENSITY	IN-PLACE	ONE PER SOIL TYPE
	COMPACTION	IN-PLACE	ONE PER HALF-MILE
TOP SOIL	GRADATION, PI, SOLUBLE SALTS, AND pH	IN-PLACE OR SOURCE	ONE PER SOIL TYPE

Table 31

Arizona Acceptance Sampling Guide For Stabilized Soils and Bases

MATERIAL CODE, NAME AND TYPES	TYPE OF TEST(S) REQUIRED	SAMPLING POINT	MINIMUM SAMPLING FREQUENCY
CEMENT TREATED BASE	PROCTOR DENSITY	ROADWAY	AT START OF PRODUCTION THEN ONE PER WEEK
	COMPACTION	ROADWAY OR POINT OF PLACEMENT	ONE SET LAYER PER 1000' OR ONE 500 CY
	COMPRESSIVE STRENGTH	ROADWAY OR POINT OF PLACEMENT	ONE SET PER HALF SHIFT
LIME TREATED SUBGRADE	PROCTOR DENSITY	ROADWAY	AT START OF PRODUCTION THEN AS MATERIAL CHANGES
	COMPACTION	ROADWAY	ONE PER LAYER PER 1000'
CEMENT TREATED SUBGRADE	PROCTOR DENSITY	ROADWAY	AT START OF PRODUCTION THEN AS MATERIAL CHANGES
	COMPACTION	ROADWAY	ONE PER LAYER PER 1000'
BITUMINOUS TREATED BASE	COMPACTION, EXTRACTION	ROADWAY	ONE PER 2000 TONS

Table 31

Arizona Acceptance Sampling Guide For Stabilized Soils and Bases (continued)

MATERIAL CODE, NAME AND TYPES	TYPE OF TEST(S) REQUIRED	SAMPLING POINT	MINIMUM SAMPLING FREQUENCY
LEAN CONCRETE BASE	COMPRESSIVE STRENGTH, SLUMP, ENTRAINED AIR	AT DISCHARGE	ONE SET (2) PER 300 CY
	THICKNESS	ROADWAY	ONE PER 1000 LIN. FT.

Table 32

Arizona Acceptance Sampling Guide For Aggregates

MATERIAL CODE, NAME AND TYPES	TYPE OF TEST(S) REQUIRED	SAMPLING POINT	MINIMUM SAMPLING FREQUENCY
AGGREGATE BASE AND SELECT MATERIAL	PROCTOR DENSITY	CRUSHER BELT OR STOCKPILE	AT START OF PRODUCTION, THEN AS MATERIAL CHANGES
	COMPACTION	ROADWAY	ONE PER LAYER PER 1000'
	GRADATION, PI	WINDROW	ONE PER 2000 T. OR ONE PER SHIFT
	THICKNESS	ROADWAY	ONE PER 1000' WITH STAGGERED OFFSETS
COVER MATERIAL	GRADATION	FINAL STOCKPILE	ONE PER 300 T.
	CRUSHED FACES AND FLAKINESS INDEX	CRUSHER BELT OR FINAL STOCKPILE	ONE PER PROJECT
	% LIMESTONE, ABRASION	SOURCE	ONE PER SOURCE
FINE AGGREGATE FOR PCC	GRADATION, SAND EQUIVALENT	BATCH PLANT CONVEYOR BELT OR STOCKPILE	ONE EVERY OTHER DAY
	MORTAR STRENGTH	STOCKPILE	ONE PER SOURCE
	MOISTURE CONTENT	BATCH PLANT CONVEYOR BELT OR STOCKPILE	TWO PER POUR

Table 32

Arizona Acceptance Sampling Guide For Aggregates (continued)

MATERIAL CODE, NAME AND TYPES	TYPE OF TEST(S) REQUIRED	SAMPLING POINT	MINIMUM SAMPLING FREQUENCY
COARSE AGGREGATE FOR PCC	GRADATION	BATCH PLANT CONVEYOR BELT OR STOCKPILE	ONE EVERY OTHER DAY
	ABRASION	STOCKPILES	ONE PER SOURCE
	MOISTURE CONTENT	BATCH PLANT CONVEYOR BELT OR STOCKPILE	TWO PER POUR
SPECIAL BACKFILL OR BACKFILL	PROCTOR DENSITY	STOCKPILE	ONE PER SOURCE
	COMPACTION	IN-PLACE	ONE EACH SIDE EVERY 50 CY
	RESISTIVITY, pH	STOCKPILE OR SOURCE	ONE PER SOURCE
	GRADATION PI	ON JOB SITE	ONE PER 300 CY PER SOURCE
BEDDING MATERIAL	PROCTOR DENSITY	STOCKPILE	ONE PER SOURCE
	COMPACTION	IN-PLACE	ONE EACH SIDE EVERY 50 CY
	RESISTIVITY, pH	STOCKPILE OR SOURCE	ONE PER SOURCE
	GRADATION, PI	STOCKPILE ON JOB SITE	ONE PER 300 CY PER SOURCE

Table 32

Arizona Acceptance Sampling Guide For Aggregates
(continued)

MATERIAL CODE, NAME AND TYPES	TYPE OF TEST(S) REQUIRED	SAMPLING POINT	MINIMUM SAMPLING FREQUENCY
MINERAL AGGREGATE FOR ASPHALT CONCRETE, SURFACE COURSE, FRICTION COURSE	CRUSHED FACES, SAND EQUIVALENT	STOCKPILE	ONE PER 5000 T. MINIMUM OF TWO PER PROJECT
	GRADATION	COLD FEED OR BINS	ONE PER 500 T. OR ONE PER SHIFT
	% LIMESTONE, ABRASION	SOURCE	ONE PER SOURCE
MINERAL AGGREGATE FOR CEMENT TREATED BASE, BITUMINOUS TREATED BASE, BITUMINOUS ROAD MIX	GRADATION	STOCKPILE	ONE PER 500 T. OR ONE PER SHIFT
BLOTTER MATERIAL	GRADATION	STOCKPILE	ONE PER SOURCE
RIP RAP	ABRASION, SPECIFIC GRAVITY	SOURCE	ONE PER SOURCE

Table 33

Arizona Acceptance Sampling Guide For Bituminous Material

MATERIAL CODE, NAME AND TYPES	TYPE OF TEST(S) REQUIRED	SAMPLING POINT	MINIMUM SAMPLING FREQUENCY
ASPHALT CEMENT			
FOR ASPHALT CONCRETE, BITUMINOUS TREATED BASE, SURFACE COURSE, AND FRICTION COURSE	VISCOSITY	CIRCULATION LINE	CERTIFICATE AND DUPLICATE SAMPLE PER 1/2-SHIFT
FOR TACK	VISCOSITY	DISTRIBUTOR	CERTIFICATE AND DUPLICATE SAMPLE PER DELIVERY UNIT
LIQUID ASPHALT TYPE MC FOR BITUMINOUS ROAD MIX, BITUMINOUS TREATED BASE, TACK, PRIME	VISCOSITY	DISTRIBUTOR	CERTIFICATE AND DUPLICATE SAMPLE PER DELIVERY UNIT
EMULSION TYPE SS, MS, RS, CSS, CMS, CRS, ERA	VISCOSITY		CERTIFICATION REQUIRED NO SAMPLES REQUIRED EMULSIONS PRE-APPROVED PPD 81-4
SPECIAL EMULSION, DILUTED ERA	RESIDUE	DISTRIBUTOR	CERTIFICATE AND DUPLICATE SAMPLE PER DELIVERY UNIT

Table 33

Arizona Acceptance Sampling Guide For Bituminous Material (continued)

MATERIAL CODE, NAME AND TYPES	TYPE OF TEST(S) REQUIRED	SAMPLING POINT	MINIMUM SAMPLING FREQUENCY
ASPHALT CONCRETE	EXTRACTIONS	PLANT	ONE PER 2000 T.
	COMPACTION	IN-PLACE	ONE PER 2000 T.

Table 34

Arizona Acceptance Sampling Guide For Portland Cement Concrete

MATERIAL CODE, NAME AND TYPES	TYPE OF TEST(S) REQUIRED	SAMPLING POINT	MINIMUM SAMPLING FREQUENCY
PORTLAND CEMENT CONCRETE PAVEMENT	COMPRESSIVE STRENGTH, SLUMP, ENTRAINED AIR	AT DISCHARGE	ONE SET (2) PER 300 CY
	THICKNESS	ROADWAY	STANDARD SPEC. 408-4
PORTLAND CEMENT CONCRETE STRUCTURAL, CLASS A, D&S	COMPRESSIVE STRENGTH, SLUMP, ENTRAINED AIR	AT DISCHARGE*	ONE SET (2) PER CONSECUTIVE 50 CY
PRESTRESSED AND POST-TENSIONED	SAME AS ABOVE	AT DISCHARGE*	ONE SET PER MEMBER
PORTLAND CEMENT STRUCTURAL CONCRETE FOR MINOR PRECAST STRUCTURES	REBOUND HAMMER	AT FABRICATION YARD	ONE SET OF READINGS PER PRECAST UNIT

*WHEN CONCRETE IS PUMPED, SAMPLES SHOULD BE TAKEN AT BOTH THE TRUCK AND HOSE DISCHARGE TO DETERMINE THAT THE SPECIFICATIONS ARE MET IN THE STRUCTURE AND TO CORRELATE THE TWO RESULTS. IF CORRELATION IS GOOD, SAMPLING CAN CONTINUE FROM THE MOST CONVENIENT LOCATION WITH OCCASIONAL RETESTING FOR CORRELATION.

Table 35

Arizona Acceptance Sampling Guide For Materials Used With Portland Cement Concrete

MATERIAL CODE, NAME AND TYPES	TYPE OF TEST(S) REQUIRED	SAMPLING POINT	MINIMUM SAMPLING FREQUENCY
PORTLAND CEMENT (ALL TYPES)			
ARIZONA SOURCES	CHEMICAL, PHYSICAL	PLANT	ONE CERTIFICATION PER SHIPMENT
CALIFORNIA SOURCES	SAME	PROJECT	ONE CERTIFICATION PER SHIPMENT AND ONE GAL. WEEKLY
OTHER SOURCES	SAME	PROJECT	CALL MATERIALS ENGINEER
FLY ASH	CHEMICAL, PHYSICAL	PROJECT	ONE CERTIFICATION PER SHIPMENT AND ONE GAL. WEEKLY
WATER	pH, SOLUBLE SALTS	SOURCE	CERTIFICATION OR ONE SAMPLE PER SOURCE* (ONE PINT IN GLASS CONTAINER)
ADMIXTURES	CHLORIDES	PROJECT OR PLANT	ONE SAMPLE PER LOT AND CERTIFICATION (ONE PINT IN GLASS CONTAINER)
JOINT FILLER	COMPRESSION, THICKNESS	PROJECT	ONE SAMPLE PER PROJECT
JOINT SEAL	COMPRESSION, VISCOSITY	PROJECT	ONE SAMPLE PER PROJECT
BEARING PADS	DUROMETER HARDNESS, THICKNESS	PROJECT	ONE SAMPLE PER PROJECT

*NO SAMPLE IS NECESSARY IF WATER IS POTABLE AND COMES FROM A PROVEN SOURCE.

Table 35

Arizona Acceptance Sampling Guide For Materials Used With Portland Cement Concrete (Continued)

MATERIAL CODE, NAME AND TYPES	TYPE OF TEST(S) REQUIRED	SAMPLING POINT	MINIMUM SAMPLING FREQUENCY
CURING COMPOUND	% SOLIDS	PROJECT	ONE SAMPLE PER LOT AND CERTIFICATION TWO QUARTS IN GLASS CONTAINER (PPD 81-2)
EPOXY COATED OR UNCOATED REINFORCEMENT BARS			
PHOENIX SOURCES	TENSILE STRENGTH, BENDING STRENGTH, ELONGATION, WEIGHT/FT. (COATING THICKNESS)	FABRICATION PLANT	ONE 6 FT. BAR PER 10 TONS PER BAR AND CERTIFICATION (PPD 82-4)
OTHER SOURCES	SAME	PROJECT	ONE 6 FT. BAR PER 10 TONS PER BAR SIZE AND CERTIFICATION
PRE-STRESSING STEEL	TENSILE STRENGTH, DIAMETER	PROJECT	TWO 6 FT. PIECES FROM EACH REEL & CERTIFICATION
WELDED WIRE FABRIC	TENSILE STRENGTH, DIAMETER, SPELTER	SUPPLIERS YARD OR PROJECT	ONE 2'x2' SAMPLE PER 10 ROLLS

Table 36

Arizona's Independent Assurance Sampling Guide Recommendations

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1. Material Type - Independent Assurance Sampling and Testing will normally be limited to:

   a. Naturally occurring materials (such as soils and aggregates, and mixtures containing naturally occurring materials),

   b. Processed aggregates, and

   c. Mixtures containing processed aggregates.

2. Sampling Frequency - Where practical, a minimum of one Independent Assurance Sample per project, per material type or combination, as sampled for acceptance, will be required.

3. Additional assurance samples shall be taken in the results of the "Acceptance" tests and the "Independent Assurance" tests vary significantly.

4. Independent Assurance Samples are to be taken by State personnel who do not normally have direct responsibility for process control and acceptance sampling. They are used for the purpose of making independent checks on the reliability of the results obtained in acceptance sampling and testing. The testing of Independent Assurance Samples is to be done with equipment other than used in the job control or acceptance testing except that separate equipment for these tests not generally considered to be field-type tests will not be required.

5. Independent Assurance samples should be obtained early in the production of any particular material types or soon after combining material as is practical for the particular testing purpose.

6. These results are to be promptly compared with those obtained from acceptance samples representing similar materials and an evaluation made as to the dependability and accuracy of the acceptance sampling and testing.

Table 37

Illinois Materials Sampling Guide For Embankments and Subgrades

MATERIAL	TYPE OF TEST	SAMPLING FREQUENCY	
		ACCEPTANCE SAMPLES	INDEPENDENT ASSURANCE SAMPLES
EARTH, STONE OR GRAVEL EMBANKMENTS	MOISTURE DENSITY CONTROL	COMPACTION CURVE DATA IS REQUIRED FOR EACH MAJOR CHANGE IN EMBANKMENT MATERIAL. THIS DATA MAY BE FURNISHED IN ADVANCE BY DISTRICT MATERIALS LAB.	OBSERVATION OF FIELD TESTING PROCEDURES AND SOILS IDENTIFICATION *
	IN-PLACE DENSITY	ONE TEST/20,000 CY, CONTINUOUS OPERATION. CONFINED AREAS, ONE TEST PER 3 FT. OF LIFT AND NOT LESS THAN ONE PER INDIVIDUAL FILL AREA	100,000 CY OF FILL MATERIAL OR ONE TEST/MILE OF ROADWAY*
SUBGRADE	IN-PLACE DENSITY	ONE TEST/1500 FT. OF ENTIRE LENGTH OF SUBGRADE THRU BOTH CUT & FILL AREAS	OBSERVATION OF FIELD TESTING; ONE TEST PER MILE*
LIME MODIFIED OR STABILIZED	IN-PLACE DENSITY	ONE TEST/1500 FT. OF TREATED AREA	OBSERVATION OF FIELD TESTING; ONE TEST PER MILE*
LIME FOR MODIFIED OR STABILIZED SOILS	CHEM LAB	MIX DESIGN SAMPLE	1 CHECK SAMPLE ON 1ST DAY, THEN 1 per 750 TONS

*AT LEAST ONE TEST, AND PREFERABLY THE FIRST, MUST BE PERFORMED BY CENTRAL LABORATORY PERSONNEL WITH EQUIPMENT OTHER THAN THAT ASSIGNED TO THE PROJECT.

Table 38

Illinois Materials Sampling Guide For Aggregate Base and Granular Subbase Materials

MATERIAL	TYPE OF TEST	SAMPLING FREQUENCY	
		ACCEPTANCE SAMPLES	INDEPENDENT ASSURANCE SAMPLES
BASE COURSE:			
AS SPREAD	QUANTITY GRADATION	*1 SOURCE INSPECTION AND 1 INV TEST PER MILE MAINLINE PAVEMENT	1 PER 5 MILE 2-LANE PAVEMENT.*3
AS COMPACTED	P.I. *2	SOURCE INSPECTION	NONE
AS COMPACTED	THICKNESS	1 PER 1000 FT. OF PAVT.	NONE
AS COMPACTED	DENSITY (Ty.A)	1 PER 1000 FT. OF PAVT.	1 PER 5 MILE 2-LANE PAVEMENT.*3
SUBBASE:			
AS SPREAD	QUANTITY GRADATION	*1 SOURCE INSPECTION AND 1 INV TEST PER MILE MAINLINE PAVEMENT	1 PER 5 MILE 2-LANE PAVEMENT.*3
AS COMPACTED	P.I. *2	SOURCE INSPECTION	NONE
AS COMPACTED	THICKNESS	1 PER 1000 FT. OF PAVT.	NONE
AS COMPACTED	DENSITY (Ty.A)	1 PER 1000 FT. OF PAVT.	1 PER 5 MILE 2-LANE PAVEMENT.*3

*1 WHERE MEASUREMENT IS BY WEIGHT AND DELIVERY IS BY TRUCK, AN INSPECTOR SHOULD BE PRESENT TO OBSERVE THE WEIGHING AND INITIAL THE TICKETS. RETAIN DAILY TARE WEIGHTS. AT THE POINT OF WEIGHING A DAILY MOISTURE DETERMINATION SHOULD BE MADE FOR PAY WEIGHT CORRECTION. AN INSPECTOR SHOULD BE PRESENT AT POINT OF DELIVERY TO RECEIVE AND INITIAL TICKETS.

*2 IF REQUIRED BY SPECIFICATIONS OR SPECIAL PROVISIONS.

*3 MAXIMUM 2 PER WEEK.

P.I. = PLASTICITY INDEX

Table 39

Illinois Materials Sampling Guide for Stabilized Bases and Shoulders

MATERIAL	TYPE OF TEST	SAMPLING FREQUENCY	
		ACCEPTANCE SAMPLES	INDEPENDENT ASSURANCE SAMPLES
<u>GENERAL</u>			
AGGREGATES	GRADATION	SOURCE INSPECTION AND ONE INV TEST ON 1ST DAY, THEN ONE PER WEEK PER PLANT	ONE PER MONTH PER PLANT
ASPHALT *1	PENETRATION OR VISCOSITY	SOURCE INSPECTION AND ONE INV TEST PER WEEK PER TYPE OF MATERIAL PER PLANT	NONE
CEMENT	CEMENT LAB	*3	NONE
LIME, LIME KILN DUST, CEMENT KILN DUST	CHEM. LAB	SOURCE APPROVAL BY MIX DESIGN AND ONE INV SAMPLE PER 5000 TONS OF MIX	NONE
FLYASH (POZZOLAN)	CHEM. LAB	SOURCE APPROVAL BY MIX DESIGN AND ONE INV SAMPLE PER 5000 TONS OF MIX	NONE
<u>STABILIZED BASE COURSES & SUBBASES</u>	DENSITY	4 CORES PER DAY *6	ONE PER MONTH *2
(1) BITUMINOUS BASE COURSE MIXTURE	THICKNESS	ONE EVERY 250 FT.	NONE
	STABILITY*5		
	EXTRAC. *7	*8	NONE
(2) BITUMINOUS AGGREGATE MIXTURES	DENSITY	4 CORES PER DAY *6	ONE PER MONTH *2
	THICKNESS	ONE EVERY 250 FT.	NONE
	STABILITY*4		
	EXTRAC. *7	*8	NONE

Table 39

Illinois Materials Sampling Guide For Stabilized Bases and Shoulders (Continued)

	MATERIAL	TYPE OF TEST	SAMPLING FREQUENCY	
			ACCEPTANCE SAMPLES	INDEPENDENT ASSURANCE SAMPLES
(3)	CEMENT AGGREGATE MIXTURE	DENSITY	ONE/1000 FT. OF PAVT.	ONE PER MONTH *2
		THICKNESS	ONE EVERY 250 FT.	NONE
(4)	POZZOLANIC AGGREGATE MIXTURE	DENSITY	ONE/1000 FT. OF PAVT.	ONE PER MONTH *2
		THICKNESS	ONE EVERY 250 FT.	NONE
(5)	LIME SOIL MIXTURE	DENSITY	ONE/1000 FT. OF PAVT.	ONE PER MONTH *2
(6)	SOIL CEMENT	DENSITY	ONE/1000 FT. OF PAVT.	ONE PER MONTH *2
		THICKNESS	ONE/1000 FT. OF PAVT.	NONE
<u>STABILIZED SHOULDERS</u>		DENSITY	4 CORES PER DAY *6	ONE PER MONTH *2
BITUMINOUS AGGREGATE MIXTURE		THICKNESS	ONE PER 1000 FT-ALTERNATE SIDES OF PAVEMENT	NONE
		STABILITY*4		
		EXTRAC.*7	*8	NONE

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*1 SAMPLES TO BE TESTED BY THE DISTRICT LABORATORY OR SENT TO CENTRAL LABORATORY AT SPRINGFIELD OR CHICAGO AS DIRECTED.

*2 PROJECT SITE TESTING OBSERVED BY DISTRICT LAB REPRESENTATIVES AND NOTED ON THE REPORT WITH ONE TEST PER PROJECT PERFORMED EARLY IN THE PROJECT WITH EQUIPMENT OTHER THAN THAT USED FOR ACCEPTANCE OR PROCESS CONTROL TESTING.

*3 REFER TO "PORTLAND CEMENT ACCEPTANCE PROCEDURES," ILLINOIS POLICY MEMORANDUM 746 AND CURRENT LIST OF QUALIFIED PLANTS.

*4 ONE INV SAMPLE FIRST DAY; THEN AS REQUIRED.

*5 ONE INV SAMPLE FIRST DAY; THEN ONE PER WEEK.

Table 39

Illinois Materials Sampling Guide For Stabilized Bases and Shoulders (Continued)

MATERIAL	TYPE OF TEST	SAMPLING FREQUENCY	
		ACCEPTANCE SAMPLES	INDEPENDENT ASSURANCE SAMPLES

*6 DIFFERENT LOCATIONS, ONE CORE EACH. NUCLEAR TESTING DEVICE MAY BE USED IF SPECIFIED OR PERMITTED BY SPECIAL PROVISIONS OR STANDARD SPECIFICATIONS.

*7 ONE INVESTIGATION TEST PER 1500 TONS MIX. SAMPLES TO BE TESTED BY DISTRICT, OR CONSULTANT, OR SENT TO CENTRAL LABORATORY AT SPRINGFIELD OR CHICAGO.

*8 ACCEPTANCE OF BITUMINOUS CONCRETE IS BASED ON HOT BIN ANALYSIS (COLD FEED FOR DRIER DRUM PLANTS), PLANT ACCEPTANCE AND CALIBRATION, TESTS ON ASPHALT SCALES AND PUMPS DURING PLANT OPERATION, AND PERIODIC WEIGHT CHECKS ON TRUCKS.

Table 40

Illinois Materials Sampling Guide For Aggregate Shoulders and Aggregate Surface Courses

MATERIAL	TYPE OF TEST	SAMPLING FREQUENCY	
		ACCEPTANCE SAMPLES	INDEPENDENT ASSURANCE SAMPLES
AGGREGATE SHOULDERS:			
(Ty.A)	QUANTITY	*1	
AS SPREAD	GRADATION	SOURCE INSPECTION	NONE
AS COMPACTED	P.I. *2	SOURCE INSPECTION	NONE
AS COMPACTED	THICKNESS	1 PER 1000 FT. PAVT.	NONE
AGGREGATE SHOULDERS:			
(Ty.B)	QUANTITY	*1	
AS SPREAD	GRADATION	SOURCE INSPECTION	NONE
AS COMPACTED	P.I. *2	SOURCE INSPECTION	NONE
AGGREGATE SURFACE			
COURSE (Ty.A)	QUANTITY	*1	
AS SPREAD	GRADATION	SOURCE INSPECTION AND 1 INV TEST PER MILE MAINLINE PAVT.	1 PER 5 MILE 2-LANE PAVT.*3
AS COMPACTED	P.I. *2	SOURCE INSPECTION	NONE
AS COMPACTED	THICKNESS	1 PER 1000 FT. OF PAVT.	NONE
AGGREGATE SURFACE			
COURSE (Ty.B)	QUANTITY	*1	
AS SPREAD	GRADATION	SOURCE INSPECTION AND 1 INV TEST PER MILE MAINLINE PAVT.	1 PER 5 MILE 2-LANE PAVT.*3

Table 40

Illinois Materials Sampling Guide For Aggregate Shoulders and Aggregate Surface Courses (continued)

MATERIAL	TYPE OF TEST	SAMPLING FREQUENCY	
		ACCEPTANCE SAMPLES	INDEPENDENT ASSURANCE SAMPLES
AS COMPACTED	P.I. *2	SOURCE INSPECTION	NONE
AS COMPACTED	THICKNESS	1 PER 1000 FT. OF PAVT.	NONE

*1 WHERE MEASUREMENT IS BY WEIGHT AND DELIVERY IS BY TRUCK, AN INSPECTOR SHOULD BE PRESENT TO OBSERVE THE WEIGHING AND INITIAL TICKETS. RETAIN DAILY TARE WEIGHTS. AT THE POINT OF WEIGHING A DAILY MOISTURE DETERMINATION SHOULD BE MADE FOR PAY WEIGHT CORRECTION. AN INSPECTOR SHOULD BE PRESENT AT POINT OF DELIVERY TO RECEIVE AND INITIAL TICKETS.

*2 IF REQUIRED BY SPECIFICATIONS OR SPECIAL PROVISION.

*3 MAXIMUM 2 PER WEEK.

P.I. = PLASTICITY INDEX

Table 41

Illinois Materials Sampling Guide For Bituminous Concrete Binder and Surface Courses, Base Course Widening, and Bituminous Patching, Class B Mixtures

		SAMPLING FREQUENCY	
MATERIAL	TYPE OF TEST	ACCEPTANCE SAMPLES	INDEPENDENT ASSURANCE SAMPLES
GENERAL AGGREGATE (ALL SIZES) FINE COARSE MINERAL FILLER	GRADATION	SOURCE INSPECTION AND 1 INV TEST ON 1ST DAY, THEN 1/WK. PER PLANT.	1 PER PLANT PER MONTH
ASPHALT	PENETRATION OR VISCOSITY	SOURCE INSPECTION AND 1 INV TEST PER WEEK PER TYPE OF AC PER PLANT *2	NONE
ALL CLASS I MIXTURES	STABILITY *8	NONE	NONE
ALL CLASS I MIXTURES	HOT BIN ANALYSIS	ONE PER DAY *11	NONE
ALL CLASS I MIXTURES	EXTRACTION *9	*10	NONE
CLASS B MIXTURES	EXTRACTION *9	*10	NONE

Table 41

Illinois Materials Sampling Guide For Bituminous Concrete Binder and Surface Courses, Base Course Widening, and Bituminous Patching, Class B Mixtures (continued)

MATERIAL	TYPE OF TEST	SAMPLING FREQUENCY	
		ACCEPTANCE SAMPLES	INDEPENDENT ASSURANCE SAMPLES
SURFACE COURSES & RESURFACING MIXTURES	DENSITY	4 CORES/MIX/DAY *1	1/WEEK *3
	THICKNESS	ONE/DAY	NONE
WIDENING MATERIALS	DENSITY	2 CORES/DAY *1	1/WEEK *3
	THICKNESS	ONE/TYPE/DAY	NONE
PATCHING MIXTURES	DENSITY	2 CORES/TYPE/MIX/DAY *1	1/WEEK *3
	THICKNESS	ONE/TYPE/MIX/DAY	NONE
QUANTITY:			
BATCH PLANTS *4 *12	TRUCK WTS.	CHECK WEIGH 1/WEEK *6	NONE
CONTINUOUS PLANTS *5 *12	TRUCK WTS.	WEIGH EVERY TRUCK *7	NONE
DRIER DRUM PLANTS *5 *12	TRUCK WTS.	WEIGH EVERY TRUCK *7	NONE

*1 DIFFERENT LOCATIONS, ONE CORE EACH. NUCLEAR DENSITY GAUGE MAY BE USED IF SPECIFIED OR PERMITTED BY SPECIAL PROVISION OR STANDARD SPECIFICATIONS.

*2 SAMPLES TO BE TESTED BY THE DISTRICT, OR CONSULTANT, OR SENT TO CENTRAL LABORATORY AT SPRINGFIELD OR CHICAGO AS DIRECTED.

Table 41
Illinois Materials Sampling Guide For Bituminous Concrete Binder and Surface Courses, Base Course Widening, and Bituminous Patching, Class B Mixtures (continued)

MATERIAL	TYPE OF TEST	SAMPLING FREQUENCY	
		ACCEPTANCE SAMPLES	INDEPENDENT ASSURANCE SAMPLES

*3 PROJECT SITE TESTING OBSERVED BY DISTRICT LABORATORY REPRESENTATIVES AND NOTED ON THE REPORT WITH ONE TEST PER PROJECT PERFORMED EARLY IN THE PROJECT WITH EQUIPMENT OTHER THAN THAT USED FOR ACCEPTANCE OR PROCESS CONTROL TESTING.

*4 WHEN MEASUREMENT IS BY WEIGHT AND DELIVERY IS BY TRUCK, AN INSPECTOR SHOULD BE PRESENT AT POINT OF DELIVERY TO RECEIVE AND INITIAL TICKETS.

*5 WHEN MEASUREMENT IS BY WEIGHT AND DELIVERY IS BY TRUCK, AN INSPECTOR SHOULD BE PRESENT TO OBSERVE THE WEIGHING AND INITIAL THE TICKETS. AN INSPECTOR SHOULD BE PRESENT AT POINT OF DELIVERY TO RECEIVE AND INITIAL TICKETS.

*6 REFER TO DOCUMENTATION SECTION OF ILLINOIS CONSTRUCTION MANUAL.

*7 RETAIN DAILY TARE WEIGHTS.

*8 ONE SAMPLE SHALL BE SENT TO THE DISTRICT, OR CONSULTANT OR TO CENTRAL LABORATORY AT SPRINGFIELD OR CHICAGO (AS DIRECTED) ON THE 1ST, 2ND, & 3RD DAY FOR EACH TYPE OF MIXTURE AND AGGREGATE COMBINATIONS THEN ONE PER 6000 TONS.

*9 ONE INVESTIGATION TEST PER 1500 TONS PER MIX. SAMPLES TO BE TESTED BY DISTRICT, OR CONSULTANT, OR SENT TO CENTRAL LABORATORY AT SPRINGFIELD OR CHICAGO.

*10 ACCEPTANCE OF BITUMINOUS CONCRETE IS BASED ON HOT BIN ANALYSIS (COLD FEED FOR DRIER DRUM PLANTS), PLANT ACCEPTANCE AND CALIBRATION, TESTS ON ASPHALT SCALES AND PUMPS DURING PLANT OPERATION, AND PERIODIC WEIGHT CHECKS ON TRUCKS.

*11 NOT REQUIRED IF DAY'S PRODUCTION IS LESS THAN 250 TONS PER MIX. (FOR PROJECTS OF 500 TONS OR MORE - MINIMUM, ONE PER PROJECT.)

*12 IF SURGE BIN IS USED, SCALE INSPECTOR MUST BE PRESENT EXCEPT WHEN AN AUTOMATIC TICKET PRINTER IS USED (MUST AUTOMATICALLY WEIGH AND PRINT BOTH TARE AND LOAD IN POUNDS - CHECK WEIGH 1/WEEK).

Table 42

Illinois Materials Sampling Guide For Portland Cement Concrete Pavement and Base

MATERIAL	TYPE OF TEST	SAMPLING FREQUENCY	
		ACCEPTANCE SAMPLES	INDEPENDENT ASSURANCE SAMPLES
CONCRETE AGGREGATES:			
FINE	GRADATION	SOURCE INSPECTION AND 1 INV TEST PER DAY OF FULL PRODUCTION	1 PER 5 MILES, 2-LANE PAVT.
COARSE*1	GRADATION	SOURCE INSPECTION AND 1 INV TEST PER DAY OF FULL PRODUCTION	1 PER 5 MILS, 2-LANE PAVT.
CEMENT	CEMENT LAB	*2	NONE
REINFORCEMENT STEEL:			
BARS	PHYS. LAB	*6	NONE
FABRIC	PHYS. LAB	SOURCE INSPECTION AND ONE 3-FT. x 3-FT. PIECE, EACH SOURCE PER PROJECT FOR INV TEST	NONE
CONCRETE	SLUMP	1 PER DAY SLIP FORMED, 1 PER 500 FT., FORMED	1 OBSERVATION PER 5 MILS, 2-LANE PAVT.
	AIR	1 PER 250 FT., 2-LANE	1 OBSERVATION PER 5 MILES*5
	AIR	1 PER 100 CY., WIDENING	1 OBSERVATION PER VISIT *5
	STRENGTH	4 BEAMS (30") FIRST DAY 2 PER DAY THEREAFTER *3	1 OBSERVATION PER PROJECT

Table 42

Illinois Materials Sampling Guide For Portland Cement Concrete Pavement and Base (continued)

MATERIAL	TYPE OF TEST	SAMPLING FREQUENCY ACCEPTANCE SAMPLES	SAMPLING FREQUENCY INDEPENDENT ASSURANCE SAMPLES
PAV'T, BASE COURSE WIDENING	THICKNESS	EVERY 250 FT.	NONE
	CORES *4	NONE	NONE

*1 EACH SIZE OR CLASS

*2 REFER TO PORTLAND CEMENT ACCEPTANCE PROCEDURE, CURRENT POLICY MEMORANDUM AND LIST OF QUALIFIED PLANTS

*3 FOR COMPRESSIVE STRENGTH, MAKE 2 CYLINDERS IN LIEU OF EACH BEAM

*4 BY BUREAU OF CONSTRUCTION

*5 CALIBRATE AIR METER WITH STANDARD GAUGE

*6 REFER TO PROCEDURE FOR REINFORCING BAR PRODUCER CERTIFICATION

*7 1 TEST PER 125 FT., IF READY MIX

Table 43

Illinois Materials Sampling Guide For Miscellaneous and Incidental Concrete Items

		SAMPLING FREQUENCY	
MATERIAL	TYPE OF TEST	ACCEPTANCE SAMPLES	INDEPENDENT ASSURANCE SAMPLES
CONCRETE AGGREGATES (ALL SIZES)			
FINE	GRADATION	OCCASIONALLY	NONE
COARSE	GRADATION	OCCASIONALLY	NONE
CONCRETE	AIR	ONE PER DAY	NONE
	SLUMP	OCCASIONALLY	NONE
	STRENGTH	2 BEAMS (30") PER 100 CY PER PLANT	NONE

ALL MATERIALS MUST BE FROM APPROVED SOURCES. ALL CONCRETE MUST COME FROM APPROVED PLANTS AND QUANTITIES REPORTED.

Table 44

Contractor's Process Control Requirements For Structural Concrete in West Virginia

PROCESS CONTROL REQUIREMENT	MINIMUM FREQUENCY
A. PLANT AND TRUCKS	PRIOR TO START OF JOB AND WEEKLY
1. MIXER BLADES	
2. SCALES	
A. TARED	DAILY
B. CALIBRATE	PRIOR TO START OF JOB
C. CHECK CALIBRATION	WEEKLY
3. GAUGES AND METERS - PLANT AND TRUCK	
A. CALIBRATE	YEARLY
B. CHECK CALIBRATION	WEEKLY
4. ADMIXTURE DISPENSER	
A. CALIBRATE	PRIOR TO START OF JOB
B. CHECK OPERATION AND CALIBRATION	DAILY
B. FINE AGGREGATE	
1. FINE AGGREGATE	
A. GRADATION AND $\bar{A}$	DAILY
B. DELETERIOUS SUBSTANCES	DAILY
C. MOISTURE	DAILY
2. COARSE AGGREGATES	
A. GRADATION	DAILY
B. PERCENT PASSING NO. 200 SIEVE	DAILY
C. $\bar{A}$ FOR COMBINED COARSE AGGREGATES, FINE AGGREGATES, AND CEMENT	PER SPECIFICATIONS
D. MOISTURE	DAILY

Table 44

Contractor's Process Control Requirements For Structural Concrete in West Virginia (continued)

PLASTIC CONCRETE

1.	ENTRAINED AIR CONTENT	ONE PER 1/2 DAY OF OPERATION
	BRIDGE SUPERSTRUCTURE	ONE PER BATCH
2.	CONSISTENCY	ONE PER 1/2 DAY OF OPERATION
	BRIDGE SUPERSTRUCTURE	EACH FIFTH BATCH
3.	TEMPERATURE	PER SPECIFICATIONS
4.	YIELD	PER SPECIFICATIONS
5.	COMPRESSIVE STRENGTH**	FOR EACH CLASS CONCRETE DELIVERED AND PLACED ON A CALENDAR DAY FROM A SINGLE SUPPLIER. ONE SET OF 0-100 C.Y. INCLUSIVE AND ONE SET FOR EACH ADDITIONAL 100 C.Y. OR FRACTION THEREOF.

*FREQUENCY FOR PROCESS CONTROL WILL VARY WITH THE SIZE AND TYPE OF AGGREGATE OR MIXTURE AND THE BATCH-TO-BATCH VARIABILITY OF THE ITEM.

**THE USE OF MATERIALS PROCEDURE MP 711.03.31, PREDICTING POTENTIAL STRENGTH OF PORTLAND CEMENT CONCRETE FROM EARLY BREAKS, IS ENCOURAGED DUE TO THE EXTENSIVE AND TIMELY INFORMATION FURNISHED BY THIS METHOD.

Table 45

West Virginia's Guidelines For the Quality Control Testing of Bituminous Concrete

TYPE OF TEST OR ACTION	PLANT SET UP	DURING PRODUCTION
STOCKPILES CONSTRUCTED, SEPARATED HANDLED TO PREVENT SEGREGATION	X	CONSTANT ATTENTION REQUIRED
DETERMINE STOCKPILE AND COLD BIN GRADATIONS	X	WEEKLY (11)
CALCULATE % AGGREGATE FROM EACH BIN, CALIBRATE COLD FEED GATES	X	IF NEEDED (11)
CHECK FEEDER GATE OUTPUT AT GATE SETTING TO BE USED	X(2)	(3)
SELECT SCREEN SIZES (BATCH AND CONTINUOUS PLANTS ONLY)	X	AS NEEDED
DETERMINE HOT BIN GRADATIONS AND CALCULATE COMBINED GRADATION (BATCH & CONTINUOUS PLANTS ONLY)	X	AS NEEDED OR WEEKLY (11)
CALCULATE BATCH WEIGHTS (BATCH PLANTS ONLY)	X	IF NEEDED (11)
CALCULATE HOT BINS, SELECT GATE OPENINGS (CONTINUOUS PLANTS ONLY)	X	IF NEEDED (11)
CHECK GATE OUTPUT AT SETTINGS TO BE USED (CONTINUOUS & DRUM MIX PLANTS ONLY)	X(2)	IF NEEDED OR WEEKLY (11)
CALIBRATE ASPHALT PUMP, CALCULATE SETTING (CONTINUOUS & DRUM MIX PLANTS ONLY)	DURING INSP.	IF NEEDED
CHECK ASPHALT PUMP AT SETTING TO BE USED (CONTINUOUS & DRUM MIX PLANTS ONLY)	X(2)	MONTHLY
RESET ASPHALT PUMP TO COMPENSATE FOR TEMP. CHANGE (CONTINUOUS & DRUM MIX PLANTS ONLY)	X	(4)
CALIBRATE FLUIDOMETER OR METERING PUMP CALCULATE SETTING	DURING INSP.	IF NEEDED

Table 45

West Virginia's Guidelines For the Quality Control Testing of Bituminous Concrete (continued)

TYPE OF TEST OR ACTION	PLANT SET UP	DURING PRODUCTION
CHECK FLUIDOMETER OR METERING PUMP AT SETTING TO BE USED	X(2)	MONTHLY
RESET FLUIDOMETER OR METERING PUMP TO COMPENSATE FOR TEMP. CHANGE	X	(4)
CALCULATE MIXING TIME (CONTINUOUS PLANTS ONLY)	-	IF PADDLE PITCH OR DAM GATE CHANGED
DETERMINE DEGREE OF COATING BY ROSS COUNT	(7)	(7)
CHECK ACCURACY OF HOPPER SUSPENDED AND PLATFORM SCALES	DURING INSP.	(12)
CHECK ACCURACY OF AGGREGATE AND ASPHALT SCALES (BATCH PLANTS ONLY)	DURING INSP.	(12) (12)
CHECK COLD BIN AGGREGATE MOISTURE CONTENT (DRUM MIX PLANTS ONLY)	X	DAILY OR AS NEEDED ADDITIONALLY
CHECK ACCURACY OF FEEDER BELT WEIGHT SENSING UNITS PER MANUFACTURERS RECOMMENDATIONS (DRUM MIX PLANTS ONLY)	X	(12)
CHECK ASPHALT AND FINES DELIVERY SYSTEM IN COATING ZONE. CHECK HEAT SHIELD AND FLIGHTS FOR UNDUE WEAR AND NEEDED REPLACEMENT (DRUM MIX PLANTS ONLY)	X	MONTHLY
CHECK ASPHALT VALVE AND METERING PUMP ACTUATOR (DRUM MIX PLANTS ONLY)	X	DAILY
ADEQUATE HEATED STORAGE FOR LIQUID ASPHALT	X	(13)
GRADATION AND ASPHALT CONTENT (8)(9)	X	MP 401.02.23

Table 45

West Virginia's Guidelines For the Quality Control Testing of Bituminous Concrete (continued)

TYPE OF TEST OR ACTION	PLANT SET UP	DURING PRODUCTION
DETERMINE OPTIMUM ASPHALT CONTENT AND MIX PROPERTIES	X	MP 401.02.22
SUBMIT PLANT MIX FORMULA	SEC. 401.4.1.6	REVISE IF NEEDED SEC. 401.4.1-6
CHECK MIX TEMPERATURE AT PLANT	CALIBRATE THERMOMETER OR PYROMETER	MP 401.02.23 (10) (10A)
CHECK BASE TEMPERATURE	-	SEC.401.5 (10)
CHECK MAT TEMPERATURE	-	SEC.401.14 (10)
CHECK MIX TEMPERATURE IN FIELD	-	MP 401.02.23 (10)
TEST COMPACTED DENSITY OF PAVEMENT	-	SEC 401.14 MP 401.03.20
TRANSPORTATION OF MIXTURE	-	SEC. 401.10
CLEANING AND SWEEPING	-	SEC. 401.11
SPREADING AND FINISHING	-	SEC. 401.13
SURFACE TOLERANCE	-	SEC. 401.16 MP 401.20.1

NOTES - THE TESTS AND ACTIONS DESIGNATED DURING PLANT SET UP ARE RECOMMENDED TO BE MADE BEFORE EACH PAVING MIX IS PRODUCED FOR THE FIRST TIME DURING A CONSTRUCTION SEASON. THE TEST RESULTS ARE USED FOR MAKING PLANT ADJUSTMENTS AND TO SELECT THE PLANT MIX FORMULA. QUALITY CONTROL TEST FREQUENCY DURING PRODUCTION SHOULD BE VARIED IN ACCORDANCE WITH THE DIFFICULTY ENCOUNTERED IN MAINTAINING QUALITY CONTROL. ALL TESTS, CHECKS, RECHECKS, CALIBRATIONS AND CALCULATIONS SHOULD BE DOCUMENTED WHEN PERFORMED, AND MADE AVAILABLE TO THE DEPARTMENT ON REQUEST.

(1) THIS MAY BE OMITTED IF THE COLD FEED HAS ALREADY BEEN CALIBRATED FOR THE SAME TYPE AND SIZE OF AGGREGATE.

(2) USE THIS DATE TO REVISE AND UPDATE THE CALIBRATION CHART.

Table 45

West Virginia's Guidelines For the Quality Control Testing of Bituminous Concrete (continued)

TYPE OF TEST OR ACTION	PLANT SET UP	DURING PRODUCTION

(3) IF A HOT BIN OVERFLOWS OR RUNS DRY, RESET THE COLD FEED TO BALANCE THE HOT BINS.

(4) IF REQUIRED BECAUSE OF A CHANGE IN ASPHALT TEMPERATURE.

(5) THIS MAY BE OMITTED IF THE FEEDER GATE HAS ALREADY BEEN CALIBRATED FOR THE SAME TYPE AND SIZE OF AGGREGATE.

(6) THIS MAY BE OMITTED IF THE PUMP HAS BEEN CALIBRATED FOR THE SAME KIND OF ASPHALT.

(7) THE ROSS COUNT TEST IS REQUIRED ONLY WHEN THE MIXING TIME IS LESS THAN 45 SECONDS.

(8) FOR AUTOMATED PLANTS, A DIGITAL PRINTOUT OF ASPHALT CONTENT MAY BE SUBSTITUTED FOR ASPHALT CONTENT TESTS.

(9) THE DEPARTMENT MAY, AT ITS OPTION, USE THE CONTRACTOR'S TEST RESULTS AS ACCEPTANCE TESTS. WHEN THE DEPARTMENT CONDUCTS ITS OWN ACCEPTANCE TESTS, THE CONTRACTOR MAY USE THE TEST RESULTS FOR QUALITY CONTROL.

(10) PROVIDE AN EMPLOYEE TO MEASURE AND RECORD MIX TEMPERATURES AT LEAST ONCE PER HOUR.

(10-A) PROVIDE RECORDING THERMOMETERS OR PRYOMETERS OR OTHER ACCEPTED RECORDING THERMOMETRIC INSTRUMENTS IN THE LOWER THIRD SECTION OF EACH SURGE OR STORAGE BIN TO RECORD AUTOMATICALLY THE TEMPERATURE OF THE BITUMINOUS CONCRETE. NOTE: UNCOVERED COLLECTING HOPPERS SHALL NOT BE DEEMED TO BE SURGE OR STORAGE BINS FOR PURPOSES OF THIS PROVISION.

(11) CHANGE OF MATERIAL SOURCE.

(12) SENSITIVITY AND 0 BALANCE EACH 1/2 DAY. ACCURACY WEEKLY.

(13) TEMPERATURE RANGE BETWEEN 250 AND 325°F.

APPENDIX B

UNIT TESTING COSTS OBTAINED DURING STATE VISITS

This appendix provides unit testing costs representative of the three SHA's visited. Table 46 provides unit testing costs for the Arizona DOT and Table 47 provides data for the Illinois DOT. As most of the material testing in West Virginia is provided by private laboratories, the unit testing costs in Table 48 were obtained as typical from a private commercial laboratory from that State. As additional testing is sometimes conducted by the State materials laboratory, unit costs were also obtained from the materials laboratory and appear in Table 49.

Table 46

Unit Testing Costs for the Arizona Materials Laboratory

ASPHALT SECTION

Type of Test	Unit Cost
Absolute Viscosity	9.00
Anti-Stripping Agent, Test for (Sand Method)	9.00
Asphalt Emulsion Particle Charge	5.00
Asphaltenes in Petroleum Resin	23.00
Cement Mixing Test	31.50
Chemical Separation of Asphalts (Rostler Analysis)	105.50
Demulsibility	29.50
Distillate (Distillation of Liquid Asphalt)	51.50
Ductility Test	25.50
Flash Point	29.00
Kinematic Viscosity	18.00
Loss by Rolling Thin Film Oven	11.50
Microviscosity Test	47.00
Penetration Test	23.00
Rapid Set Cationics - Uncoated Particles	7.50
Residue (percent by volume)	24.50
Residue from Evaporation - 163°C	27.50
Residue from Vacuum Recovery	19.00
Saybolt-Furol Viscosity	21.50
Settlement	23.00
Sieve Test	19.00
Solubility (in prescribed solvent)	20.00
Specific Gravity of Asphalt	15.00
Spot Test	9.50
Stripping Test - Accelerated Method	25.50
Write-up	7.50
Rotary Vacuum Recovery	23.50
Saturates	105.50
Ash Correction	8.00
Schweyer Viscosity	33.50

Table 46

Unit Testing Costs for the Arizona Materials Laboratory (continued)

BITUMINOUS MIXES

Type of Test	Unit Cost
Bitumen, percent by Soxhlet Extraction	24.00
Bitumen, percent by Vacuum Extraction	26.00
Moisture Determination	25.00
Write-up	8.50
Asphalt Retention Factor (6 samples)	220.50
CEMENT TESTING SECTION	
Air Content	19.00
Compressive Strength (each set of three cubes)	37.50
Fineness - Specific Surface	8.00
Normal Consistency	20.50
Soundness - Autoclave Expansion	28.00
Time of Set	19.00
Write-up and Prepare	16.00
Mortar Strengths-Compressive Strength-2 inches by 4 inches Cylinder	93.50
Organic Impurities	8.00
Soundness - Sodium Sulfate Method	74.00
ASPHALTIC CONCRETE MIX DESIGNS	
Crush Sample	35.00
Composite Grading	16.00
Sample Preparation & Mixing	11.00
Hveem Compaction	10.00
Stability (Hveem)	7.00
Cohesion	2.50

Table 46

Unit Testing Costs for the Arizona Materials Laboratory (continued)

ASPHALTIC CONCRETE MIX DESIGNS (continued)

Type of Test	Unit Cost
Bulk Density	3.50
Voids Analysis	2.50
Maximum Density - Rice Method for 3 flasks	119.00
CKE Values (coarse or fine)	19.00
IMC (Compacting & Breaking each specimen)	12.00
Write-up	10.00
Slurry Seal Design	105.50
Modulus of Resilience	9.50
Marshall Compaction	6.00
Marshall Stability and Flow	4.50
Sawing Core	6.00
A.C.F.C. Design	150.00

CHEMISTRY SECTION

Aggregates - Percent Limestone	46.00
Air Entraining Agents	
Total Solids	7.50
Vinsol Resin	11.50
I.R. Identification	15.50
Barbed Wire - Spelter, Gauge & Barb Spacing	10.50
Bituminous Coated Galvanized Shapes	
Adherence of Coating	25.00
Heat Stability	50.00
Moisture Resistance	25.00
Bridge Pad - Durometer Hardness, Numbers of Fines, etc.	21.50
Cellular Bridge Deck Seal - Compression Set & Cold Flex	17.00

Table 46

Unit Testing Costs for the Arizona Materials Laboratory (continued)

CHEMISTRY SECTION (continued)

Type of Test	Unit Cost
Cement Fly Ash	
Total Alkali (Na20 + K20)	30.50
Complete Analysis (KLNa, Al, Fe, Ca, Mg, Si, S03) Insoluable Residue, Loss on Ignition	198.50
Qualitative Cl Test	46.00
Chain Link Fence Fabric - Spelter & Gauge	10.50
Concrete (Chemical Analysis)	
Cement Content of Hardened Portland Cement Concrete	645.50
Chloride Content of Hardened Concrete	23.00
Curing Compounds	
Percent Non-Volatiles	25.50
Pigment - percent	42.00
Total Solids	28.00
Reflectivity	29.50
Expansion Joint Filler-Compression & Recovery	17.00
Fence Post-wt./ft. hardness & tensile strength	12.50
Glass Beads - Total Test	99.50
Gypsum	
Loss on Ignition	23.00
A.A. Analysis of Ca, Mg	61.00
S04 - Gravimetric Analysis	46.00
[R Scan - Spectrum Analysis	29.50
Lime and Quicklime	
A.A. Analysis for Ca, Mg	61.00
Loss on Ignition	23.00
Sieve Test	7.50
Water Loss kg/m^2	54.00

Table 46

Unit Testing Costs for the Arizona Materials Laboratory (continued)

CHEMISTRY SECTION (continued)

Type of Test	Unit Cost
Paint	
Wt./gal.	4.00
IR Scan	29.50
Viscosity	7.50
Set to Touch	11.50
Dry Hard	7.50
No Pickup Time	4.00
Non-Volatiles	30.50
Hot Water Resistance	7.50
Cold Water Resistance	7.50
Polishing Lubricant	30.50
Retained on a 325 Mesh Screen	30.50
Chemical Analysis of Pigment	47.00
Pozzoliths	
Qualitative Cl Test	23.00
IR Scan	29.50
Total Solids	7.50
Prismatic Reflector - Vacuum Test	18.00
Prismatic Reflector - Specific Brightness	15.50
Roofing Paper - Plies & Weight 1 Roll	14.00
Sulfur (Soil Conditioner) - Solubility in CS2	46.00
Pourable Joint Seal - Pot-life, Non Volatiles & Penetration	71.50
Spelter on Galvanized Articles	10.50
Porcelain Sign Panels - Boiling Citric Acid Test	91.50
Sign Panel - Paint Thickness & Color	5.00
Reflective Sheeting	
Trichromatic Coefficients	18.00

Table 46

Unit Testing Costs for the Arizona Materials Laboratory (continued)

CHEMISTRY SECTION (continued)

Type of Test	Unit Cost
Water Stop - Durometer Hardness, etc.	18.00
Water for Cement	
Total Dissolved Solids	9.00
pH	7.50
A.A. Analysis for:	
Cl	61.00
S04	61.00
Ca	46.00
Mg	46.00
Na	46.00
K	46.00
Fe	46.00
Write-up - Satisfactory for Intended Use	8.50
Rockwell Hardness	6.50

Table 46

Unit Testing Costs for the Arizona Materials Laboratory (continued)

SOIL AND AGGREGATE SECTION

Type of Test	Unit Cost
Abrasion Test	23.50
Cement Treated Base Design (charge for each change of percent cement and/or each change or aggregate)	110.50
Coarse Sieve Test	6.00
Composite Grading or Average Grading	6.00
Crush Sample (set up and run through crusher)	24.50
Expansive Pressure of Soil	33.00
Fine Sieve/Elutriation Test	16.50
Fractured Faces Determination	27.50
Maximum Density, Rich Method or Proctor Mold	90.50
Permeability Test for Soil	66.50
Plasticity Index Test	13.00
Pulverize Soil Sample	8.00
"R" Value Test	166.50
Resistivity and pH	32.50
Sand Equivalent Test	8.00
Shear Strength of Soil (Single Sheet)	22.00
Soil Consolidation Test	177.00
Soil Hydrometer Analysis	18.00
Soil - Moisture Content	8.00
Soil - Swell Percent	31.50
pH & Soluble Salts in Soil	8.00
Washed P.I. Test	23.00
Write-up	7.00
Flakiness Index Test	16.50
Coarse Specific Gravity and Absorption	13.50
Fine Specific Gravity and Absorption	50.50

Table 46

Unit Testing Costs for the Arizona Materials Laboratory (continued)

TESTING MACHINE SECTION

Type of Test	Unit Cost
Concrete Blocks, Bricks, Sewer Bricks, Manhole Bricks	
Absorption Test	24.50
Measure, Cap and Break	33.00
Concrete and Ceramic Break	
Absorption Test	12.50
Inspect, Compress, and Stamp	32.50
Concrete Cores	
Saw, Cap and Break	8.00
Measure Only	16.50
Concrete Cylinders	8.00
Pre-Stress Concrete Cable Strand	15.00
Reinforcing Steel	16.50
Reinforcing Wire Mesh (Cut, Measure, Break)	12.00
Strain Cable for Wire Fencing	12.00
Swiss Hammer Impact Test on Concrete	24.50
Write-up	8.00
Concrete Mix Design - Weigh, Mix Fabricate, Calculate	107.50
PVC Pipe & Conduit - Measure, Cap, Break & Compress	24.50
Time of Set Concrete Admixture	263.00
Epoxy Testing (complete)	131.50

Table 47

Unit Testing Costs for the Illinois Materials Laboratory

Material Group	Unit of Measure	Quantities Tested in in 1981	Cost for Labor Reported in 1981	Cost of Materials Testing per Unit of Measure
Aggregates	Tons	12,157,564	1,476,956.09	.1215
Bituminous Materials	Tons	408,240	901,789.26	1.5720
	Gals.	39,699,608		.0066
Castings	Lbs.	5,304.011	12,126.64	.0023
Concrete Masonry Units	Each	87,419	70,680.29	.8085
Concrete Bridge Beams	Each	7,817	314,652.53	40.2523
Electrical Cable, Conduit	Lin. Ft.	3,726,878	34,863.87	.0094
Standards, Light & Signal	Each	8,545	1,605.57	.1879
Lumber and Timber	FBM	64,013	2,565.23	.0401
Piling	Lin. Ft.	559,809	25,924.31	.0463
Portland Cement	CWT	5,674.614	245,309.94	.0432
Paints	Gals.	871,899	97,522.31	.1119
Chemicals	Gals.	151,142	5,634.84	.0373
Pipe, Corrugated Steel	Lin. Ft.	221,776	26,061.06	.1175
Pipe, Concrete	Lin. Ft.	572,149	110,603.27	.1933
Pipe, Plastic	Lin. Ft.	965,730	4,435.78	.0046
Pipe, Clay	Lin. Ft.	11,175	2,243.79	.2008
Pipe, Cast Iron	Lin. Ft.	22,079	4,043.64	.1831
Pipe, Corrugated Aluminum	Lin. Ft.	1,807	103.78	.0574
Pipe Bituminous Fibre	Lin. Ft.	332,747	2,464.59	.0074
Bridge Rail	Lin. Ft.	95,742	10,776.59	.1126
Guard Rail	Lin. Ft.	579,781	10,798.75	.0186
Fencing	Lin. Ft.	590,620	10,088.36	.0171
Steel, Reinforcing	Lbs.	49,420,346	137,818.36	.0028
Steel, Structural	Lbs.	21,855,830	110,355.55	.0050
Steel, Miscellaneous	Lbs.	1,590,491	25,478.18	.0160
			4,012,187.00	
Concrete, Portland Cement	Cu. Yds.	862,101	775,576.00	.8996

Table 48

Unit Testing Costs for a Private Materials Laboratory in West Virginia

SOILS SECTION

Type of Test	Unit Cost
SOIL PROPERTY IDENTIFICATION & UNIFIED or AASHTO SOIL CLASSIFICATION including sample preparation, sieve analysis, Atterberg limits, specific gravity, natural density and moisture content	90.00
MOISTURE CONTENT, Jar Sample (ASTM D-2116)	5.50
NATURAL DENSITY & MOISTURE CONTENT (Undisturbed Sample)	26.50
SPECIFIC GRAVITY (ASTM D-854)	26.50
pH TEST	12.00
SOIL RESISTIVITY (CALIF C-643)	60.00
ATTERBERG LIMITS (ASTM D-423 and 424)	30.00
SHRINKAGE LIMIT (ASTM D-427)	35.00
SIEVE ANALYSIS (Dry Sample)	25.00
SIEVE ANALYSIS (With No. 200 Wash), Sample Less than 2.0 kg	30.00
SIEVE ANALYSIS (With No. 200 Wash), Sample More than 2.0 kg	50.00
Percent Finer than No. 200 SIEVE (Washed) (ASTM D-1140)	17.50
HYDROMETER ANALYSIS & SPECIFIC GRAVITY on soil passing No. 10 Sieve (ASTM D-422)	85.00
RELATIVE DENSITY for Cohesionless Soils (ASTM D-2049-69)	125.00
PERMEABILITY: (a) including back pressure saturation, per test	125.00
(b) to remold sample, per test	15.00
SWELL TEST	125.00
PERCENT ORGANIC by Loss on ignition	12.50
UNCONFINED COMPRESSION, SOIL (ASTM D-2166)	
(a) Undisturbed Sample	40.00
(b) With Stress Strain Curve, Add	20.00

Table 48

Unit Testing Costs for a Private Materials
Laboratory in West Virginia (continued)

SOILS SECTION (continued)

Type of Test		Unit Cost
DIRECT SHEAR (ASTM D-3080), UNDISTURBED SAMPLE (2.5 inch diameter)		
(a) Each normal pressure		65.00
(b) Additional Cycles for Residual Strength, per cycle		22.00
LARGE-SCALE DIRECT SHEAR TEST for material up to 4-inch particle size,		
3 ft x 3 ft sample, per normal pressure		850.00
UNCONSOLIDATED-UNDRAINED TRIAXIAL TEST (ASTM D-2850), each lateral pressure, undisturbed		70.00
CONSOLIDATED-UNDRAINED TRIAXIAL TESTS, each lateral pressure, undisturbed, with Pore Pressure Measurement		135.00
CONSOLIDATED-DRAINED TRIAXIAL TEST, each lateral pressure, undisturbed		135.00
CONSOLIDATION TEST (ASTM D-2435) with up to seven load increments		180.00
(a) additional load increments, each		15.00
CYCLIC TRIAXIAL TEST (ASTM STP 654), each lateral pressure		350.00
REMOLDED SAMPLES FOR Items L-17 thru L-24, additional cost per sample		15.00
STANDARD PROCTOR (ASTM D-698):	4-inch mold	75.00
	6-inch mold	85.00
MODIFIED PROCTOR (ASTM D-1557):	4-inch mold	85.00
	6-inch mold	95.00
SOIL CEMENT PROCTOR (ASTM D-558)		200.00
CORPS OF ENGINEERS, CE-55, 6-inch mold		100.00
CBR, @ Optimum Moisture Content (incl. Compaction Test), ASTM D-1883 or VTM-8)		200.00
CBR, Corps of Engineers Method		850.00

Table 48

Unit Testing Costs for a Private Materials Laboratory in West Virginia (continued)

AGGREGATE SECTION

Type of Test	Unit Cost
SULFATE SOUNDNESS, SODIUM OR MAGNESIUM (ASTM C-88)	
a. Initial five cycles	140.00
b. Additional five cycles without loss determination	50.00
c. Additional five cycles with loss determination	80.00
pH DETERMINATION, each	20.00
POTENTIAL ALKALI REACTIVITY (Chemical), ASTM C-289 each	120.00
POTENTIAL ALKALI REACTIVITY(Mortar Bar), ASTM C-227 each	450.00
PETROGRAPHIC EXAMINATION, ASTM C-295, minimum charge	600.00
COMPLETE ASTM C-330 (except freeze-thaw tests) for lightweight aggregates	450.00
SCRATCH HARDNESS, ASTM C-851, each	100.00
FLAT AND ELONGATED PARTICLES, CRD C-119, each	100.00
BASIC ANALYSIS OF AGGREGATES, ASTM C-33,	
a. Fine Aggregate, per sample	350.00
b. Coarse Aggregate, per sample	425.00
SIEVE ANALYSIS	
a. Dry (ASTM C-136), each	30.00
b. With percent finer than No. 200 Sieve, (ASTM C-136 and C-117), each	45.00
c. Percent finer than No. 200 Sieve only (ASTM C-117), each	25.00
SPECIFIC GRAVITY AND ABSORPTION	
a. Fine Aggregate (ASTM C-128)	
(1) Specific gravity and absorption, each	50.00
(2) Either test separately, each	40.00
b. Coarse Aggregate (ASTM C-127)	
(1) Specific gravity and absorption, each	35.00
(2) Either test separately, each	30.00

Table 48

Unit Testing Costs for a Private Materials
Laboratory in West Virginia (continued)

AGGREGATE SECTION (continued)

Type of Test	Unit Cost
UNIT WEIGHT (ASTM C-29)	30.00
ORGANIC IMPURITIES, COLORIMETRIC (ASTM C-40)	22.00
EFFECT OF ORGANIC IMPURITIES (ASTM C-87)	180.00
CLAY LUMPS IN AGGREGATE (AASHTO T-112)	50.00
SOFT PARTICLES (ASTM C-235)	60.00
FRIABLE PARTICLES (ASTM C_142)	50.00
ABRASION (LOS ANGLES), (ASTM C-131)	
a. 500 continuous cycles, no sample preparation	140.00
b. Loss after additional 100 or 200 cycles, each measurement	65.00
STAINING TEST, lightweight aggregate visual only (ASTM C-641)	70.00
POPOUT, lightweight aggregate, visual only (ASTM C-330)	50.00
LOSS ON IGNITION, lightweight aggregate, (ASTM C-330, C-331)	50.00
MOISTURE CONTENT (ASTM C-566), each	20.00
SULFATE SOUNDNESS, SODIUM OR MAGNESIUM (ASTM C-88)	
a. Initial five cycles	140.00
b. Additional five cycles without loss determination	50.00
c. Additional five cycles with loss determinations	80.00

Table 48

Unit Testing Costs for a Private Materials Laboratory in West Virginia (continued)

ASPHALT AND ASPHALTIC MATERIALS SECTION

Type of Test	Unit Cost
Bitumen content of paving mixtures by centrifuge method, AASHTO, T-164	65.00
Density of compressed bituminous mixtures, AASHTO, T-166	25.00
Stripping test for bitumen aggregate mixtures, AASHTO, T-182	75.00
Asphalt or Tar for Waterproofing, AASHTO, M-115 or M-118	136.50
Primer for Waterproofing, AASHTO, M-116 or M-121	82.00
Asphalt, Penetration Grade	
AASHTO, T-49	50.00
AASHTO, T-55	70.00
AASHTO, T-40	50.00
AASHTO, T-44	50.00
AASHTO, T-51	50.00
AASHTO, T-48	50.00
AASHTO, T-179	50.00
AASHTO, T-102	50.00
AASHTO, M-20 complete series	223.00

ASPHALT LIQUID

AASHTO, M-81 Cut-back grades	300.00
M-140 Emulsions	327.00
M-52 Without Sulfonation	240.00
M-52 Including Sulfonation	

Table 48

Unit Testing Costs for a Private Materials Laboratory in West Virginia (continued)

Type of Test	Unit Cost
ASPHALT MIX DESIGNS	
ASTM, D-1539-65 Plastic Flow Resistance to, of bituminous mixtures using marshall apparatus	500.00
STEEL SECTION	
AASHTO, M-31, No. 4 through No. 11 bars, per test, yield point, ultimate strength, Deformation and Elongation	41.00
Certifications of welders, including bend and tensile tests, including machine shop work and test plates - 3/8" plate	356.00 to 432.00
1" plate	388.00 to 460.00
Bend Test, reinforcing bars, per test	19.25
Bend Test, on welded coupon, per test	15.75
Tensile test on welded coupon, per test	
3/8" plate	33.00 to 54.00
1" plate	38.50 to 59.50
Brinell hardness of bolt, each	16.00
Proof load on bolts, each	16.70
Ultimate breaking load on bolts, each	12.85
Rockwell test, washers each	18.45
Proof load on nuts, each	8.00

The above rates on bolts, nuts and washers do not include machining costs to prepare test specimens.

Table 48

Unit Testing Costs for a Private Materials Laboratory in West Virginia (continued)

CONCRETE SECTION

Type of Test	Unit Cost
COMPRESSIVE STRENGTH OF CONCRETE	
Test Cylinders, (ASTM C-39), each	7.50
Reserves not tested, each	7.50
COMPRESSIVE STRENGTH OF CONCRETE CORES (ASTM C-42)	
Including preparation, each	25.00
SPLITTING TENSILE TEST (ASTM C-496), each	20.00
SPECIFIC GRAVITY, ABSORPTION AND/OR AIR VOID CONTENT (ASTM C-642, C-497)	
Minimum charge	50.00
If more than one sample, each	30.00
CEMENT CONTENT (ASTM C-85), each	250.00
pH and CHLORIDE DETERMINATION	78.00
UNIT WEIGHT OF STRUCTURAL LIGHTWEIGHT CONCRETE, Oven or Air Dried, (ASTM C-567, C-573, C-405, C-332), set of three (3) specimens, minimum	75.00
FLEXURAL STRENGTH TEST (ASTM C-78), each	15.00
LENGTH CHANGE OF DRILLED SPECIMENS (ASTM C-341), set of three (3) specimens, minimum	100.00
MOISTURE CONDITION BY RELATIVE HUMIDITY METHOD (ASTM C-427), per sample	200.00
PETROGRAPHIC EXAMINATION, dependent on type of sample, nature of problems, information required, etc., minimum charge	400.00
MODULUS OF ELASTICITY, ASTM C-469, each	200.00
CYLINDER MOLDS, per case of 24	40.00

*Specimens and/or materials are to be delivered prepaid ready-to-test. Any sampled preparation required prior to testing such as sawing, grinding, polishing, etc., plus all report writing, interpretation, etc., is additional and will be charged at $40.00 per man-hour regular time (minimum charge $40.00).

Table 48

Unit Testing Costs for a Private Materials Laboratory in West Virginia (continued)

CONCRETE, MIX DESIGNS AND VERIFICATIONS*

Type of Test	Unit Cost
INTIAL MIX VERIFICATION, including sieve analysis of fine and coarse aggregate and six (6) confirmatory strength tests, per mix	200.00
ADDITIONAL MIXES, same aggregate, six (6) confirmatory strength tests, per mix	160.00
MIX, no strength tests and no aggregate testing	125.00
MIX DESIGN, including gradation, unit weight, specific gravity and absorption of aggregates and a series of mixes at three cement contents, each design	600.00
Consultation, per hour	50.00
PACKAGED CONCRETE MIXTURES (ASTM C-387)	100.00
For mixes involving lightweight aggregates, additional cost, per mix	40.00
For using six (6) confirmatory flexural strength tests, additional cost, per mix	100.00
ASTM C-494, TYPES A, B, C, D, and E, not including Resistance to Freezing and Thawing	5000.00
ASTM C-260, AIR ENTRAINING ADMIXTURES, not including Resistance to Freezing and Thawing	5000.00

* Specimens and/or materials are to be delivered prepaid ready-to-test. Any sample preparation required prior to testing such as sawing, grinding, polishing, etc., plus all report writing, interpretation, etc., is additional and will be charged at $40.00 per man-hour, regular time (minimum charge $40.00).

Table 48

Unit Testing Costs for a Private Materials Laboratory in West Virginia (continued)

Unit Fees

Concrete, Plastic*

Time of Set, PROCTOR PENETROMETER (ASTM C-403) not including mixes:

No. of Test Specimens	Base Coat	Plus $35.00 per hour that tests run over hours below
1	$ 80.00	8
2	$ 100.00	6
3	$ 125.00	4
4	$ 160.00	2
5	$ 225.00	1
6	$ 260.00	1

BLEEDING OF CONCRETE (ASTM C-232), not including mix, each test	$ 50.00
LENGTH CHANGE OF CONCRETE (ASTM C-157), includes molding specimens and five (5) sets of readings, not including mix	$125.00
SHRINKAGE (ASTM C-330, C-331), not including mix	$ 75.00

*If a special mix is required, it will be charged in accordance with Item MC-3 at $80.00 each. Specimens and/or materials are to be delivered prepaid ready-to-test. Any sample preparation required prior to testing such as sawing, grinding, polishing, etc., plus all report writing, interpretation, etc., is additional and will be charged at $40.00 per man-hour, regular time (minimum charge $40.00).

Table 48

Unit Testing Costs for a Private Materials Laboratory in West Virginia (continued)

	Unit Fees
Portland Cement*	
COMPRESSIVE STRENGTH, including mixes, 2 x 2 cubes (ASTM C-109)	
a. Set of six (6) specimens	$150.00
b. Set of nine (9) specimens	$200.00
An additional charge of $35.00 per hour is required for work performed on weekends or holiday.	
TENSILE STRENGTH (ASTM C-190), including mix, per set of three (3) briquets, minimum	$ 70.00
COMPLETE STANDARD PHYSICAL TESTING, ASTM C-150, each	$300.00
COMPLETE STANDARD CHEMICAL TESTING, ASTM C-150, each	$200.00

*Specimens and/or materials are to be delivered prepaid ready-to-test. Any sample preparation required prior to testing such as sawing, grinding, polishing, etc., is additional and will be charged at $40.00 per man-hour, regular time (minimum charge $40.00).

Table 48

Unit Testing Costs for a Private Materials Laboratory in West Virginia (continued)

Mortar and Grouts*	Unit Fees
COMPRESSIVE STRENGTH, including mixes, 2 x 2 cubes, 1 x 2 or 2 x 4 cylinders, (ASTM C-270, C-91, C-476, C-579)	
a. Set of six (6) specimens	$150.00
b. Set of nine (9) specimens	$200.00
COMPRESSIVE STRENGTH AND MODULUS OF ELASTICITY, including mix, (ASTM C-348, C-580)	
a. Set of six (6) specimens	$300.00
b. Set of nine (9) specimens	$450.00
FLEXURAL STRENGTH AND MODULUS OF ELASTICITY, including mix, (ASTM C-348, C-580)	
a. Set of six (6) specimens	$300.00
b. Set of nine (9) specimens	$450.00
BOND STRENGTH (ASTM C-321), including mix brick specimens delivered to our laboratory (ASTM C-321)	
a. Set of six (6) specimens	$300.00
b. Set of nine (9) specimens	$450.00
SHRINKAGE AND COEFFICIENT OF THERMAL EXPANSION (ASTM C-531), including mix, set of four (4) specimens	$300.00
TENSILE STRENGTH (ASTM C-190), including mix per set of three (3) briquets	$ 80.00
TENSILE STRENGTH (ASTM C-190), on samples delivered and ready-to-test, each	$ 20.00

Table 48

Unit Testing Costs for a Private Materials Laboratory in West Virginia (continued)

	Unit Fees
Mortar and Grouts* (continued)	
WATER RETENTION (Flow after suction) (ASTM C-91), per mix	$ 75.00
AIR CONTENT AND INITIAL FLOW (ASTM C-185), per mix	$ 50.00
PACKAGED MORTAR MIXTURES (ASTM C-287)	$120.00
Concrete and/or Clay Pipe*	
ABSORPTION (ASTM C-301, C-497), minimum charge	$ 50.00
If more than one (1) sample, each	$ 30.00
EXTERNAL LOAD CRUSHING STRENGTH (ASTM C-301, C-497), 3-edge, 5-edge or sand bearing, one-foot length, minimum charge	$150.00

Additional charge for use of forklift, cutting, etc. will be charged at $60.00 per hour, regular time (minimum charge $60.00).

*Specimens and/or materials are to be delivered prepaid ready-to-test. Any sample preparation required prior to testing such as sawing, grinding, polishing, etc., plus all report writing, interpretation, etc., is additional and will be charged at $40.00 per man-hour, regular time (minimum charge $40.00).

Table 49

Unit Costs for West Virginia Materials Laboratory

Type of Test	Unit Cost
Gradation (Each test)	$ 75.00
In-Place Density (5 Tests)	375.00
Coring (Each Core)	75.00
Pavement Smoothness (Per 5000 lane-feet)	500.00
Marshall Mix Design	500.00

APPENDIX C

INPUT GUIDE FOR PROGRAM "COSTOP1"

PROGRAM DESCRIPTION

"COSTOP1" is a computer program which simulates the appearance and growth of pavement distress with age and number of vehicles, determines a time at which one or more failure criteria are exceeded, and evaluates the economic results of such failure. These results are tied to a testing program for materials used in construction by varying the value, or the standard deviation, or both of a test result as a function of the number of tests performed. The program can analyze a large number of "testing programs" and perform a differential benefit/cost analysis on the results to indicate to the user the most beneficial test program, subject to the assumptions and distress models used.

COSTOP1 uses distress models provided by the user in the form of FORTRAN function subprograms, examples of which will be given later. Each function has a name FUNCnn, where nn is an integer from 1 to 20. This enables the program to select and evaluate the correct function based on the input data.

The program requires the following types of information to perform the simulations and the associated economic analyses (the exact combination needed for any particular analysis depends on the specific distresses being modeled):

Traffic variables:	ADT, percent trucks, 18 kip ESAL per truck, rate of growth - to provide quantities (like total vehicles to date, total ESAL to date) which are often used in distress models.

Material variables:	Asphalt concrete variables (e.g., percent asphalt, percent voids), portland cement concrete variables (aggregate types and quantity) base and subgrade variables (density, moisture content, gradation).
Functions (as needed):	A. Relations between material variables and inputs to distress models. B. Distress models
Testing program variables:	Identification of the material parameter under test, the cost of such testing, the numbers of tests to be performed under different testing programs, and information relating the material parameter to the number of tests.
Economic variables:	The cost of initial construction and of annual maintenance; the user costs associated with normal use and with rehabilitation. The interest rate to be used in the analysis. The width of pavement.
Control variables:	The maximum time a simulation will run, and the age at which detailed simulation should begin.
Rehabilitation variables:	Types of rehabilitation to be considered, their cost in some convenient units, values of the different distress types which trigger rehabilitation, and information relating the type of rehabilitation selected to the levels of the various distresses present when rehabilitation is needed.

For a specific test program, COSTOP1 determines the adjusted values of the tested parameters based on the input values and the number of tests. For each year considered it then obtains the values and coefficients of variation for each function (some of which can depend on functions already evaluated; the order of evaluation is significant) and compares those results representing distress values to input critical values to see if any critical value has been attained or passed. If no distress has occurred, it proceeds to the next year; if one or more has been exceeded, a more precise time of failure is determined by interpolation and a rehabilitation is prescribed.

All costs are reduced to a uniform annual cost basis, and the results saved. After all test programs have been evaluated, these results are sorted by testing cost and compared using a differential benefit/cost analysis. Up to fifty programs which have differential benefit/cost ratios greater than one (implying that an additional dollar of testing cost returns more than one dollar in economic benefit) are presented for examination by the user.

Although the program runs as a single unit, the input data for COSTOP1 is of two types: distress/rehabilitation data and economic data. The purpose of the distress/rehabilitation data is to allow the program to simulate the deterioration of a roadway with time to a condition such that rehabilitation is required. The type and rate of deterioration, in terms of distress development and/or performance loss, are determined by user-provided functions. These functions have to be mathematical relationships or series of relationships that express distress or performance as a function of quality control tests results as well as other items (e.g., traffic, environment). The simulation continues until a specified value is reached for one or more distresses, at which time rehabilitation occurs. Based on the severity and extent of the predicted distresses, a unique rehabilitation type is recommended. Thus, the main output of the simulation routine is the time to failure and the type of rehabilitation required.

Input data for the distress simulation consists of ten card types, forms for which are subsequently presented in Attachment C.2 at the end of this appendix. Input on the cards consists of variables which provide information pertaining to distress or performance relationships, rehabilitation criteria and alternatives, quality control test results, traffic information, and simulation run control.

The purpose of the economic data is to allow the program to determine the most cost-effective quality control testing scheme. Each testing scheme (hereafter termed alternative) has a unique cost with which it is associated. The primary difference among alternatives is the frequency of testing. For example, one alternative could require five tests per unit of material, whereas another might require only one. Thus, the former alternative would be more expensive than the latter.

The output from the distress/rehabilitation simulation that is used as input to the economic analysis is: (1) time to reach rehabilitation and (2) type of rehabilitation used. The time to rehabilitation is required for use in compound interest formulas to determine the equivalent annual cost. The type of rehabilitation is required because each rehabilitation scheme possesses a unique cost which affects the cost calculations.

The economic analysis requires as input the following types of costs:

(1) testing,
(2) construction,
(3) rehabilitation,
(4) user (associated with time and vehicle cost),
(5) user (associated with rehabilitation), and
(6) maintenance.

For each alternative, construction, maintenance, user, and rehabilitation costs are combined into an equivalent uniform annual cost over the life of the pavement. Similarly, testing costs are converted to equivalent uniform annual costs. Alternatives are then arrayed in order of increasing (annual) testing costs. A challenger-defender approach is then used to directly compare alternatives. A benefit-cost ratio is computed between the first two alternatives:

$$B/C = \frac{A_{Td} - A_{Tc}}{A_{tc} - A_{td}}$$

where, A_{tc} = equivalent annual costs of testing for challenger,

A_{td} = equivalent annual costs of testing for defender,

A_{Td} = sum of other equivalent annual costs for defender, and

A_{Tc} = sum of other equivalent annual costs for challenger.

If the B/C ratio is greater than one, the challenger becomes the defender to the next challenging alternative. Conversely, if its B/C ratio is less than one, the defender remains a defender to the next challenger. This procedure continues until all challengers are examined and one defender remains. Input data for this portion of the program consists of five card types, the forms for which are subsequently presented.

DATA INPUT

An abbreviated input guide is presented in Attachment C.1, which serves as a concise summary of the input data outlined in the following sections. Attachment C.2 contains the card forms for required input data.

Card Type A1 - This card provides an identification for the problem being run.

> RUNID - An eighty character verbal description listing origin of input variables is input on this card.

Card Type A2 - These cards are a verbal run description.

> RUNDES (2 cards required) - these cards can be used to provide additional information about the problem, such as the origin of the data.

Card Type B1 - The purpose of these cards is to provide information pertaining to the dependent and independent variables and the relationship (function) used to calculate distress or performance. Usually, dependent variables are some measure of distress or performance and independent variables are quality control test results used in the relationship to predict distress or performance. Dependent variables can also be intermediate results required for the distress calculations.

> NAM (ID) - This variable is an abbreviated identifier of the input variable or function.

> ID - This variable is a unique identification number assigned to the variable or function.

VAL (ID) - This is the input mean value of an independent variable used to predict distress. If ID is a function this variable is left blank.

CV (ID) This variable is the coefficient of variation of the input independent variable. If ID is a function this variable is left blank.

IFN (ID) - If ID is a function, this is an index number to identify the user-provided Fortran subprogram used to calculate the function. This variable is entered as a negative number if the user desires to calculate the required value only at the start of the analysis period. If ID is an independent variable, IFN is left blank.

IDEC (ID) - This is a switch to indicate whether the associated function increases with time (IDEC = 0) or decreases with time (IDEC = 1). If ID is an independent variable, IDEC is left blank.

NQ (ID) - This input variable represents the number of independent variables or previously calculated functions upon which function ID depends. If ID is an independent variable, NQ is left blank. At present, NQ is restricted to 10 or less. If NQ is entered as a negative number, no derivatives of the function are taken, and the coefficient of variation of the function value remains zero.

IQ (1-10, ID) - These variables are the identification numbers of input variables for previously calculated functions upon which ID depends. If ID is an independent variable, IQ is left blank.

As a simple example, assume that a relationship exists such that timewise rutting in asphalt concrete as a function of time is dependent on Hveem stability, density, asphalt content, percent crushed aggregate, and number of 18-kip equivalent axle loads. Table 50 lists the input data and the proper coding.

Note that since stability, density, asphalt content, crushed stone fraction, and 18-kip EAL per year are independent variables in the rutting relationship, IFN, NQ, and IQ are left blank. Similarly, since cumulative EAL and rutting are the dependent variables in the functions, VAL and CV are left blank. In addition, index numbers (arbitrarily assigned in this example) for the cumulative EAL and rutting functions were assigned for IFN; a positive value indicates computation of cumulative EAL and rutting is required at each time during the analysis period. Values for variables NQ and IQ were also required for RUT since it depends on the four independent variables and one function specified.

Card Type B2 - This card is used to provide more complete information pertaining to the variables and functions on cards B1.

NM - This is a dummy variable, and is the same as used for NAM (ID) on cards B1.

ID - This is the same variable as used on cards B1.

UNITS (J, ID) This provides a label for the units on independent and dependent variables listed on cards B1.

Table 50

Sample Input and Coding Information For Card Type B1

Input assumptions:

Rutting with time = F (Hveem stability, density, asphalt content, crushed stone fraction, number of 18-kip axle loads)

Calculate rutting at each time in analysis period.

Index number of rutting relationship = 18

Variable	NAM	ID	VAL	CV	IFN	IDEC	NQ	IQ
Hveem Stability	HSTAB	11	36.	.05	-	-	-	-
Density	DEN	12	142.	.02	-	-	-	-
Asphalt Content	ACONT	13	5.2	.06	-	-	-	-
Crushed Stone Fraction	CSF	14	65.4	.12	-	-	-	-
18-kip EAL's/Year	EAL	11	100,000.	.10	-	-	-	-
Cumulative EAL	CUMEAL	5			3	0	1	1
Rutting	RUT	16	-	-	5	0	5	1-5

Note: The program assumes for output labeling purposes that variables and functions with ID < 11 are associated in some way with traffic variables (e.g., the computation of equivalent axle loads.)

LNAME (J, ID) - This input permits a longer (up to 30 characters) description of the variables listed on cards B1. For example, the description of independent variable CSF in Table 50 would be "crushed stone fraction."

Card Type C1 - This card inputs information controlling the execution of the program: the number of years the simulation is to run, the number of variables to be varied during the simulation, and the first year for which distress is to be calculated.

NYR - The maximum number of years for which the simulation will continue in the absence of required rehabilitation.

NTT - The number of independent variables to be included in the test program; also the number of test types, since one variable can be affected by only one test in this program (NTT less than or equal to 5).

FY - The first year for which distress is to be calculated. It is useful if one knows from previous runs that failure will not occur before a certain time. May be used in this way as long as the value obtained for distress at a particular time does not depend on values of distress calculated for a previous time. If left blank, defaults to 1.

Card Type D1 - This card gives certain information about the testing program.

IDT - The ID of the independent variable affected by testing.

NTS - The number of test programs (less than or equal to 10) to be simulated for variable IDT.

NTEST (I) - The number of tests/lane mile in each of the NTS test programs.

Card Type D2 - This card gives more information about the particular test being studied.

ICONF - A confidence level (used for the statistical approach). Given an observed mean value and coefficient of variation then for a specific number of tests the variable is set to a new value such that there is an ICONF percent probability that the true mean (the mean of the population from which the sample number of tests was taken) lies below (ICONF > 0) or above (ICONF < 0) the new value.

TESTC - The cost of performing one test on variable IDT, in dollars.

AT, BT - The coefficient and exponent in the assumed relation for mean value of variable IDT as a function of number of tests, from contractor variation.

CT, DT - The coefficient and exponent in the assumed relation for standard deviation of variable IDT as a function of number of tests, from contractor variation.

AT, BT, CT, and DT are used only if ICONF is input as zero or left blank.

Card Type E1 - The purpose of this card is to provide costs (construction, maintenance, user, etc.) for the economic analysis.

CONSTC - The cost of initial construction for the project under study (must be the same for all alternatives). This cost is entered in thousands of dollars per lane mile.

USRREC - The additional costs incurred by roadway users during rehabilitation operations (due to detours, etc.) in thousands of dollars per lane mile.

ANMNTC - Uniform annual maintenance costs, in thousands of dollars per lane mile.

ANUSRC - Uniform annual road user costs, in thousands of dollars per lane mile (fuel, time, vehicle maintenance, etc.)

The two user costs of course depend on the level of traffic, as they are not entered in units of dollars per vehicle mile.

Card Type E2 - This card contains lane width and interest rate. Lane width is used along with rehabilitation option unit cost (see variable RCOST) to calculate rehabilitation costs. The input interest rate is used in compound interest formulas to convert present and future costs to equivalent uniform annual costs.

WIDTH - This variable is the single lane width for the project under consideration.

PCTINT - This variable is the interest rate in percent per year to be used in the economic analysis.

Card Type F1 - This provides information pertaining to the mathematical relationships used to calculate distress or performance and criteria used to determine initiation of rehabilitation. It is usually best to construct a table such as that shown in Table 51, which lists distresses considered, rehabilitation trigger values, and decision criteria levels.

ICC (1, I) - The number assigned to this variable identifies the appropriate function used to calculate distress. This identification number remains constant for a given function throughout an input file.

ICC (2, I) - This variable is the number of distress criteria which are to be considered when monitoring development of distress.

ICC (3, I) - This variable conveys which distress criterion (severity and/or extent of distress) is to be used to initiate rehabilitation. These criteria are listed in order to subsequent spaces on this card.

XCC (1, 1-4) and
XCC (2, 1-4) - These paired variables are the severity and extent, respectively, of the calculated distresses used to determine initiation of rehabilitation. Four pairs are allowed for a given distress type. Distress severity is usually a value such that when this value of distress is achieved, rehabilitation occurs. Distress extent is most often listed as percent roadway area that experiences distress. In certain cases, both values are required. For example, a rutting criterion could be

Table 51
Example of Distress Criteria and Levels Used to Determine Rehabilitation Requirements

No.	Distress	Trigger Value	Decision Criterion Levels	Number of Distress Intervals
1	Fatigue Cracking, percent	20	1, 20	3
2	Rutting, inches	0.5	0.5	2
3	Skid Resistance	43	43	2
4	PSI	2.0	3.0, 2.0	3
5	Surface Distress, percent	50	50	2
6	Traffic Level	None	1000 (ADT)	2

defined such that rehabilitation is needed when a roadway experiences at least 0.5 inches of rutting over 20 percent of its area. In other cases only severity need be specified. For example, rehabilitation could occur when the mean PSI is less than 2.5. If a distress is used for which only the extent is significant (e.g., bleeding on asphalt concrete pavements), and for which a model is available which calculates extent directly, then consider this calculated extent to be a severity and leave the extent fields blank.

Card Type F2 - The purpose of this card is to specify a number (< 31) of rehabilitation options and to map combinations of distresses of various level, as defined on card F1, to these options. One card is required for each rehabilitation option. The most expeditious approach to completing this card is by constructing a maintenance "decision tree" (see, for example, Table 52) which lists rehabilitation procedures for the various types, levels, and combinations of distresses.

IRB (I) - This variable is the identification number of the rehabilitation type listed in the decision tree (and must be 50).

RKEY (J, I) - These variables are "keys" which associate the rehabilitation type with various combinations of distress or other criteria (e.g., traffic level). Up to six keys for a single rehabilitation option may be specified with each digit corresponding to a distress or other criteria specified on cards F1 (Table 51 for example). Each key is entered as a single digit that specifies the distress interval that is being considered. Distresses or other rehabilitation criteria are assigned levels

Table 52
Example Rehabilitation Requirements and Decision Criteria For An Asphalt Concrete Pavement

AREA WITH CLASS 2 OR 3 FATIGUE CRACKING	DISTRESS OR PERFORMANCE CRITERIA	REHABILITATION TYPE
>20 percent		1. Structural Rehabilitation- 4 inch Overlay
1-20 percent	D_4-PSI < 2.0	2. Mill 1 inch Plus 2 inch Overlay
	D_2-Rutting >0.50	3. 1-1/2 inch Leveling Course Plus 1-1/2 inch Overlay
	D_3 Skid Resistance <43 or D_6-Surface Distress	4. Membrane with 1-1/2 inch Overlay
0%	D_4-PSI <2.0	5. Mill 1 inch Plus 1-1/2 inch Overlay
	D_2-Rutting >0.50	6. 1 inch Leveling Course Plus 1 inch Overlay

Table 52
Example Rehabilitation Requirements and Decision Criteria For An Asphalt Concrete Pavement (continued)

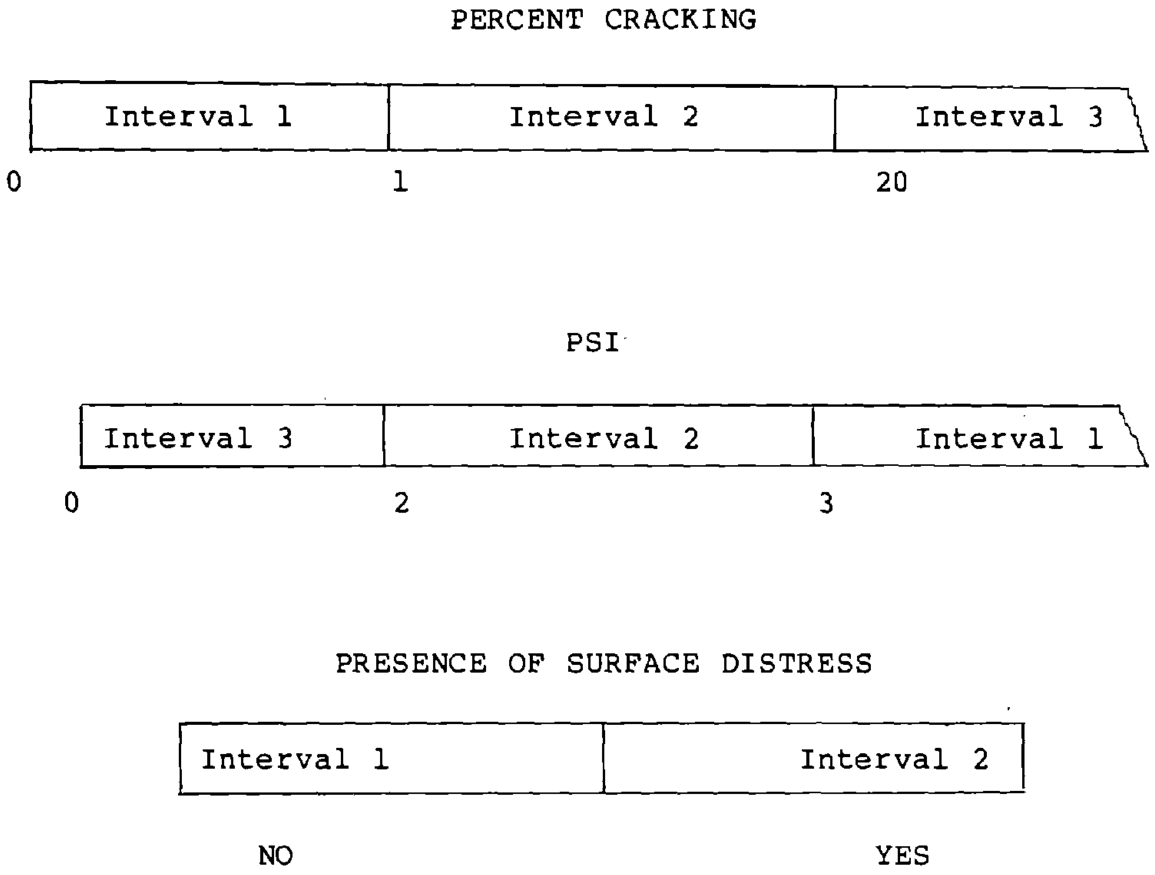
AREA WITH CLASS 2 OR 3 FATIGUE CRACKING	DISTRESS OR PERFORMANCE CRITERIA			REHABILITATION TYPE
0 percent	D_3-Skid Resistance <43	D_4-PSI 2.0 - 3.0		7. Mill 1/2 inch Plus 1 inch Overlay
		D_4-PSI > 3.0	ADT <1000	8. Chip Seal
			ADT >1000	9. ACFC
0 percent	D_5-Surface Distress, Raveling > 50 percent	D_4-PSI 2.0 - 3.0		10. Mill 1/2 inch Plus 1 inch Overlay
		D_4-PSI > 3.0	ADT <1000	11. Chip Seal
			ADT >1000	12. ACFC

Chart based on different Distress Modes to be checked that are the most critical or costly to rehabilitate. For example, Fatigue Cracking - if its critical value is exceeded, a structural overlay is required. Distortion is the next distress mode checked - Roughness (PSI) and Rutting are checked for different levels of cracking. Surface failure (stripping-ravelling) and surface friction are the last distress modes to be considered, and both may depend on relative values of fracture and distortion.

(recall variables XCC on Cards F1) such that severity and/or extent define the boundaries of the distress intervals. The number of intervals is one greater than the number of criteria specified on card F1. Since a maximum of four criteria is allowed, a corresponding maximum of five intervals is possible. The severity increases with interval number. The examples shown in Figure 26 illustrate this concept for several of the distresses listed in Table 51.

For the sample criteria shown in Table 51, the first key corresponds to fatigue cracking, the second rutting, the third skid resistance, the fourth PSI, the fifth surface distress, and the sixth traffic level. As an example of selecting the proper distress interval, consider fatigue cracking. If the rehabilitation option depended on cracking greater than 20 percent, then a 3 would be entered in the first key; if cracking was between 1 and 20 percent, then a 2 would be entered in the first key; a 1 would be entered if cracking was less than 1 percent.

For a complete example of coding rehabilitation keys, see Figure 27. This example is for rehabilitation option No. 12 in the decision tree shown in Table 52. The keys for this option are coded as 100122. Since fatigue cracking is less than 1 percent (actually zero) the first distress interval applies and a 1 is entered in the first key. Note that rutting and skid resistance are not considered for this rehabilitation option. Thus, the second and third keys are assigned a value of zero. In the example, PSI is greater than 3 (i.e., least distressed) and thus lies within the first distress interval; accordingly, a 1 is entered in the fourth key. Surface distress is considered present which signifies the second distress



(Note that the most severe condition is always contained in highest intervals).

Figure 26. Example of Distress Intervals For Use In Coding Rehabilitation Keys

Rehabilitation Option: Asphalt Concrete Friction Course

Pavement condition as described by decision tree:

1. Fatigue cracking = 0 (Interval 1)
2. Rutting not applicable (Interval 0)
3. Skid resistance not applicable (Interval 0)
4. PSI > 3 (Interval 1)
5. Surface distress present (Interval 2)
6. Traffic level (ADT) > 1000 veh/day (Interval 2)

The key for rehabilitation option No. 12 is coded as:

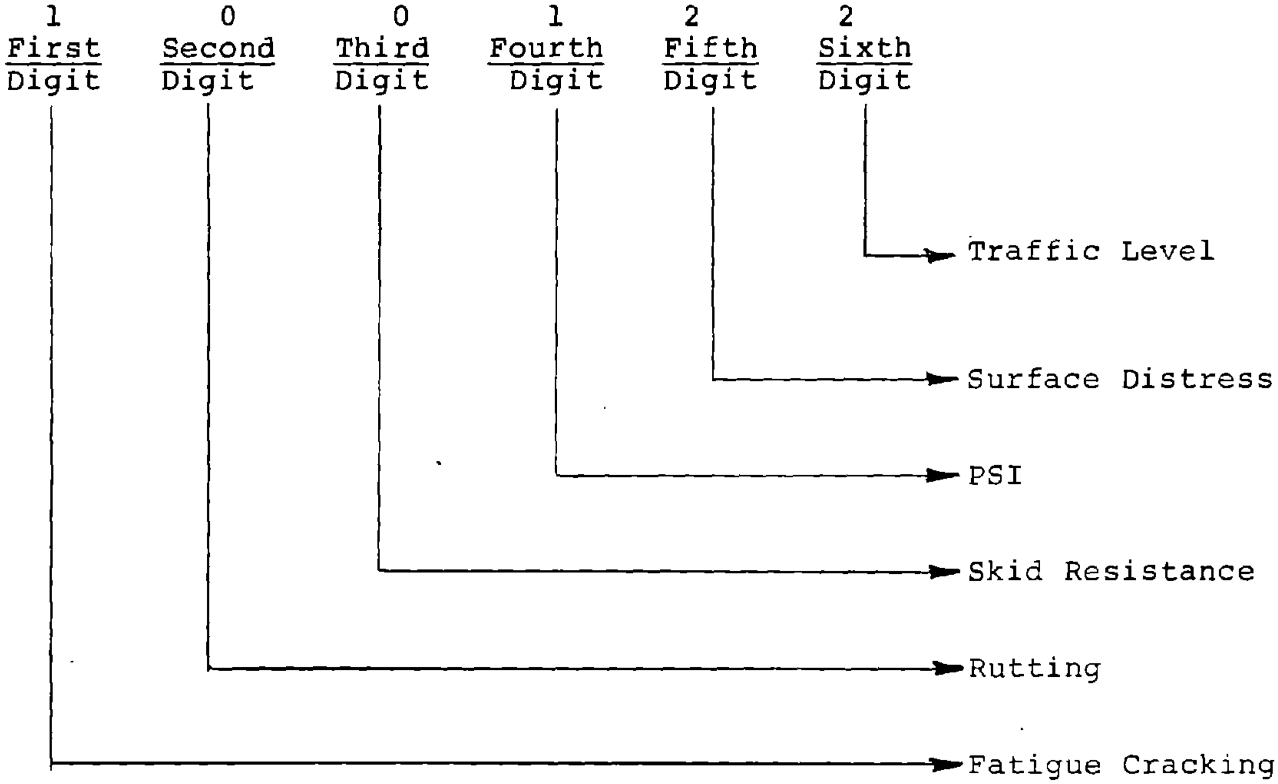


Figure 27. Example To Illustrate Coding Of a Six-Digit Key For Rehabilitation Option No. 12 (Table 52)

interval and a 2 is entered in the fifth key. Note that traffic level, while not a distress, is considered a rehabilitation criterion. Since ADT is greater than 1,000, which lies within the second distress interval, a 2 is entered in the sixth key. Appendix E provides a more detailed discussion of this coding format for an example.

RCOST(I) - This variable represents the unit cost of the rehabilitation option under consideration.

COSTKY(I) - This variable is a code associating a units label with the value entered for RCOST(I); these units labels are stored in the array LBLCST by a data statement in subroutine REHABL. At present there is only one unit label: "SQ. YD.," associated with a value of 1 for COSTKY. "Dollars per" is assumed. Other units labels, such as "LANE MILE," can be added to the data statement by the user.

RLABEL (J,I) - This variable is a verbal description of the rehabilitation option detailed on this card.

ATTACHMENT C.1
ABBREVIATED INPUT GUIDE FOR PROGRAM COSTOP1

Card type	Cols	Format	Var name	Description
A1	1 - 80	10A8	RUNID	Identification of run
A2	1 - 80	10A8	RUNDES	More complete run description (2 cards)

no blank card following; three cards per run

Card type	Cols	Format	Var name	Description
B1	1 - 8	A8	NAM(ID)	Short name of input variable or of function
	11 - 12	I2	ID	Identification number of variable or function
	13 - 24	E12.4	VAL(ID)	Value of input variable; blank if function
	27 - 30	F4.2	CV(ID)	Coefficient of variation of input variable
	32 - 33	I2	IFN(ID)	Zero or blank if input variable; otherwise, index number of user-provided function used to calculate this quantity. If >0, calculate and display for each year during analysis period. If < 0, calculate only for the first pass through the simulation. (used if the quantity does not depend on time or traffic.)
	35 - 36	I2	IDEC (ID)	Zero or blank if input variable or if a function which increases with time; 1 if a function which decreases with time.

Card type	Cols	Format	Var name	Description
B1 (con't)	39 - 40	I2	NQ(ID)	Number of input variables and previously defined functions upon which this function directly depends (<10). Zero or blank input variable. If NQ is entered as a negative value, no derivatives of the function are taken and the coefficient of variation of the function value remains zero.
	41 - 43	I3	IQ(1,ID)	Identification numbers of input variables and functions upon which this function depends
	68 - 70	I3	IQ(10,ID)	

repeat until a blank card; < 40 cards of Type B1.

Card type	Cols	Format	Var name	Description
B2	1 - 8	A8	NM	Dummy repeat of short name for variable or function
	11 - 12	I2	ID	Identification number, same as ID on B1
	16 - 28	A8,A5	UNITS(J,ID) J=1,2	Units label for variable or function
	31 - 60	3A8,A6	LNAME(J,ID) J= 1,4	Long name of variable or function

Same number of cards of Type B2 as of Type B1; no blank card following

Card type	Cols	Format	Var name	Description
C1	1 - 5	I5	NYR	Maximum number of years in the simulation

Card type	Cols	Format	Var name	Description
C1	6 - 10	I5	NTT	The number of independent test types to be evaluated.
	11 - 20	F10.2	FY	The first year for which distress is to be calculated

no blank card following; 1 Card Type C1 per run

D1	1 - 5	I5	IDT	Identification number of the independent variable affected by a specific test type.
	6 - 10	I5	NTS	"Numbers of tests" to be evaluated for this test type.
	11 - 60	10I5	NTEST (r),	Number of tests per lane mile for this test type (NTS values are read)
D2	1 - 5	I5	ICONF	Confidence level, (Zero value forces use of contractor effect approach; non-zero value must be selected from [75, 90, 95, 99] and forces use of statistical approach)
	11 - 20	F10.2	TESTC	Unit cost to perform one test, in dollars
	21 - 30	F10.2	AT	Coefficient in the assumed relation for the mean value (contractors effect).
	31 - 40	F10.2	BT	Exponent in the assumed relation for the mean value
	41 - 50	F10.2	CT	Coefficient in the assumed relation for the standard deviation.

Card type	Cols	Format	Var name	Description
D2 (con't)	51- 60	F10.2	DT	Exponent in the assumed relation for the standard deviation.

NTT pairs of cards D1 and D2; no blank card following

Card type	Cols	Format	Var name	Description
E1	1 - 10	F10.3	CONSTC	Construction cost (thousands of dollars/ lane mile)
	11 - 20	F10.3	USRREC	User cost-associated with rehabilitation (thousands of dollars/lane mile)
	21 - 30	F10.3	ANMNTC	Uniform annual maintenance cost (thousands of dollars/lane mile)
	31 - 40	F10.3	ANUSRC	Uniform annual user cost (thousands of dollars/lane mile)

no blank card following

Card type	Cols	Format	Var name	Description
E2	1 - 10	F10.3	WIDTH	Lane width for project (feet)
	11 - 20	F10.3	PCTINT	Annual interest rate (per cent)

no blank card following

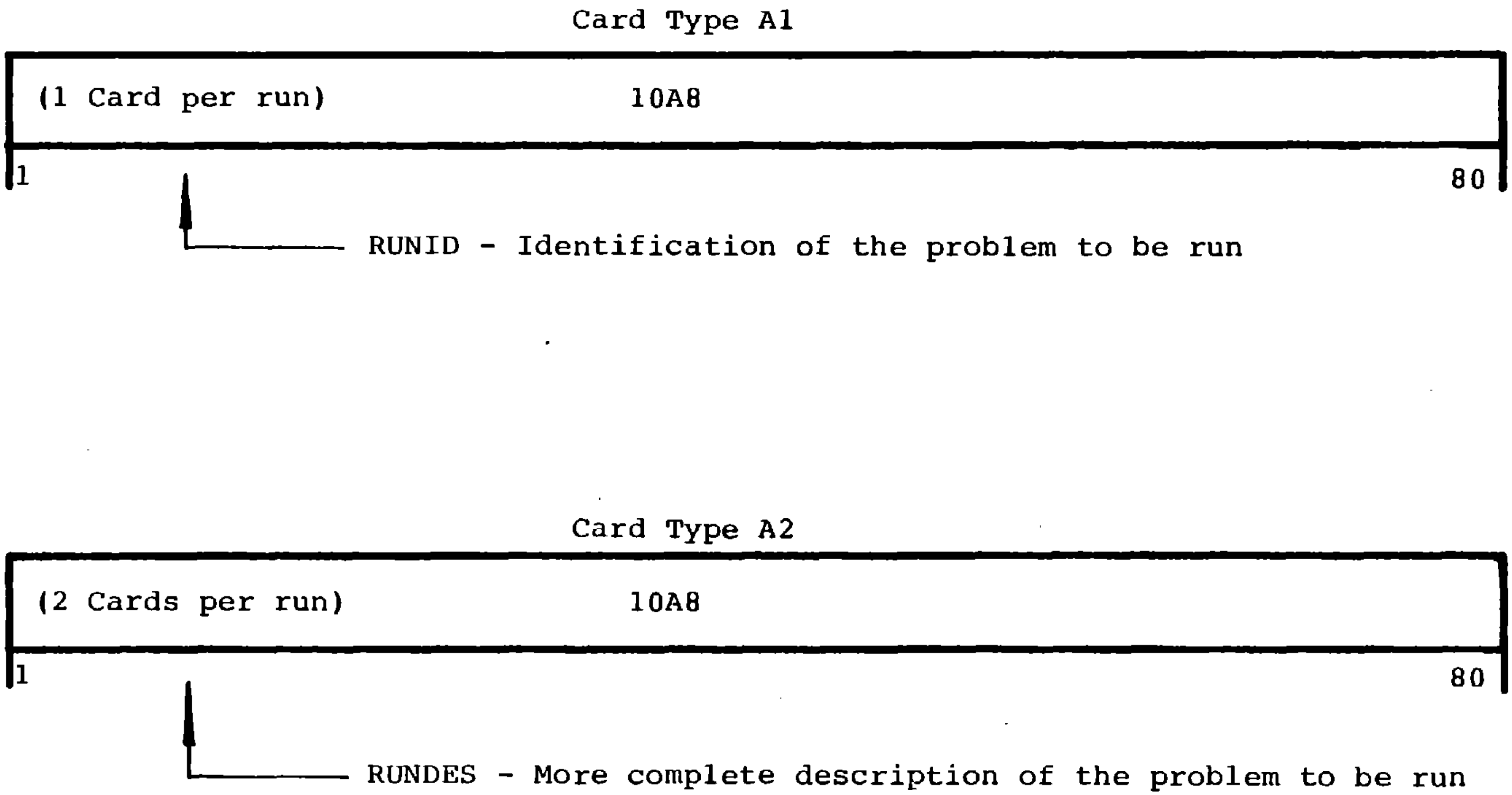
Card type	Cols	Format	Var name	Description
F1	1 - 3	I3	ICC(1,I)	Identification of associated distress function.
	4 - 6	I3	ICC(2,I)	Number of distress criteria to follow
	7 - 9	I3	ICC(3,I)	Which criterion triggers rehabilitation

Card type	Cols	Format	Var name	Description
F1 (con't)	11 - 15	F5.1	XCC(1,1,I)	Severity of first level criterion
	16 - 20	F5.1	XCC(2,1,I)	Extent(%area)
		.		.
		.		.
		.		.
	41 - 45	F5.1	XCC(1,4,I)	Severity of fourth level criterion
	46 - 50	F5.1	XCC(2,4,I)	Extent(%area)
repeat type F1 until a blank card				
F2	4 - 5	I2	IRB(I)	Rehabilitation option number (<40)
	7	I1	RKEY(1,I)	Keys which associate this option with specific combinations of distress
	.	.	.	
	.	.	.	
	.	.	.	
	12	I2	RKEY(6,I)	
	16 - 20	F5.2	RCOST(I)	Unit cost of this option
	22	I1	COSTKY(I)	Index to units on cost
	26 - 57	4A8	RLABEL (J,I) J=1,4	Verbal description of rehabilitation option
repeat type F2 until blank card				

ATTACHMENT C.2

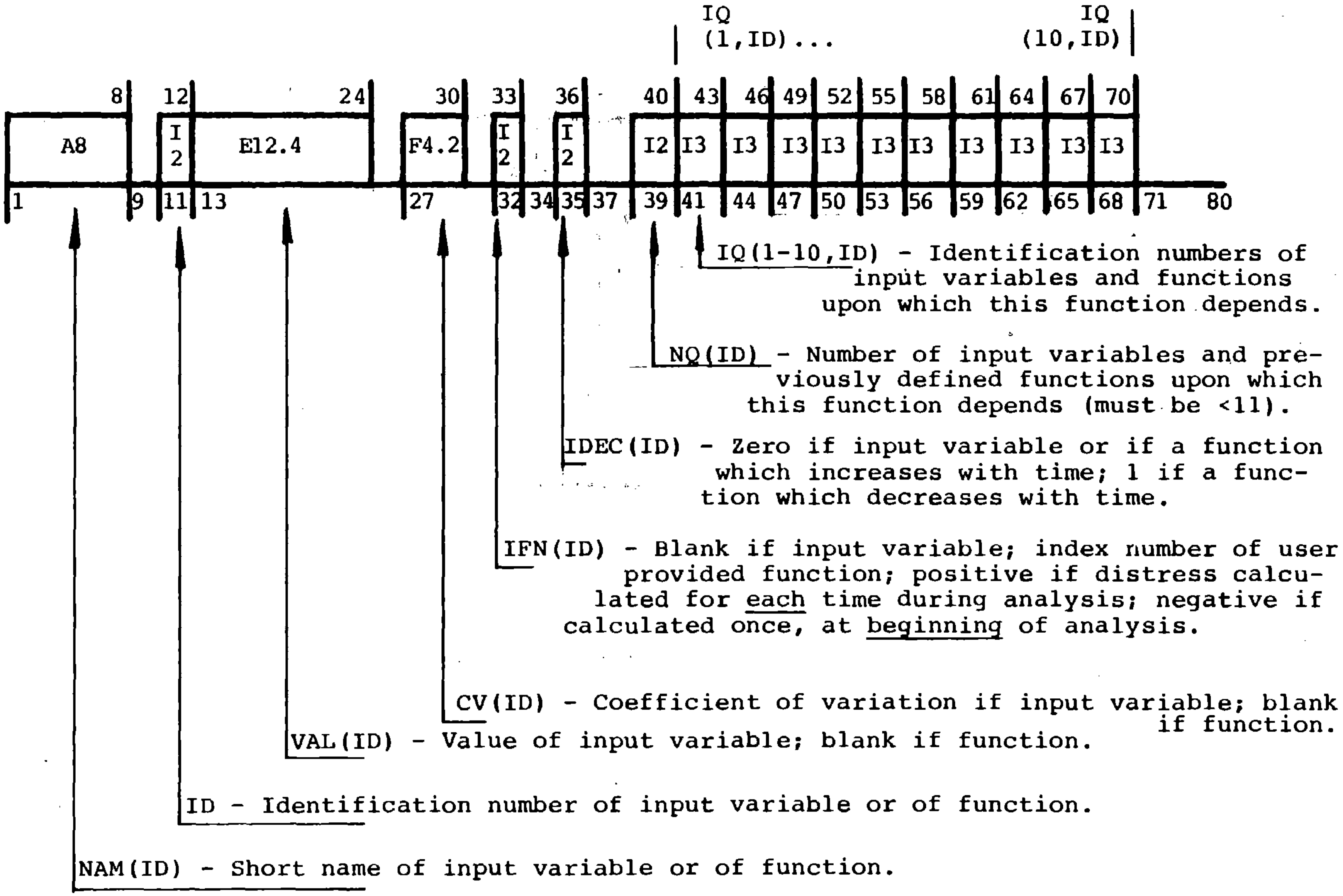
CARD FORMS FOR PROGRAM COSTOP1

The following are card forms to assist the user in coding the required input data.



(NOTE: A blank card does not follow either card types A1 or A2)

Figure 28. Card Form for Program COSTOP1 - Card Types A1 and A2



IQ(1-10,ID) - Identification numbers of input variables and functions upon which this function depends.

NQ(ID) - Number of input variables and previously defined functions upon which this function depends (must be <11).

IDEC(ID) - Zero if input variable or if a function which increases with time; 1 if a function which decreases with time.

IFN(ID) - Blank if input variable; index number of user provided function; positive if distress calculated for each time during analysis; negative if calculated once, at beginning of analysis.

CV(ID) - Coefficient of variation if input variable; blank if function.

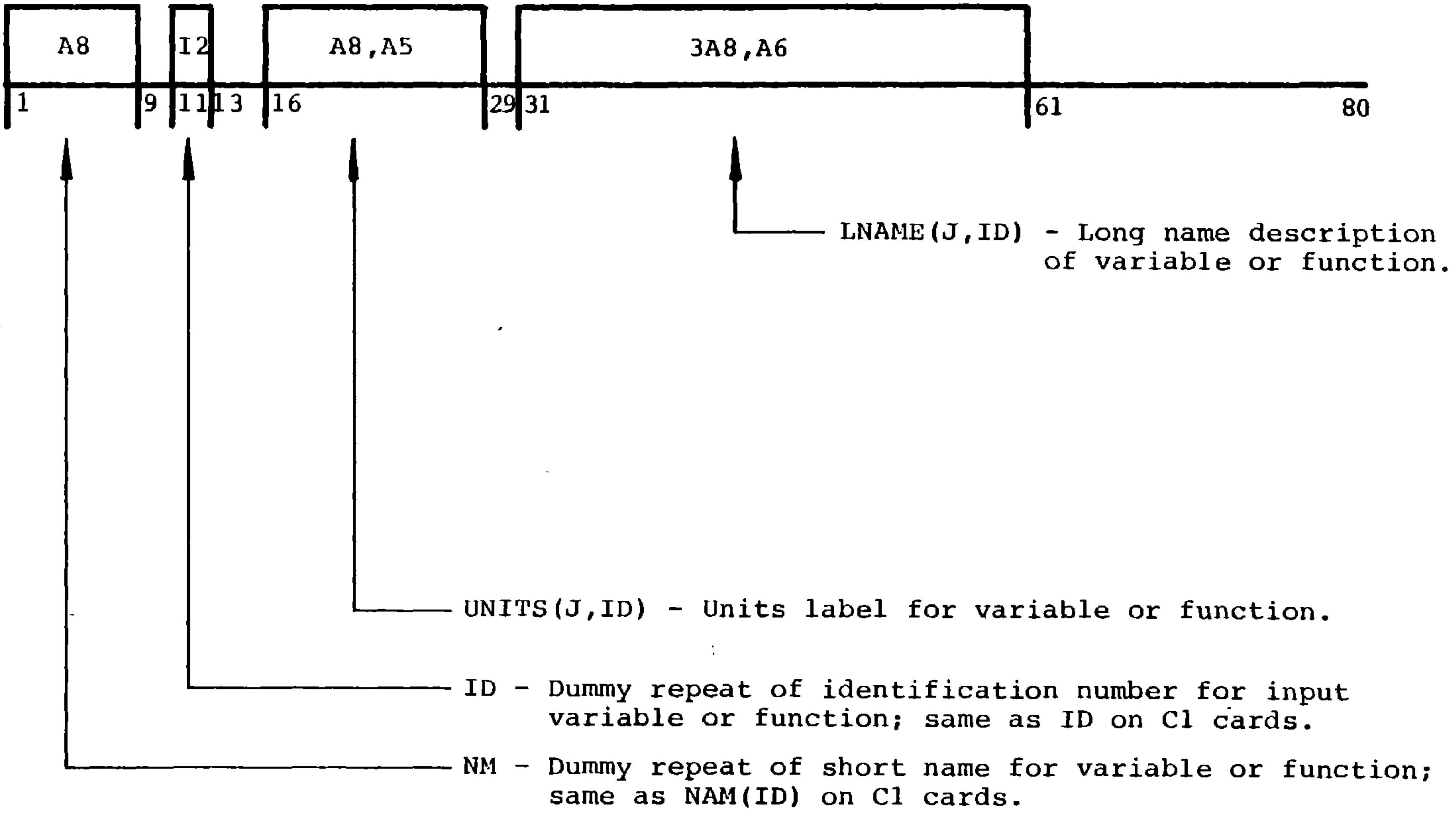
VAL(ID) - Value of input variable; blank if function.

ID - Identification number of input variable or of function.

NAM(ID) - Short name of input variable or of function.

(NOTE: A blank card must follow a group of B1 cards; maximum number of B1 cards is 40).

Figure 29. Card Form for Program COSTOP1 - Card Type B1



LNAME(J,ID) - Long name description of variable or function.

UNITS(J,ID) - Units label for variable or function.

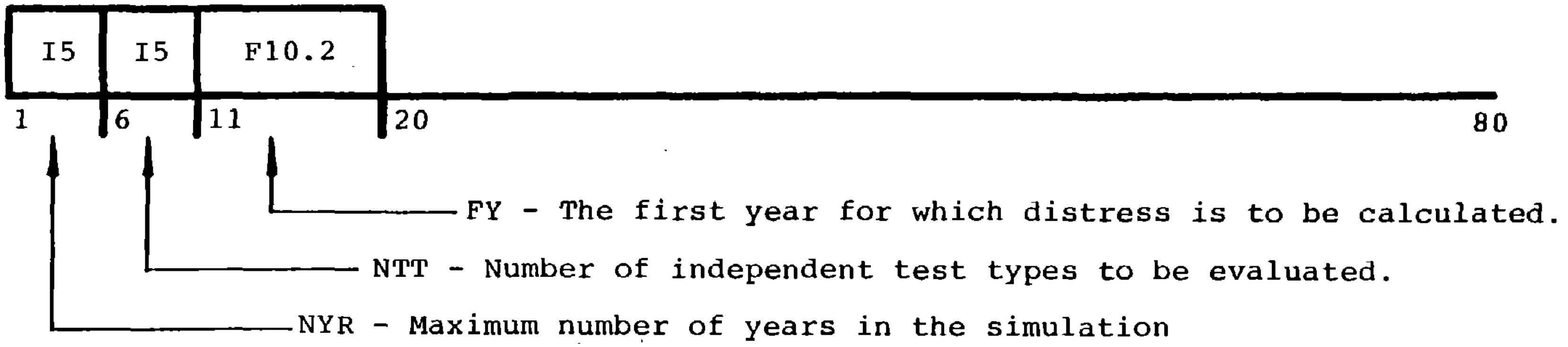
ID - Dummy repeat of identification number for input variable or function; same as ID on C1 cards.

NM - Dummy repeat of short name for variable or function; same as NAM(ID) on C1 cards.

(NOTE: A blank card does not follow a group of B2 cards; there must be a B2 card for every B1 card).

Figure 30. Card Form for Program COSTOP1 - Card Type B2

Card Type C1



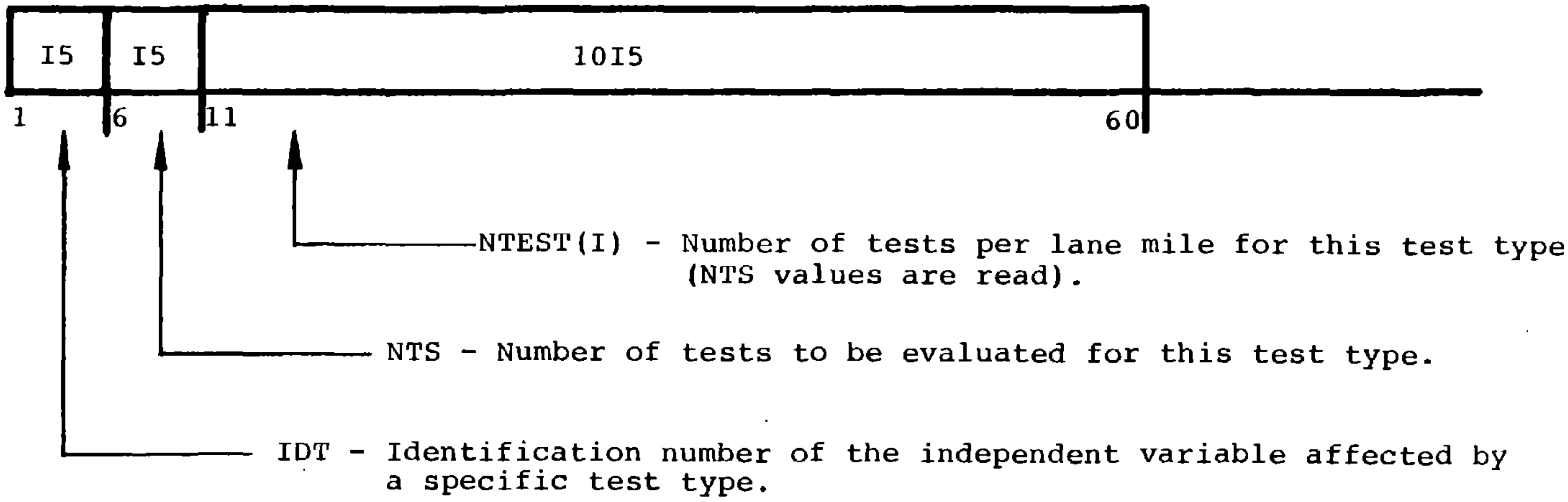
FY - The first year for which distress is to be calculated.

NTT - Number of independent test types to be evaluated.

NYR - Maximum number of years in the simulation

(NOTE: A blank card does not follow a C1 card; only one C1 card per run).

Card Type D1

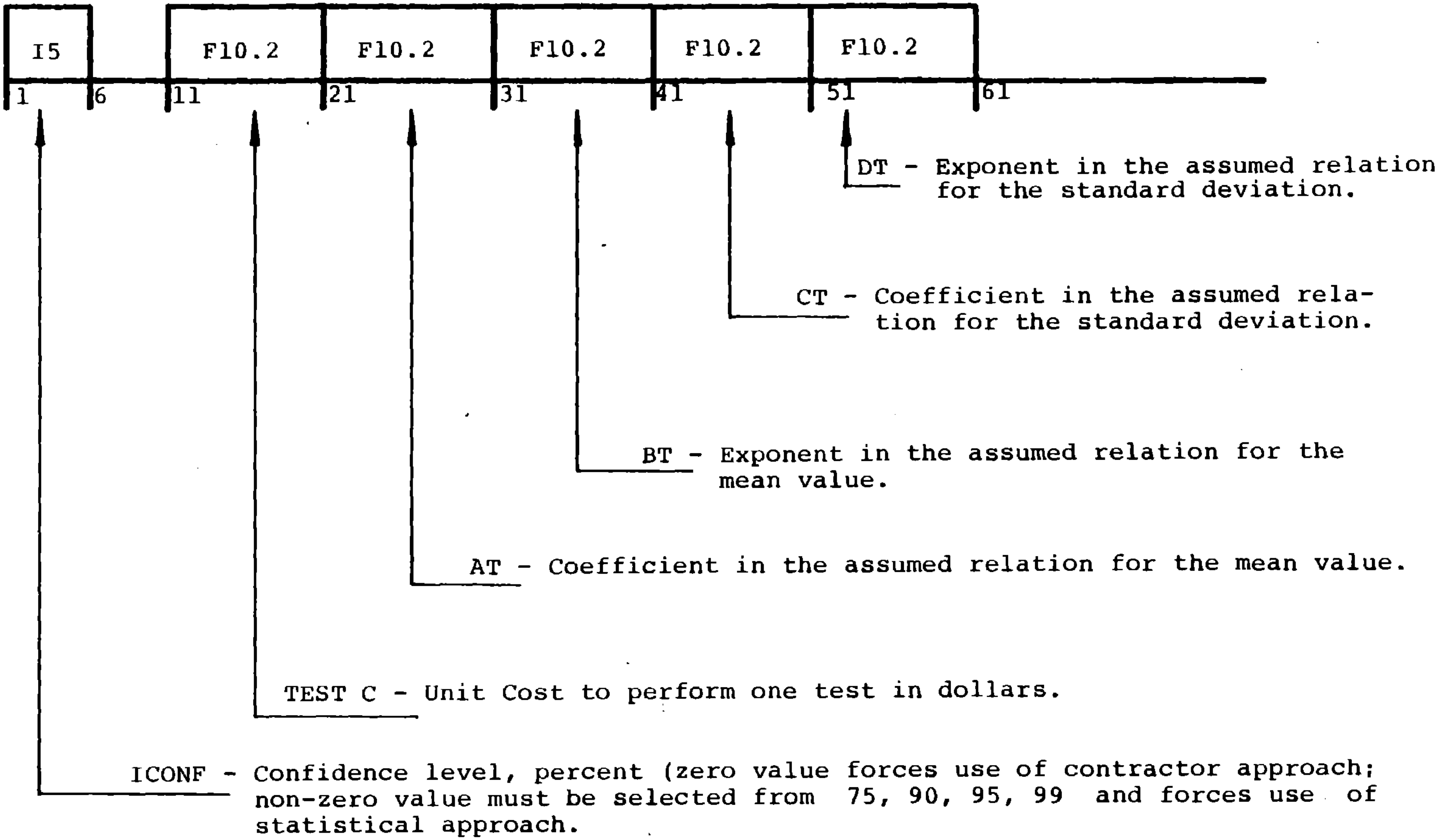


NTEST(I) - Number of tests per lane mile for this test type (NTS values are read).

NTS - Number of tests to be evaluated for this test type.

IDT - Identification number of the independent variable affected by a specific test type.

Figure 31. Card Form for Program COSTOP1 - Card Types C1 and D1



DT - Exponent in the assumed relation for the standard deviation.

CT - Coefficient in the assumed relation for the standard deviation.

BT - Exponent in the assumed relation for the mean value.

AT - Coefficient in the assumed relation for the mean value.

TEST C - Unit Cost to perform one test in dollars.

ICONF - Confidence level, percent (zero value forces use of contractor approach; non-zero value must be selected from 75, 90, 95, 99 and forces use of statistical approach.

(NOTE: A blank card does not follow a D2 card)

Figure 32. Card Form for Program COSTOP1 - Card Type D2

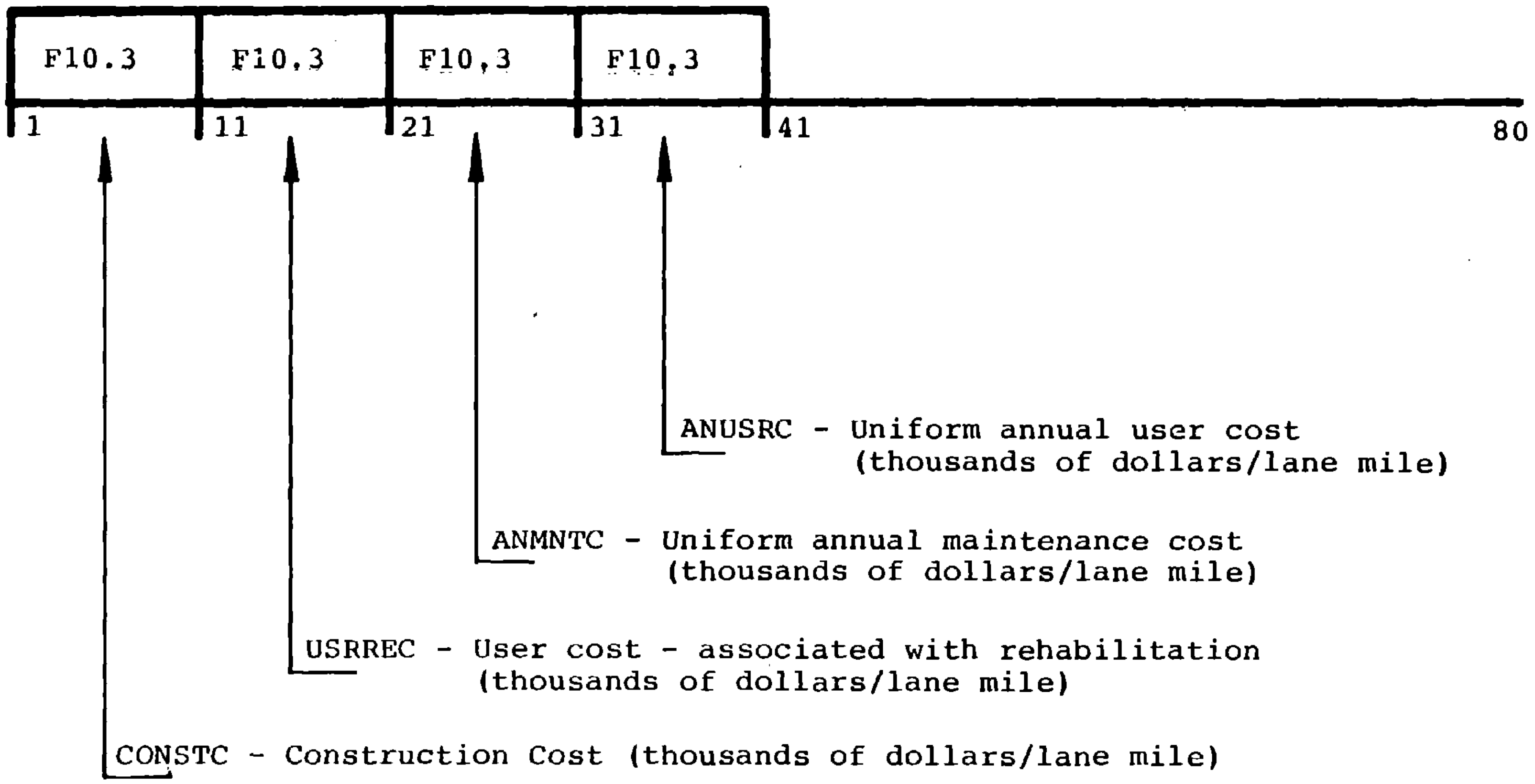
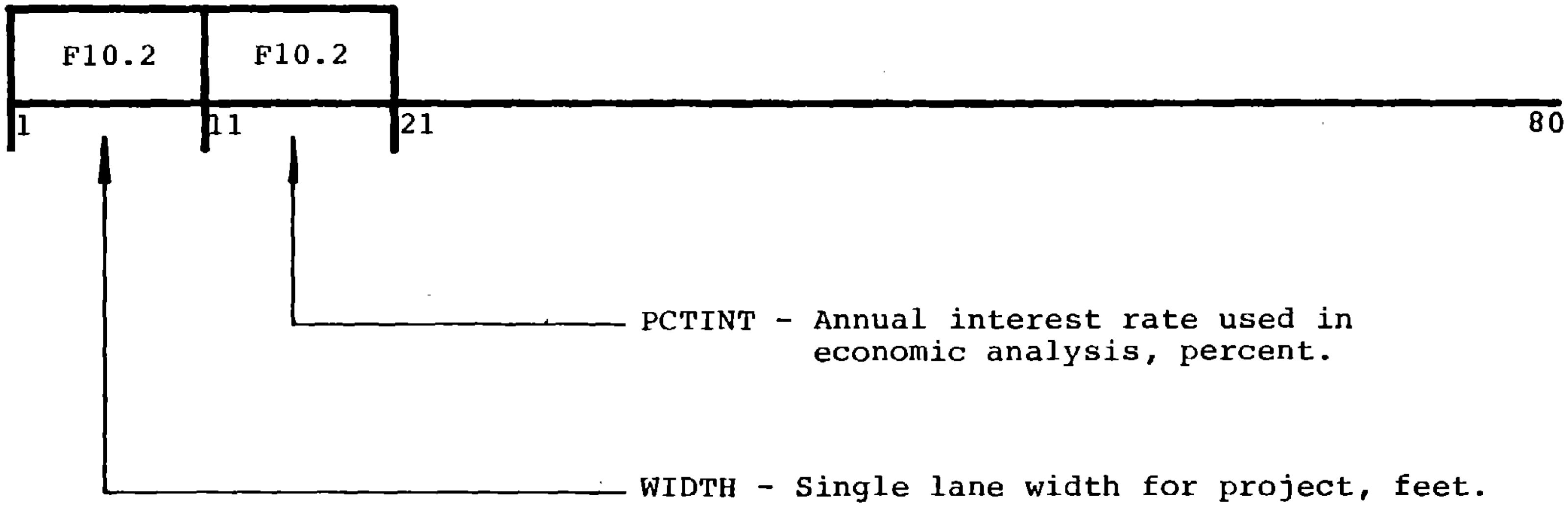


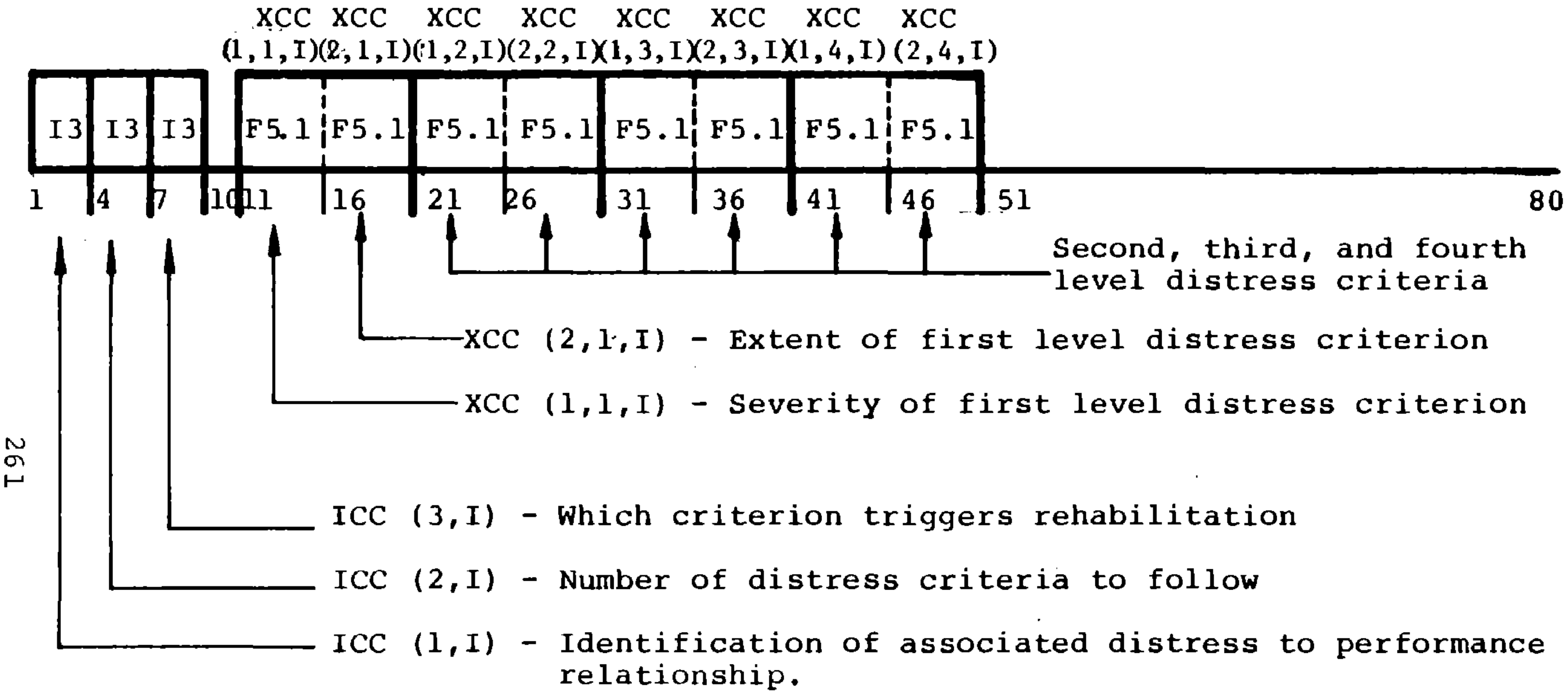
Figure 33. Card Form for Program COSTOP1 - Card Type E1



PCTINT - Annual interest rate used in economic analysis, percent.

WIDTH - Single lane width for project, feet.

Figure 34. Card Form for Program COSTOP1 - Card Type E2



Second, third, and fourth level distress criteria

XCC (2,1,I) - Extent of first level distress criterion

XCC (1,1,I) - Severity of first level distress criterion

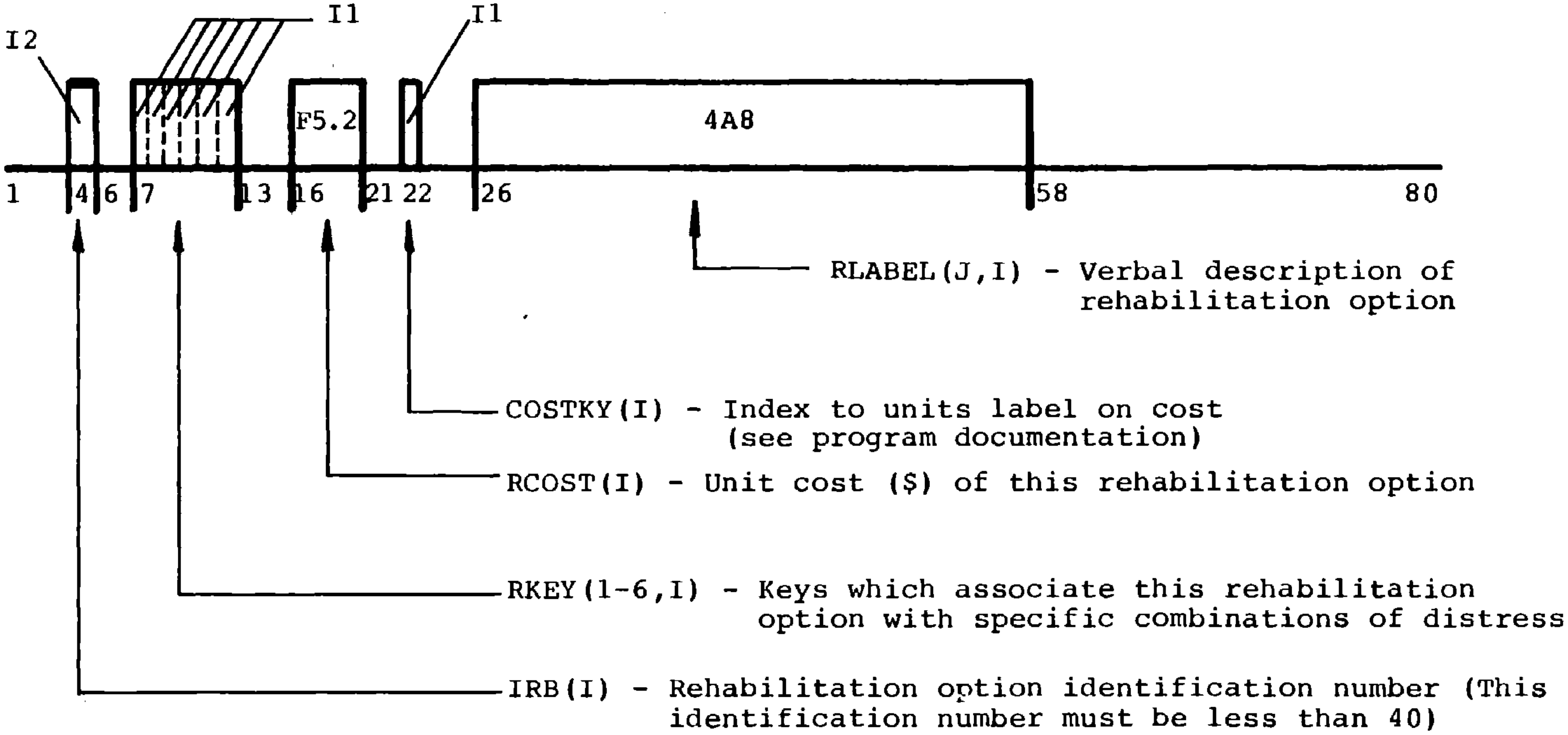
ICC (3,I) - Which criterion triggers rehabilitation

ICC (2,I) - Number of distress criteria to follow

ICC (1,I) - Identification of associated distress to performance relationship.

(A blank card must follow a group of F1 cards).

Figure 35. Card Form for Program COSTOP1 - Card Type F1



RLABEL(J,I) - Verbal description of rehabilitation option

COSTKY(I) - Index to units label on cost (see program documentation)

RCOST(I) - Unit cost ($) of this rehabilitation option

RKEY(1-6,I) - Keys which associate this rehabilitation option with specific combinations of distress

IRB(I) - Rehabilitation option identification number (This identification number must be less than 40)

(A blank card must follow a group of F2 cards).

Figure 36. Card Form for Program COSTOP1 - Card Type F2

APPENDIX D

PROGRAMMER'S NOTES AND PROGRAM LISTING FOR COSTOP1

GENERAL COMMENTS

Program COSTOP1 is written in Fortran 77, and can be compiled and run on a microcomputer as well as a larger computer. It was finalized, and all of the simulations were run, on a ZENITH Z-100 microcomputer using MICROSOFT MS-Fortran. Compilations are usually done in pieces due to the very large intermediate files generated by this compiler; the object files resulting from the second pass of the compiler are then linked, together with the Fortran library, by the LINK program provided with the compiler; the executable file for the submitted version is about 120K bytes long.

REQUIRED FILES

Files required for the program are defined below by the associated logical unit; MS-Fortran permits interactive definition of required file names during execution of the program, whereas operation of the program on a larger computer, especially if non-interactive, will probably require association of the logical units with file names in the job control language supplied with the job. If the program is run on a larger computer requiring such job control language, the call to subroutine IOSET in the main program should be commented out, and the parameters in the CALL OPEN statement in IOSET used to define the file associated with unit 9 should be used instead in the JCL.

Logical Unit	Associated File	File Contents
1	Debug output file	1. Echo print of input 2. Detail results from each simulation (parameter values, time to failure, distress values at failure, and prescribed rehab.
5	Input data file	
6	Output file	1. Labeled print of input data 2. Final benefit/cost analysis results
9	Intermediate store	Results from individual simulations: time to failure, mode of failure, prescribed rehabilitation code, cost data. Defines the simulation by the number of tests used for each tested parameter.

The file on logical unit 1 can become very long if many simulations are run; in such situations the information can be written to the screen (microcomputer version) by giving the console device name CON when asked for the file name, or it can be dumped by giving it the NUL device name. The file can easily exceed the capacity of a diskette (more than 300 Kbyte) for a large run; if storage space is exhausted, the system will abort the program without properly closing the file, so that not only is the benefit/cost analysis not performed on the successful portion of the run, but the detailed output being saved is also not accessible.

In functions EVALFN and EVALDF there are statements which write to unit 1 the current values of functions and derivatives at the point of computation; these statements currently have a C in column 1 so that they are ignored by the compiler. If a new set of functions is used, the C may be removed and the output used to check the results more directly on a short run. The statements should not be left active for a run of any size, as the output will be very large.

DIMENSIONS

The program is presently (for submission to FHWA) dimensioned for the following sizes for various aspects of a problem:

1. Number of input and calculated variables: 40
2. Number of permissible levels in the rehabilitation decision tree: 6
3. Number of test types which can be run simultaneously: 5
4. Number of passes through the performance models for different numbers of tests of various types: 250

To change these dimensions in some cases merely requires changing dimension statements, while in other cases changes in the code are required.

The total number of passes (number 4 above) is the easiest to increase; it is set by dimension statements in subroutine BC on the variables C, TC, DUMMY, and IS, and by the value assigned to the variable MAX in a DATA statement in BC. The dimensions and the value for MAX should agree. The number of passes is equal to the product of all the values of NTS read for the different test types. For example, if one had 3 test types for which one had 2 levels of testing each and 2 types with 3 levels of testing each, the number of passes would equal 2 x 2 x 2 x 3 x 3 = 72.

To increase the number of permitted variables and functions requires changes in COMMON blocks CURVAL, HDG, and INDAT, in which every occurrence of the value 40 must be changed to the new limit in every occurrence of the block. In addition, the statement DIMENSION X(40) must be changed in each user-supplied function, as well as the dimensions on X, CVX, and DFDX in functions EVALFN, EVALDF, EVALVR, and YFUNC, and the dimension on JFN in subroutine KERNEL and in the main program. No changes are required in the program code itself.

To change the number of permissible test types to be examined in one run, one must change all the occurrences of the digit 5 in common block TEST to the new value, and add the corresponding number of DO loops to the set of nested loops in subroutine LOOP, following exactly the existing pattern.

To change the number of permissible levels in the rehabilitation decision tree will require more work than the above, and at present seems unlikely to be needed. (This number determines the number of separate types of distress which can enter into the decision making process.) Changes in output formats will be needed as well as changes in the code of subroutine SETRB (again, the adding of more loops in the set of nested DO loops); dimensions in common blocks REHCHK and REHAB and in subroutine SETRB (all occurrences of the digit 6) would be changed to the new value, as would be the limit of the DO loop with which INRB begins. One would also be well advised to increase the dimension on the variable RS in common block REHAB, as this must be equal to or greater than the total number of combinations of rehabilitation situations.

PROGRAM LISTING

The remainder of Appendix D is a listing of the main program COSTOP1 and its subroutine.

```
C     PROGRAM COSTOP1 - FHWA
C     MAIN PROGRAM FOR 'COST EFFECTIVENESS PROCEDURE'
C
C     WRITTEN UNDER FHWA CONTRACT DTFH61-82-C-00015
C     BY BRENT RAUHUT ENGINEERING, INC., AUSTIN, TEXAS
C     PROGRAM DOCUMENTATION AND INPUT GUIDE INCLUDED IN FINAL REPORT
C     FHWA-RD-85/030.
C
      CHARACTER*8 RUNID, RUNDES, LNAME, UNITS, NAM, RLABEL
      INTEGER RS, RKEY, COSTKY
      DIMENSION JFN(40)
      COMMON /COSTIN/ CONSTC,USRREC,ANMNTC,ANUSRC,WIDTH,PCTINT
      COMMON /CTRL  / NIN, NOUT, NDERV, LSAVE, LOUT
      COMMON /CURTFC/ CURADT, CURTRK, CURSAL, CUMVEH,CUMTRK, CUMSAL
      COMMON /CURVAL/ X(40), CVX(40), DFDX(40), AGE
      COMMON /HDG   / RUNID(10), RUNDES(20), LNAME (4,40), UNITS(2,40)
      COMMON /INDAT / NAM(40), IDX(40), VAL(40), CV(40), IFN(40),
     1                NQ(40), IQ(10,40), IDEC(40), NI, NYR
      COMMON /INTFC / ADTZ, PCTPYR, PCTTRK, SALPTK, FY
      COMMON /RECRIT/ XCC(2,4,10), ICC(3,10), NCC
      COMMON /REHCHK/ ND, IR(6), LV(6), PCTA(2,6), XD(2,6), AGET(2),
     1                IRSEL, FAILT, IDF
      COMMON /REHAB / RLABEL(4,31), RCOST(31), COSTKY(31), RKEY(6,31),
     1                IRB(31),IZR(50),NL(6),RS( 200),NDIM,NRB,LRN,NN
      COMMON /TEST  / NTT, IDT(5), NTEST(11,5), ICONF(5), TESTC(5),
     1                AT(5), BT(5), CT(5), DT(5)
      DATA MDIM /50/
C
C     INITIALIZE ARRAYS TO ZERO.  SET I/O UNIT NUMBERS.
      CALL INITLZ(1)
C
C     OPEN ANY I/O DEVICES THAT HAVE NON-DEFAULT PARAMETERS.
C     AT PRESENT, IOSET SETS UP A DIRECT ACCESS FILE FOR REHABILI-
C     TATION AND COST RESULTS.  ALL OTHER FILES ARE SEQUENTIAL FILES,
C     AND THE USER IS PROMPTED FOR THEIR NAMES WHEN THEY ARE FIRST
C     ACCESSED.  (UNDER MICROSOFT FORTRAN-86 ON MICROCOMPUTER)
      CALL IOSET
      NYR = 0
C
  100 CALL READIN
      IF (NYR .LE. 0) GO TO 999
C     READ REHAB DATA (OPTIONS AND TIES TO DISTRESS MANIFESTATIONS)
      CALL INRB
      CALL SETRB
      MAX = INVNDX (IRB, NRB, IZR, MDIM, NERR)
C     MAX IS THE LARGEST VALUE FOUND FOR -IRB- (REHAB SELECT INDEX).
C
C     INITIALIZE ALL FUNCTIONS TO ZERO AND THOSE VARIABLES
C     NOT AFFECTED BY TEST RESULTS TO THEIR READ-IN VALUES.
      CALL INITLZ(2)
C     PRINT INPUT DATA
      CALL INPRT
```

```
C     CHECK FUNCTION SPECIFICATIONS FOR CORRECT ORDERING.
      CALL DATACK (1, IFERR)
C     ABORT THE RUN IF ERRORS FOUND BY DATACK.
      IF (IFERR .GT. 0) GO TO 999
C
C     GO TO LOOP MANAGER FOR MULTIPLE PASSES THROUGH PERFORMANCE
C     ANALYSIS.
      CALL LOOP (NPASS)
      WRITE (1,1) NPASS
    1 FORMAT (1X,'NPASS AFTER LOOP =', I5)
  300 CONTINUE
      CALL BC (NPASS)
  999 CONTINUE
      END
C
      SUBROUTINE IOSET
      COMMON /CTRL  / NIN, NOUT, NDERV, LSAVE, LOUT
      OPEN (LOUT, FILE=' ', STATUS='NEW', ACCESS='DIRECT',RECL=40)
      RETURN
      END
C
      SUBROUTINE INITLZ (ISW)
C     INITIALIZATION ROUTINE.  'ISW' TELLS WHAT FUNCTION TO PERFORM.
      CHARACTER*8 NAM, RUNID, RUNDES, LNAME, UNITS, IBL8, RLABEL
      INTEGER RS, RKEY, COSTKY
      COMMON /CTRL  / NIN, NOUT, NDERV, LSAVE, LOUT
      COMMON /CURVAL/ X(40), CVX(40), DFDX(40), AGE
      COMMON /HDG   / RUNID(10), RUNDES(20), LNAME(4,40), UNITS(2,40)
      COMMON /INDAT / NAM(40), IDX(40), VAL(40), CV(40), IFN(40),
     1                NQ(40), IQ(10,40), IDEC(40), NI, NYR
      COMMON /REHAB / RLABEL(4,31), RCOST(31), COSTKY(31), RKEY(6,31),
     1                IRB(31),IZR(50),NL(6),RS( 200),NDIM,NRB,LRN,NN
      COMMON /REHCHK/ ND, IR(6), LV(6), PCTA(2,6), XD(2,6), AGET(2),
     1                IRSEL, FAILT, IDF
      COMMON /TEST  / NTT, IDT(5), NTEST(11,5), ICONF(5), TESTC(5),
     1                AT(5), BT(5), CT(5), DT(5)
C
      DATA IBL8 /'        '/
      DATA NPAS /5/
      GO TO (100,200,300), ISW
  100 DO 110 I = 1, 40
          X(I)   = 0.
          CVX(I) = 0.
          VAL(I) = 0.
          CV(I)  = 0.
          IDX(I) = 0
          IFN(I) = 0
          NQ(I)  = 0
          IDEC(I)= 0
          NAM(I) = IBL8
          DO 105 J = 1, 4
              LNAME(J,I) = IBL8
```

```
  105     CONTINUE
  110 CONTINUE
C     SET ALL PARAMETERS DEALING WITH TEST PROGRAMS TO 0.
      NTT = 0
      DO 120 I = 1, 5
          IDT(I) = 0
          ICONF(I) = 0
          TESTC(I) = 0.
          AT(I) = 0.
          BT(I) = 0.
          CT(I) = 0.
          DT(I) = 0.
          DO 115 J = 1, 11
              NTEST(J,I) = 0
  115     CONTINUE
  120 CONTINUE
C     ADDS FOR LACK OF 'BLOCK DATA' IN MS-FORTRAN.
C     LSAVE NOT CURRENTLY USED, SO NO NEED TO INITIALIZE.
C     IS AVAILABLE FOR USE AS A LOGICAL UNIT NUMBER IF A SPECIAL
C     OUTPUT FILE IS DESIRED FOR A SPECIFIC PURPOSE.
      NDIM  = 200
      NN    =   6
      LRN   =  31
      NIN   =   5
      NOUT  =   6
      NDERV =   0
      LOUT  =   9
      RETURN
  200 CONTINUE
C
C     SET FUNCTIONS AND VARIABLES NOT AFFECTED BY TEST RESULTS
C     TO THEIR INITIAL (READ-IN) VALUES.
C
      DO 220 I = 1, NI
          ID = IDX(I)
          DO 210 J = 1, NTT
              IF (ID .EQ. IDT(J)) GO TO 220
  210     CONTINUE
          X(ID) = VAL(ID)
          CVX(ID) = CV(ID)
  220 CONTINUE
      RETURN
  300 CONTINUE
  900 RETURN
    1 FORMAT (1X,'FROM INITLZ - INITIAL VALUES OF VARS. AND C.V.')
    2 FORMAT (1X,8G10.2)
    3 FORMAT (1X,'NTST(I) FOR I=',I3,' ENTERED AS ',I5,'.'/
     1        1X,'ILLEGAL VALUE.  ABORT')
    5 FORMAT (1X,'ORIGINAL VALUE, STD. DEV. FOR VAR. ',I2,'=',2F10.3)
    6 FORMAT (1X,'IPASS, NR. TESTS, VAL., SIGMA =', 2I5,2F10.3)
      END
C
```

```
      SUBROUTINE DATACK (ISW,IFERR)
C     THIS ROUTINE CHECKS THE ORDER OF THE FUNCTIONS INPUT AGAINST
C     THE DEPENCENCIES  ON PREVIOUS FUNCTIONAL RESULTS.  THE FUNC-
C     TIONS ARE EVALUATED IN THE ORDER IN WHICH THEY WERE READ.
C     THE IQ VALUES ARE STORED IN SUBROUTINE -READIN- BY -ID-.
C     NQ(ID) MAY BE NEGATIVE, INDICATING DEPENDENCE OF A FUNCTION ON
C     VARIABLES WITH NO NEED FOR DERIVATIVES TO BE TAKEN.
C
      DIMENSION NED(20)
      CHARACTER*8 NAM
      COMMON /CTRL  / NIN, NOUT, NDERV, LSAVE, LOUT
      COMMON /INDAT / NAM(40), IDX(40), VAL(40), CV(40), IFN(40),
     1                NQ(40), IQ(10,40), IDEC(40), NI, NYR
      IFERR = 0
      NE = 0
      DO 100 I = 1,NI
          ID = IDX(I)
          NR = IABS(NQ(ID))
          IF (NR .EQ. 0) GO TO 100
          DO 50 J = 1,NR
              IF (IQ(J,ID).LT.ID) GOTO 50
              NE = NE + 1
              IF (NE .GE. 21) GOTO 110
              NED(NE) = ID
              NE = NE + 1
              NED(NE) = IQ(J,I)
   50     CONTINUE
  100 CONTINUE
  110 CONTINUE
      IF (NE.EQ.0) GOTO 999
      IFERR = 1
      NEM = MIN0(NE,20)
      DO 120 J = 1,NEM,2
          WRITE (    1,1)
          WRITE (NOUT,1) NED(J), NED(J+1)
  120 CONTINUE
    1 FORMAT (1X,'FOR ID =',I4,' A FUNCTIONAL REFERENCE IS REQUESTED'
     1 ' FOR ID =',I4,/1X,' WHICH IS CALCULATED AFTER THE ORIGINAL'
     2 ' FUNCTION.',/1X,' PLEASE CHECK ORDERING OF INPUT DATA.')
      IF (NE.EQ.21) WRITE (NOUT,2) NED(NE)
    2 FORMAT (/1X,' MORE THAN 10 ORDERING ERRORS FOUND.',
     1 /1X,' ID FOR LAST ERROR DETECTED WAS ',I2)
  999 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE READIN
      CHARACTER*8 RUNID, RUNDES, LNAME, UNITS, NAM
      CHARACTER*8 NM, IBL8
      CHARACTER*1 IBL
      DIMENSION IQI(10)
      COMMON /COSTIN/ CONSTC,USRREC,ANMNTC,ANUSRC,WIDTH,PCTINT
      COMMON /CTRL  / NIN, NOUT, NDERV, LSAVE, LOUT
      COMMON /HDG   / RUNID(10), RUNDES(20), LNAME(4,40), UNITS(2,40)
      COMMON /INDAT / NAM(40), IDX(40), VAL(40), CV(40), IFN(40),
     1                NQ(40), IQ(10,40), IDEC(40), NI, NYR
      COMMON /INTFC / ADTZ, PCTPYR, PCTTRK, SALPTK, FY
      COMMON /TEST  / NTT, IDT(5), NTEST(11,5), ICONF(5), TESTC(5),
     1                AT(5), BT(5), CT(5), DT(5)
C
      DATA IBL, IBL8 /' ','        '/, IDMAX, NTTMAX /40, 5/
C     IDMAX = DIMENSION ON ARRAYS IN /INDAT/.
C     NTTMAX= MAX NUMBER OF TEST TYPES ALLOWED BY DIMENSIONS IN /TEST/.
C
      READ (NIN,1) RUNID
      WRITE (1,2) RUNID
C     HEADING FOR ALL OUTPUT PAGES
      READ (NIN,1) RUNDES
      WRITE (1,2) RUNDES
C     MORE COMPLETE DESCRIPTION OF PARTICULAR RUN - 2 CARDS.(COLS 1-79)
      I = 0
  100 I = I + 1
      READ (NIN,10) NM, ID, VALZ, CVZ, IFNZ, IDC, NR, (IQI(J),J=1,10)
      WRITE (1,20)  NM, ID, VALZ, CVZ, IFNZ, IDC, NR, (IQI(J),J=1,10)
      IF (NM .EQ. IBL8) GO TO 200
C     CHECK INPUT ID AGAINST MAX ALLOWABLE BY DIMENSIONS.
      IF (ID .LE. IDMAX) GO TO 105
      WRITE (   1,31) ID, IDMAX, NM
      WRITE (NOUT,31) ID, IDMAX, NM
      NYR = 0
      RETURN
  105 NAM(ID) = NM
      IDX(I) = ID
      NQ(ID) = NR
C     NQ(ID) MAY BE NEGATIVE, INDICATING DEPENDENCE OF A FUNCTION ON
C     VARIABLES WITH NO NEED OR DESIRE FOR DERIVATIVES TO BE TAKEN.
      NR = IABS(NR)
      VAL(ID) = VALZ
      CV(ID)  = CVZ
      IFN(ID) = IFNZ
      IDEC(ID) = IDC
      DO 110 J = 1, NR
          IQ(J,ID) = IQI(J)
  110 CONTINUE
      GO TO 100
C     END THIS LOOP ON A LINE OF 40 COLS OR MORE, BLANK IN COL 1-8.
  200 CONTINUE
```

```
      NI = I - 1
      DO 250 I = 1, NI
          READ (NIN,14) NM, ID, (UNITS(J,ID),J=1,2),(LNAME(J,ID),J=1,4)
          WRITE (1,24)  NM, ID, (UNITS(J,ID),J=1,2),(LNAME(J,ID),J=1,4)
  250 CONTINUE
C
      READ (NIN, 12) NYR, NTT, FY
      IF (FY .LT. 1.) FY = 1.
      WRITE (1,  22) NYR, NTT, FY
C     NYR - NUMBER OF YEARS IN ANALYSIS PERIOD.
C     NTT - NUMBER OF DIFFERENT TEST PROCEDURES TO BE EVALUATED
C           SIMULTANEOUSLY (CURRENTLY MUST BE .LE. 5)
C     FY  - FIRST YEAR FOR WHICH THE SYSTEM IS TO BE EVALUATED FOR
C           FAILURE.  USE TO SAVE TIME IF APPROX FAILURE TIME KNOWN.
C           MUST NOT BE GREATER THAN 1 -IF- ANY DISTRESS DEPENDS
C           DIRECTLY ON THE DEVELPMENT OF ANOTHER DISTRESS.
C
      IF (NTT .GT. NTTMAX) THEN
           WRITE (1, 32) NTT, NTTMAX
           WRITE (6, 32) NTT, NTTMAX
           NYR = 0
           RETURN
           ENDIF
      DO 270 I = 1, NTT
      READ (NIN,18) IDT(I), NTS, (NTEST(J+1,I), J=1,NTS)
      NTS = MIN0(NTS,10)
      WRITE ( 1,28) IDT(I), NTS, (NTEST(J+1,I), J=1,NTS)
      READ (NIN,19) ICONF(I), TESTC(I), AT(I), BT(I), CT(I), DT(I)
      WRITE ( 1,29) ICONF(I), TESTC(I), AT(I), BT(I), CT(I), DT(I)
      NTEST(1,I) = NTS
      IF (ICONF(I) .EQ. 0) GO TO 270
C     IF NON-ZERO CONFIDENCE LEVEL SPECIFIED, IGNORE ANY SPECIFICATION
C     OF VALUES FOR AT-DT .
      AT(I) = 0.
      BT(I) = 0.
      CT(I) = 0.
      DT(I) = 0.
  270 CONTINUE
C
C     READ PAVEMENT COSTS AND MISC. COSTS, LANE WIDTH, AND INTEREST RATE
      READ (NIN, 11) CONSTC, USRREC, ANMNTC, ANUSRC
      WRITE ( 1, 21) CONSTC, USRREC, ANMNTC, ANUSRC
      READ (NIN, 11) WIDTH, PCTINT
      WRITE ( 1, 21) WIDTH, PCTINT
  299 CONTINUE
      RETURN
    1 FORMAT (9A8,A7)
    2 FORMAT (1X,9A8,A7)
   10 FORMAT (A8,2X,I2,E12.4,2X,F4.2,1X,I2,1X,I2,2X,I2,10I3)
   11 FORMAT (5F10.3)
   12 FORMAT (2I5,F10.2)
   13 FORMAT (I2,8X,4(I2,F7.1,1X,F5.1),1X/(10X,4(I2,F7.1,1X,F5.1)))
```

```
   14 FORMAT (A8,2X,I2,3X,A8,A5,2X,3A8,A6)
   15 FORMAT (I5,5X,F10.2)
   16 FORMAT (8(I3, F7.3))
   17 FORMAT (10I5)
   18 FORMAT (12I5)
   19 FORMAT (I5,5X,5F10.2)
   20 FORMAT (1X,A8,1X,I2,E12.4,2X,F4.2,1X,I2,1X,I2,2X,I2,10I3)
   21 FORMAT (1X,5F10.3)
   22 FORMAT (1X,2I5,F10.2)
   23 FORMAT (1X,I2,6X, 4(I2,F7.1,1X,F5.1),1X/(10X,4(I2,F7.1,1X,F5.1)))
   24 FORMAT (1X,A8,2X,I2,3X,A8,A5,2X,3A8,A6)
   25 FORMAT (1X,I5,5X,F10.2)
   26 FORMAT (1X, 7(I4, F7.3))
   27 FORMAT (1X, 10I5)
   28 FORMAT (1X,12I5)
   29 FORMAT (1X,I5,5X,5F10.2)
   31 FORMAT (/1X,'ID =', I3, 'IS .GT. THAN MAXIMUM ALLOWED (=',I2,
     1            ') ON ',A8,' CARD.  ABORT RUN')
   32 FORMAT (/1X,'NTT GREATER THAN THE NUMBER (NTTMAX) PERMITTED BY '
     1        'CURRENT DIMENSIONS'/1X,'NTT=',I4,', NTTMAX=',I4)
C
      END
C
      SUBROUTINE INPRT
      CHARACTER*12 WORD3, WORD4, WORDX
      CHARACTER*8 RUNID, RUNDES, LNAME, UNITS, NAM, RLABEL
      CHARACTER*8 WMEAN, WGTHAN, LBLCST
      CHARACTER*4 WORD, WORD1, WORD2
      CHARACTER*1 DASH
      INTEGER COSTKY, RKEY, RS
      DIMENSION LBLCST(10), Y(20), CY(20), IDY(20), WMEAN(2), WGTHAN(2)
      COMMON /COSTIN/ CONSTC,USRREC,ANMNTC,ANUSRC,WIDTH,PCTINT
      COMMON /CTRL  / NIN, NOUT, NDERV, LSAVE, LOUT
      COMMON /CURTFC/ CURADT, CURTRK, CURSAL, CUMVEH, CUMTRK, CUMSAL
      COMMON /CURVAL/ X(40), CVX(40), DFDX(40), AGE
      COMMON /HDG   / RUNID(10), RUNDES(20), LNAME(4,40), UNITS(2,40)
      COMMON /INDAT / NAM(40), IDX(40), VAL(40), CV(40), IFN(40),
     1                NQ(40), IQ(10,40), IDEC(40), NI, NYR
      COMMON /INTFC / ADTZ, PCTPYR, PCTTRK,SALPTK, FY
      COMMON /RECRIT/ XCC(2,4,10), ICC(3,10), NCC
      COMMON /REHAB / RLABEL(4,31), RCOST(31), COSTKY(31), RKEY(6,31),
     1                IRB(31),IZR(50),NL(6),RS( 200),NDIM,NRB,LRN,NN
      COMMON /REHCHK/ ND, IR(6), LV(6), PCTA(2,6), XD(2,6), AGET(2),
     1                IRSEL, FAILT, IDF
      COMMON /TEST  / NTT, IDT(5), NTEST(11,5), ICONF(5), TESTC(5),
     1                AT(5), BT(5), CT(5), DT(5)
      DATA LBLCST /' SQ. YD.', 9*'        ' /
      DATA WORD3, WORD4 /'GREATER THAN', 'LESS THAN   '/
      DATA WORD1, WORD2 /'STAT', 'FUNC' /
      DATA WMEAN  /'(MEAN VA', 'LUE)    '/
      DATA WGTHAN /'FOR MORE', ' THAN   '/
      DATA NCOL /6/
```

```
      DATA DASH /'-'/
  100 CONTINUE
C     INPUT DATA PRETTY-PRINT
      WRITE (NOUT, 1000) (DASH, I=1,10), RUNID
      WRITE (NOUT, 1001) (DASH, I=1,16), RUNDES
C     PRINT COST AND GEOMETRICAL DATA
      WRITE (NOUT, 1003) (DASH, I=1,32), CONSTC,ANMNTC,ANUSRC,USRREC,
     1                   PCTINT
      WRITE (NOUT, 1004) (DASH, I=1,24), WIDTH
C     PRINT TRAFFIC AND MISC. VARIABLES.  (ID .LT. 10)
      WRITE (NOUT, 1005) (DASH, I=1,20)
      DO 105 I = 1, NI
          ID = IDX(I)
          IF (ID .GT. 10) GO TO 105
          IF (IFN(ID) .NE. 0) GO TO 105
          WRITE (NOUT,1011) NAM(ID), ID, VAL(ID), (UNITS(J,ID),J=1,2),
     1                      CV(ID), (LNAME(J,ID),J=1,4)
  105 CONTINUE
      WRITE (NOUT, 1010) (DASH, I=1,22)
      DO 110 I = 1, NI
          ID = IDX(I)
          IF (ID .LE. 10) GO TO 110
          IF (IFN(ID) .NE. 0) GO TO 110
          WRITE (NOUT,1011) NAM(ID), ID, VAL(ID), (UNITS(J,ID),J=1,2),
     1                      CV(ID), (LNAME(J,ID),J=1,4)
  110 CONTINUE
      WRITE (NOUT,1014) (DASH, I=1,38)
      DO 120 I = 1, NI
          ID = IDX(I)
          IF (IFN(ID) .EQ. 0) GO TO 120
          WRITE (NOUT,1015) NAM(ID), (UNITS(J,ID), J=1,2), ID, IFN(ID),
     1                      (LNAME(J,ID), J=1,4)
          NR = IABS(NQ(ID))
          IF (NR .EQ. 0) GO TO 120
          DO 115 J = 1, NR
              L = IQ(J,ID)
              WRITE (NOUT,1016) L, NAM(L), (LNAME(K,L),K=1,4)
  115     CONTINUE
  120 CONTINUE
C     PRINT DISTRESS CRITERIA
      WRITE (NOUT,1002)
      WRITE (NOUT,1101) (DASH, I=1,24)
      DO 125 I=1, NCC
          ID = ICC(1,I)
          NC = ICC(2,I)
          NCP = NC + 1
          WORDX = WORD3
          IF (IDEC(ID) .EQ. 1) WORDX = WORD4
          IF (XCC(2,NC,I) .EQ. 0) WRITE (NOUT,1102) NAM(ID), ID, NCP,
     1                            WORDX,XCC(1,NC,I), WMEAN
          IF (XCC(2,NC,I) .GT. 0) WRITE (NOUT,1102) NAM(ID), ID, NCP,
     1                            WORDX,XCC(1,NC,I), WGTHAN,XCC(2,NC,I)
```

```
          IF (NC .EQ. 1) GO TO 125
          NCM = NC - 1
          DO 124 K = 1, NCM
              J = NCM + 1 - K
              JP = J + 1
              IF (XCC(2,J,I) .EQ. 0) WRITE (NOUT,1103) JP, WORDX,
     1                               XCC(1,J,I), WMEAN
              IF (XCC(2,J,I) .GT. 0) WRITE (NOUT,1103) JP, WORDX,
     1                               XCC(1,J,I), WGTHAN, XCC(2,J,I)
 124      CONTINUE
 125  CONTINUE
C     PRINT REHAB OPTION INPUT.
      WRITE (NOUT,1111) (DASH, I=1,25)
      DO 130 I = 1, NRB
      ICS = COSTKY(I)
      WRITE (NOUT,1112) IRB(I), (RKEY(J,I),J=1,6),RCOST(I),
     1                  LBLCST(ICS), (RLABEL(J,I), J=1, 4)
 130  CONTINUE
      WRITE (NOUT,1020) (DASH, I=1,38)
      DO 135 L = 1,NTT
          WORD = WORD1
          IF (ICONF(L) .EQ. 0) WORD = WORD2
          IDZ = IDT(L)
          WRITE (NOUT,1021) IDZ, NAM(IDZ), WORD, ICONF(L),
     1                      AT(L), BT(L), CT(L), DT(L), TESTC(L)
 135  CONTINUE
      WRITE (NOUT,1022) (DASH, I=1,46)
      DO 140 L = 1, NTT
          NT = NTEST(1,L)
          ID = IDT(L)
          DO 138 J = 1, NT
              N = NTEST(J+1, L)
              CALL SETVAR (ID, N, L)
              Y(J) = X(ID)
              CY(J) = CVX(ID)
 138      CONTINUE
          M = MIN0(4,NT)
          WRITE (NOUT,1023) ID, NAM(ID), (NTEST(J+1,L), Y(J), J=1,M)
          WRITE (NOUT,1024) (CY(J), J=1,M)
          IF (NT .LE. 4) GO TO 140
          M = MIN0(NT, 8)
          WRITE (NOUT,1023) ID, NAM(ID), (NTEST(J+1,L), Y(J), J=5,M)
          WRITE (NOUT,1024) (CY(J), J=5,M)
          IF (NT .LE. 8) GO TO 140
          WRITE (NOUT,1023) ID, NAM(ID), (NTEST(J+1,L), Y(J), J=9,NT)
          WRITE (NOUT,1024) (CY(J), J=9,NT)
 140  CONTINUE
      RETURN
1000  FORMAT (1H1,'RUN TITLE:'/1X, 10A1//1X,9A8,A7/)
1001  FORMAT (/1X,'RUN DESCRIPTION:'/1X, 16A1 /
     1         /1X, 9A8, A7/1X, 9A8, A7)
1002  FORMAT (1H1 //)
```

```
1003 FORMAT (//1X,'INPUT DATA (COSTS)                 '
    1         /1X,'(THOUSANDS OF DOLLARS/LANE MILE'/1X,32A1,
    2        //1X,'INITIAL CONSTRUCTION    ',F7.1,
    3         /1X,'ANNUAL MAINTENANCE COST ',F7.1,
    4         /1X,'ANNUAL USER COST        ',F7.1,
    5         /1X,'USER COST OF REHAB.     ',F7.1,
    6        //1X,'COST OF MONEY (INTEREST)',F7.1,' PERCENT')
1004 FORMAT (//1X,'INPUT DATA (GEOMETRICAL)'/1X,24A1,
    1         /1X,'LANE WIDTH (FEET)       ',F7.1)
1005 FORMAT (//1X,'INPUT DATA (TRAFFIC)' / 1X,20A1 //
    1          1X,' ABBREV.  ID                          COEF.    ',
    2             '      FULL'/
    3          1X,'  NAME    NO.   VALUE       UNITS      OF VAR.   ',
    4             '      NAME'/)
1010 FORMAT (//1X,'INPUT DATA (MATERIALS)'/ 1X, 22A1 //
    1          1X,' ABBREV.  ID                          COEF.    ',
    2             '      FULL'/
    3          1X,'  NAME    NO.   VALUE       UNITS      OF VAR.   ',
    4             '      NAME'/)
1011 FORMAT (1X,A8,2X,I2,2X,G11.2,1X,A8,A5,F5.2,5X,3A8,A6)
1014 FORMAT (/' SPECIFICATION OF INDEPENDENT VARIABLES'
    1        /' FOR INDICATED MODELS'/1X,38A1,
    3       //'  ABBREV.               ID  FN  DEPENDENT ON',
    4        /'   NAME     UNITS       NO. NO. ID    NAME      ',
    5             'FULL NAME' )
1015 FORMAT (/1X,A8,1X,A8,A5,1X,I2,1X,I3,18X,3A8,A6)
1016 FORMAT (1X,31X,I2,2X,A8,4X,3A8,A6)
1017 FORMAT (//1X,'INPUT DATA (CONTROL)' /1X, 20A1)
1018 FORMAT (/ 1X,'LENGTH OF ANALYSIS (YEARS) = ', I2)
1020 FORMAT (//' PARAMETERS DETERMINING VARIABLE VALUES'
    1         /' AS A FUNCTION OF NUMBER OF TESTS       ',/1X,38A1,
    2       //'                          CONF.    PARAMETERS FOR     '
    3         '   COST PER   '
    4        /'            TYPE OF     LEVEL  FUNCTIONAL VARIATION   '
    5         '     TEST     '
    6        /'  ID   NAME   VARIATION   (PCT)    A     B     C     D '
    7         '   (DOLLARS)  '/)
1021 FORMAT (2X,I2, 2X,A8, 3X,A4, 5X,I3, 2X,4F6.2, 3X,F6.0)
1022 FORMAT (//' VALUES OF TESTED VARIABLES USED IN SIMULATIONS '
    1         /' (CALCULATED FROM NUMBER OF TESTS)'/1X,46A1,
    2       //'             NR OF   VALUE   NR OF   VALUE   NR OF   VAL'
    3         'UE   NR OF  VALUE'
    4        /'  ID   NAME    TESTS   (C.V.)  TESTS   (C.V.)  TESTS  (C.'
    5         'V.)  TESTS  (C.V.)'/)
1023 FORMAT (2X,I2,2X,A8,1X,I3,1X,F9.4, 2X,I3,1X,F9.4, 2X,I3,1X,F9.4,
    1         2X,I3,1X,F9.4)
1024 FORMAT (14X, 5X,F9.4, 6X,F9.4, 6X,F9.4, 6X,F9.4)
1101 FORMAT(/' INPUT CRITERIA AFFECTING'
    1       /' MAINT OR REHAB DECISIONS',/1X,24A1/
    2       /'              ASSIGNED ASSIGNED      DEFINITION OF ASSIGNED'
    3       /' CRITERION  ID NO.  LEVEL NO.        CRITERION LEVEL      '
    4       /)
```

```
1102 FORMAT (2X,A8,4X,I2,7X,I2,5X,A12,1X,F9.2,1X,A8,A5,1X,F4.1,
    1        ' PCT AREA' )
1103 FORMAT (23X,I2,5X,A12,1X,F9.2,1X,A8,A5,1X,F4.1,' PCT AREA')
1111 FORMAT(/' INPUT MAINTENANCE OR'
    1        /' REHABILITATION PROCEDURES'/1X,25A1/
    2        /'   NR   KEYS    COST   COST',13X,'DESCRIPTION'
    3        /15X,'(DOL.) UNITS '/  )
1112 FORMAT (3X,I2,2X,6I1,1X,F6.2,1X,A8,6X,4A8)
     END
```

```
      SUBROUTINE INRB
C
C     THIS SUBROUTINE INPUTS THE DISTRESS CRITERIA AND THE REHAB.
C     DECISION TREE (OR NETWORK) INFORMATION
C
      INTEGER COSTKY, RKEY, RS
      CHARACTER*8 RLABEL, RLBL
      DIMENSION RLBL(4)
      COMMON /CTRL/ NIN, NOUT, NDERV, LSAVE, LOUT
      COMMON /RECRIT/ XCC(2,4,10), ICC(3,10), NCC
      COMMON /REHAB / RLABEL(4,31), RCOST(31), COSTKY(31), RKEY(6,31),
     1                IRB(31),IZR(50),NL(6),RS( 200),NDIM,NRB,LRN,NN
      DATA RLBL /'DO NOTHI', 'NG      ', 2*'        '/
C
C     SET NN = MAX. NUMBER OF LEVELS IN NETWORK ANALYSIS BASED ON CODE
C     IN SUBROUTINE  -SETRB- AND DIMENSIONS IN /REHAB/.
      NN = 6
C
C     INITIALIZE ALL -RKEY- TO 0.
      DO 90 I = 1, NN
          NL(I) = 1
          DO 90 J = 1, 31
              RKEY(I,J) = 0
   90 CONTINUE
C
      I = 0
   95 I = I + 1
      READ (NIN,3) (ICC(J,I), J=1,3), (XCC(1,J,I),XCC(2,J,I), J=1,4)
      WRITE (1, 4) (ICC(J,I), J=1,3), (XCC(1,J,I),XCC(2,J,I), J=1,4)
      IF (ICC(1,I) .GT. 0) GO TO 95
      NCC = I - 1
C     LIMIT NUMBER OF REHAB CRITERIA TO BE USED.
      NCC = MIN0(NCC,NN)
      DO 100 I = 1, NCC
          NL(I) = ICC(2,I) + 1
  100 CONTINUE
C     NOTE DEFAULT NL=1 FOR UNUSED DISTRESS SLOTS (NCC .LT. I .LE. 6)
C
      I = 0
  110     I = I + 1
          READ (NIN,2) IRB(I), (RKEY(J,I), J=1,6), RCOST(I), COSTKY(I)
     1                          ,(RLABEL(J,I), J=1,4)
          WRITE (1, 2) IRB(I), (RKEY(J,I),J=1,6), RCOST(I), COSTKY(I)
     1                          ,(RLABEL(J,I), J=1,4)
          IF (IRB(I) .GT. 0) GO TO 110
C     SET LAST OPTION TO 'DO-NOTHING' ALTERNATIVE.
      IRB(I) = LRN
      NRB = I
      COSTKY(I) = 10
      DO 120 J=1,4
          RLABEL(J,I) = RLBL(J)
```

```
  120 CONTINUE
      RETURN
    1 FORMAT (6(1X,I1))
    2 FORMAT (3X,I2,1X,6I1,3X,F5.2,1X,I1,3X,4A8)
    3 FORMAT (3I3,1X,8F5.1)
    4 FORMAT (1X,3I3, 1X,8F7.1)
      END
C
      SUBROUTINE SETRB
C
C     THIS SUBROUTINE USES THE INFORMATION READ IN -INRB- AND SETS UP
C     UP THE REHABILITATION OPTIONS TO BE SELECTED FOR ANY COMBINATION
C     OF DISTRESSES REQUIRING REHABILITATION.
C
      INTEGER RKEY, COSTKY, RS
      CHARACTER*8 RLABEL
      DIMENSION LV(6)
      COMMON /REHAB / RLABEL(4,31), RCOST(31), COSTKY(31), RKEY(6,31),
     1                IRB(31),IZR(50),NL(6),RS( 200),NDIM,NRB,LRN,NN
C
C     INITIAL SETUP
C     INITIALIZE ENTIRE ARRAY TO THE 'DO-NOTHING' ALTERNATIVE.
C     BE SURE ALL -RKEY- SET TO 0 BEFORE READING REHAB OPTIONS.
C
      DO 10 LOC = 1, NDIM
          RS(LOC) = LRN
C         LRN - LAST REHAB NUMBER.  SERVES AS "DEFAULT" REHAB.
   10 CONTINUE
      NRM = NRB - 1
C     NN = 6      SET IN INRB.
C     NN IS THE NUMBER OF -LEVELS- IN THE REHABILITATION ANALYSIS.
C     SKIP SETTING THE DO-NOTHING ALTERNATIVE.  ALREADY SET.
      DO 100 I = 1, NRM
          IS = IRB(I)
          J = 0
          JL = 0
C     ASSUME 6-DIGIT CODE MAXIMUM
      KB1 = MAX0(RKEY(1,I), 1)
      KE1 =KB1
      IF (RKEY(1,I) .EQ. 0) KE1 = NL(1)
      KB2 = MAX0(RKEY(2,I), 1)
      KE2 = KB2
      IF (RKEY(2,I) .EQ. 0) KE2 = NL(2)
      KB3 = MAX0(RKEY(3,I), 1)
      KE3 = KB3
      IF (RKEY(3,I) .EQ. 0) KE3 = NL(3)
      KB4 = MAX0(RKEY(4,I), 1)
      KE4 = KB4
      IF (RKEY(4,I) .EQ. 0) KE4 = NL(4)
      KB5 = MAX0(RKEY(5,I), 1)
      KE5 = KB5
      IF (RKEY(5,I) .EQ. 0) KE5 = NL(5)
```

```
      KB6 = MAX0(RKEY(6,I), 1)
      KE6 = KB6
      IF (RKEY(6,I) .EQ. 0) KE6 = NL(6)
C     WRITE (1,201) I, IS, KB1,KB2,KB3,KB4,KB5,KB6,
C    1                     KE1,KE2,KE3,KE4,KE5,KE6
      DO 30 K1 = KB1, KE1
          LV(1) = K1
          DO 30 K2 = KB2, KE2
              LV(2) = K2
              DO 30 K3 = KB3, KE3
                  LV(3) = K3
                  DO 30 K4 = KB4, KE4
                      LV(4) = K4
                      DO 30 K5 = KB5, KE5
                          LV(5) = K5
                          DO 30 K6 = KB6, KE6
                              LV(6) = K6
                              LOC = LOCN (LV, NL, NN, NDIM)
                              J = J + 1
                              IF (RS(LOC) .NE. LRN) GO TO 30
                              RS(LOC) = IS
                              JL = JL + 1
   30 CONTINUE
      NJ = J
C     WRITE (1,202) NJ, JL
C     NOTE THAT -RS(LOC)- IS NOT CHANGED IF ALREADY SET TO A REHAB
C     OPTION OTHER THAN THE 'DO-NOTHING' ALTERNATIVE.
  100 CONTINUE
      RETURN
  201 FORMAT (1X,'LOOP LIMITS KB1-KE6 FOR REHAB',I3,' CODE', I3/
     1         1X, 6I5/ 1X,6I5)
  202 FORMAT (1X,I4,' LOCATIONS CHECKED', I4,' LOCNS STORED' /)
C    1         1X,'THE LOCATIONS ARE:')
  203 FORMAT (1X,15I4)
      END
C
      FUNCTION LOCN (LV, NL, NN, NDIM)
      DIMENSION LV(NN), NL(NN)
C
C     EVALUATES THE LOCATION IN A SINGLY-DIMENSIONED ARRAY CORRES-
C     PONDING TO THE INDICES (LV(1),...,LV(NN)) IN AN NN-DIM. ARRAY
C     WITH DIMENSIONS (NL(1),...,NL(NN)).  CHECKS RESULTING POSITION
C     AGAINST STATED SIZE -NDIM- OF SINGLY DIMENSIONED ARRAY.
C
      MUL = 1
      LOC = LV(1)
      DO 10 I = 2, NN
          MUL = MUL*NL(I-1)
          LOC = LOC + MUL*(LV(I) - 1)
   10 CONTINUE
      IF (LOC .GT. NDIM) GO TO 20
      LOCN = LOC
```

```
      RETURN
   20 WRITE (1, 1) LOC, NDIM, NN, (LV(I),I=1,NN), (NL(I),I=1,NN)
    1 FORMAT (1X, 'LOC (=', I5,') IS .GT. ARRAY SIZE (=',I5,').' /
     1       1X,'NN, LV, NL =',I5/1X, 20I3)
      STOP 'LOCN'
      END
C
      FUNCTION INVNDX (IA, N, IB, M, IERR)
C
C     PURPOSE: IF L=IA(J), THEN SET IB(L)=J (INVERTS THE INDEXING).
C
      DIMENSION IA(N), IB(M)
      IERR = 0
      MAX = 0
      DO 1 J=1, M
    1 IB(J) = 0
      DO 10 J = 1, N
          L = IA(J)
          IF (L .GT. M) GO TO 5
          IB(L) = J
          MAX = MAX0(MAX, L)
          GO TO 10
    5     IERR = IERR + 1
   10 CONTINUE
C
C     SET FUNCTION VALUE.
      INVNDX = MAX
      RETURN
      END
```

```
      SUBROUTINE LOOP (NPASS)
      CHARACTER*8 RUNID, RUNDES, NAM, WORD, UNITS, LNAME, RLABEL
      INTEGER RS, RKEY, COSTKY
      COMMON /COSTIN/ CONSTC, USRREC, ANMNTC,ANUSRC,WIDTH,PCTINT
      COMMON /CTRL  / NIN, NOUT, NDERV, LSAVE, LOUT
      COMMON /CURTFC/ CURADT, CURTRK, CURSAL, CUMVEH,CUMTRK, CUMSAL
      COMMON /CURVAL/ X(40), CVX(40), DFDX(40), AGE
      COMMON /HDG   / RUNID(10), RUNDES(20), LNAME (4,40), UNITS(2,40)
      COMMON /INDAT / NAM(40), IDX(40), VAL(40), CV(40), IFN(40),
     1                NQ(40), IQ(10,40), IDEC(40), NI, NYR
      COMMON /INTFC / ADTZ, PCTPYR, PCTTRK, SALPTK, FY
      COMMON /RECRIT/ XCC(2,4,10), ICC(3,10), NCC
      COMMON /REHCHK/ ND, IR(6), LV(6), PCTA(2,6), XD(2,6), AGET(2),
     1                IRSEL, FAILT, IDF
      COMMON /REHAB / RLABEL(4,31), RCOST(31), COSTKY(31), RKEY(6,31),
     1                IRB(31),IZR(50),NL(6),RS( 200),NDIM,NRB,LRN,NN
      COMMON /TEST  / NTT, IDT(5), NTEST(11,5), ICONF(5), TESTC(5),
     1                AT(5), BT(5), CT(5), DT(5)
C
      NPASS = 0
C     BEGIN LOOP OVER THE TEST VARIABLES.
      ID5 = IDT(5)
      N5 = MAX0(1,NTEST(1,5))
      DO 100 I5 = 1, N5
          M5 = NTEST(I5+1, 5)
          CALL SETVAR (ID5, M5, 5)
          ID4 = IDT(4)
          N4 = MAX0(1,NTEST(1,4))
          DO 100 I4 = 1, N4
              M4 = NTEST(I4+1, 4)
              CALL SETVAR (ID4, M4, 4)
              ID3 = IDT(3)
              N3 = MAX0(1,NTEST(1,3))
              DO 100 I3 = 1, N3
                  M3 = NTEST(I3+1, 3)
                  CALL SETVAR (ID3, M3, 3)
                  ID2 = IDT(2)
                  N2 = MAX0(1,NTEST(1,2))
                  DO 100 I2 = 1, N2
                      M2 = NTEST(I2+1, 2)
                      CALL SETVAR (ID2, M2, 2)
                      ID1 = IDT(1)
                      N1 = MAX0(1,NTEST(1,1))
                      DO 100 I1 = 1, N1
                          M1 = NTEST(I1+1, 1)
                          CALL SETVAR (ID1, M1, 1)
C
C     NOW ALL TEST RELATED VARIABLES ARE SET.
C
                          CALL KERNEL (LAST)
```

```
C
C     KERNEL IS THE -CORE- OF THE PROGRAM, LOOPING OVER AGE FOR A
C     SET OF PERFORMANCE RELATIONS AND A SPECIFIC SET OF TEST NUMBERS
C     (AND RELATED TEST VALUES AND VARIANCES) TO FIND TIME AND TYPE
C     OF FAILURE.
C
                        CALL DOCOST (M1, M2, M3, M4, M5, COST, TCOST)
C
C     DOCOST OBTAINS THE UNIFORM ANNUAL COST AND UNIFORM ANNUAL TESTING
C     COST FOR THIS SET OF TEST NUMBERS.
C
                        CALL SAVRES (M1, M2, M3, M4, M5, COST, TCOST)
C
C     SAVRES SAVES RESULTS FOR AGE AT FAILURE, DISTRESS CAUSING FAILURE,
C     AND SELECTED REHABILITATION FOR THIS SET OF TEST NUMBERS.
C
C     NOW INCREMENT PASS COUNTER
                        NPASS = NPASS + 1
  100 CONTINUE
      RETURN
      END
C
      SUBROUTINE SETVAR (ID, N, L)
C
C     INPUT VARIABLES:
C     ID - ID NUMBER OF VARIABLE WHOSE VALUE IS TO BE VARIED
C     N  - NUMBER OF TESTS PERFORMED TO DETERMINE THIS VALUE
C     L  - LOCATION OF THIS VARIABLE IN THE LIST OF TESTING INPUTS.
C
      CHARACTER*8 NAM, ERRMSG(6,2)
      COMMON /CURVAL/ X(40), CVX(40), DFDX(40), AGE
      COMMON /INDAT / NAM(40), IDX(40), VAL(40), CV(40), IFN(40),
     1                NQ(40), IQ(10,40), IDEC(40), NI, NYR
      COMMON /TEST  / NTT, IDT(5), NTEST(11,5), ICONF(5), TESTC(5),
     1                AT(5), BT(5), CT(5), DT(5)
      DATA ERRMSG /'DEG. OF ','FREEDOM=','0 ABORT ','IN TVAL ',
     1             '        ','        ',
     2             'INPUT CO','NF. LEVE','L NOT=75',', 90, 95',
     3             'OR 99 - ','ABORT   '/
C     CHECK IF THIS IS FOR AN -ACTIVE- VARIABLE.
      IF (ID .EQ. 0) RETURN
C     IF YES, THEN SET UP NEEDED TEMPORARY VARIABLES.
      VZ = VAL(ID)
      SIGMA = CV(ID)*VZ
      XN = N
      XNP = XN + 1.
      SIG = SIGMA
C
C     SEE WHAT KIND OF VARIATION WITH NUMBER OF TESTS IS EXPECTED.
C
      IF (AT(L) .EQ. 0. .OR. BT(L) .EQ. 0.) GO TO 20
C
```

```
C     HERE IF CONTRACTOR VARIATION OF MEAN VALUES.
C     WE USE AN -ASSUMED- MATHEMATICAL FORM FOR THIS VARIATION.
C     THIS EQUATION SHOULD -NOT- BE USED WITHOUT INDEPENDENT
C     VERIFICATION.
      X(ID) = VZ * (1. + AT(L) * XNP**BT(L))
      GO TO 30
C
C     HERE FOR 'STATISTICAL CONFIDENCE LEVEL' TYPE OF VARIATION.
   20 ICON = ICONF(L)
      N1 = N - 1
      X(ID) = VZ + TVAL(N1, ICON, IERR) * SIGMA / SQRT(XN)
      IF (IERR .GT. 0) GO TO 99
C     NOW EXAMINE THE TYPE OF VARIATION OF STD DEV. DESIRED, IF ANY.
   30 IF (CT(L) .EQ. 0. .OR. DT(L) .EQ. 0.) GO TO 40
      SIG = SIGMA * (1. + CT(L) * XNP**DT(L))
   40 CVX(ID) = SIG / X(ID)
      RETURN
C
   99 WRITE (1,101) (ERRMSG(I,IERR), I=1,6)
      WRITE (1,102) ID, N, L, ICON
  101 FORMAT (1X,6A8)
  102 FORMAT (1X,'ENTRY VALUES OF ID, N, L =', 3I5, 'ICON = ',I5)
      STOP
      END
C
      SUBROUTINE DOCOST (M1,M2,M3,M4,M5,COST,TCOST)
C
C     -COST- IS UNIFORM ANNUAL COST OF CONSTRUCTION, REPAIR, MAINT., USER COST.
C     -TCOST- IS COST OF TESTING FOR THIS COMBINATION OF TESTS.
C
      CHARACTER*8 RLABEL
      CHARACTER*2 TF1,TF2
      INTEGER RS, RKEY, COSTKY
      COMMON /REHCHK/ ND, IR(6), LV(6), PCTA(2,6), XD(2,6), AGET(2),
     1                IRSEL, FAILT, IDF
      COMMON /REHAB / RLABEL(4,31), RCOST(31), COSTKY(31), RKEY(6,31),
     1                IRB(31),IZR(50),NL(6),RS( 200),NDIM,NRB,LRN,NN
      COMMON /COSTIN/ CONSTC, USRREC, ANMNTC, ANUSRC, WIDTH, PCTINT
      COMMON /TEST  / NTT, IDT(5), NTEST(11,5), ICONF(5), TESTC(5),
     1                AT(5), BT(5), CT(5), DT(5)
      DATA TF1, TF2 /'AP', 'AF'/
C
      IZ = IZR(IRSEL)
      COSTR = RCOST(IZ)*(WIDTH/3.)*(5280./3.)/1000.
      F1 = CMPFAC (TF1, PCTINT, FAILT)
      F2 = CMPFAC (TF2, PCTINT, FAILT)
      COST = F2*(USRREC + COSTR) + F1*CONSTC + ANMNTC + ANUSRC
      TCOST = F1*(M1*TESTC(1) + M2*TESTC(2) + M3*TESTC(3) + M4*TESTC(4)
     1                         + M5*TESTC(5) )/1000.
C
C     WRITE (1,1) IZ, PCTINT, F1, F2, RCOST(IZ), COSTR, COST, TCOST
C   1 FORMAT (1X,'FROM DOCOST:  IZ, PCTINT, F1,F2, RCOST(IZ),COSTR,'
```

```
C    1           ' COST, TCOST='/1X, I2, F7.2,2F10.5,F7.2, 3F12.5)
      RETURN
      END
C
      SUBROUTINE SAVRES (M1, M2, M3, M4, M5, COST, TCOST)
      COMMON /REHCHK/ ND, IR(6), LV(6), PCTA(2,6), XD(2,6), AGET(2),
     1                IRSEL, FAILT, IDF
      COMMON /CTRL  / NIN, NOUT, NDERV, LSAVE, LOUT
C
C     SAVE THE RESULTS OF EACH TESTING PROGRAM ON FILE -LOUT-
C
      WRITE (LOUT,ERR=10) M1, M2, M3, M4, M5, FAILT, IDF, IRSEL,
     1                    COST, TCOST
C     WRITE (1,21) M1, M2, M3, M4, M5, FAILT, IDF, IRSEL, COST, TCOST
      RETURN
   10 WRITE (1,11) M1, M2, M3, M4, M5, FAILT, IDF, IRSEL, COST, TCOST
      WRITE (NOUT,12)
      STOP 'I/O ERROR IN SAVRES'
   11 FORMAT (1X, 'ERROR FROM SAVRES: I/O ERROR IN WRITING TO -LOUT-'/
     1        1X, 'M1,M2,M3,M4,M5,FAILT,IDF,IRSEL,COST,TCOST ='/
     2        1X, 5I3,F7.3,1X,2I3, 2F12.3 /
     3        1X, 'ABORT'/
   12 FORMAT (/1X,'I/O ERROR IN SAVRES; MUST ABORT')
C  21 FORMAT (/1X,'FROM SAVRES:  M1-M5,FAILT,IDF,IRSEL,COST,TCOST=',
C    1        /1X, 5I3,F7.3,1X,2I3,2F12.3)
      END
```

```
      SUBROUTINE KERNEL (LAST)
      CHARACTER*8 NAM
      DIMENSION JFN(40)
      COMMON /CURVAL/ X(40), CVX(40), DFDX(40), AGE
      COMMON /INDAT / NAM(40), IDX(40), VAL(40), CV(40), IFN(40),
     1                NQ(40), IQ(10,40), IDEC(40), NI, NYR
      COMMON /INTFC / ADTZ, PCTPYR, PCTTRK, SALPTK, FY
      COMMON /REHCHK/ ND, IR(6), LV(6), PCTA(2,6), XD(2,6), AGET(2),
     1                IRSEL, FAILT, IDF
      COMMON /TEST  / NTT, IDT(5), NTEST(11,5), ICONF(5), TESTC(5),
     1                AT(5), BT(5), CT(5), DT(5)
C
C     INITIALIZE
      FAILT = 100.
      IRSEL = 0
      IDF = 0
      DO 20 I = 1, 6
          DO 20 J = 1, 2
              PCTA(J,I) = 0.
              XD(J,I)   = 0.
   20 CONTINUE
C     WRITE THE CURRENT VALUES OF TEST VARIABLES.
      WRITE (1,1)
      WRITE (1,2) (NAM(IDT(I)), X(IDT(I)), CVX(IDT(I)), I=1,NTT)
    1 FORMAT (/1X,'TEST VARIABLE VALUES AND COEFFICIENTS OF VARIATION',
     1        /1X,'CURRENT PASS:'/)
    2 FORMAT ( 1X, A8, 2X, F10.4, 2X, F7.4)
C
C     SET FUNCTIONS AND INPUT VARIABLES NOT AFFECTED BY TEST RESULTS
C     TO THEIR INITIAL READ-IN VALUES.
      DO 120 I = 1, NI
          ID = IDX(I)
          DO 110 J = 1, NTT
              IF (ID .EQ. IDT(J)) GO TO 120
  110     CONTINUE
          X(ID) = VAL(ID)
          CVX(ID) = CV(ID)
  120 CONTINUE
      DO 130 ID = 1, 40
          JFN(ID) = IFN(ID)
  130 CONTINUE
      IFYR = INT(FY + 0.5)
      DO 200 JY = IFYR, NYR
          AGE = JY
          DO 150 I = 1, NI
              ID = IDX(I)
              IFM = IABS(JFN(ID))
              IF (IFM .EQ. 0) GO TO 150
              CALL EVALFN (ID, IFM, X)
              CALL EVALDF (ID, IFM, NQ(ID), IQ(1,ID), X, DFDX)
              CALL EVALVR (ID, NQ(ID), IQ(1,ID))
```

```
              IF (JFN(ID) .LT. 0) JFN(ID) = 0
 150          CONTINUE
          CALL CONDCK
          IF (ND .EQ. 0) GO TO 200
          CALL REHABL
          GO TO 210
 200      CONTINUE
 210  RETURN
      END
C
      SUBROUTINE CONDCK
C     MODIFIED 83/6/23 TO SAVE THE PREVIOUS VALUES OF XD, PCTA, AND AGE
C     AS WELL AS PRESENT VALUES - TO PERMIT INTERPOLATION FOR TIME OF
C     FAILURE.
      CHARACTER*8 NAM
      COMMON /CTRL  / NIN, NOUT, NDERV, LSAVE, LOUT
      COMMON /CURVAL/ X(40), CVX(40), DFDX(40), AGE
      COMMON /INDAT / NAM(40), IDX(40), VAL(40), CV(40), IFN(40),
     1                NQ(40), IQ(10,40), IDEC(40), NI, NYR
      COMMON /RECRIT/ XCC(2,4,10), ICC(3,10), NCC
      COMMON /REHCHK/ ND, IR(6), LV(6), PCTA(2,6), XD(2,6), AGET(2),
     1                IRSEL, FAILT, IDF
      IN = 0
      AGET(1) = AGET(2)
      AGET(2) = AGE
      DO 10 I = 1, NCC
          ID = ICC(1,I)
          NL = ICC(2,I)
          IT = ICC(3,I)
          XD(1,I) = XD(2,I)
          XD(2,I) = X(ID)
          PCTA(1,I) = PCTA(2,I)
          PCTA(2,I) = 0.
          IF (IT .EQ. 0) GO TO 10
          IF (XCC(2,IT,I) .GT. 0.) GO TO 5
C
C         HERE IF DISTRESS TEST ON SEVERITY ONLY, NOT AREA.
C         CHECK TO SEE IF 'DISTRESS INDICATOR' IS AN INCREASING
C         (IDEC=0) OR DECREASING (IDEC=1) FUNCTION OF TIME OR TRAFFIC.
          IF (IDEC(ID) .EQ. 0) THEN
              IF (X(ID) .LT. XCC(1,IT,I))  GO TO 10
            ELSE
              IF (X(ID) .GT. XCC(1,IT,I))  GO TO 10
            ENDIF
          IN = IN + 1
          IR(IN) = I
          WRITE (1,101) NAM(ID), X(ID), XCC(1,IT,I)
          GO TO 10
C
C         HERE IF USING -PERCENT AREA- TEST.  ASSUME PERCENT AREA
C         ALWAYS AN -INCREASING- FUNCTION OF TIME (OR TRAFFIC),
C         SO NO NEED TO CHECK -IDEC-.
```

```
    5      SIGMA = X(ID)*CVX(ID)
           PCTA(2,I) = 100.*FCRIT(X(ID), SIGMA, XCC(1,IT,I))
           IF (PCTA(2,I) .LT. 0. .OR. PCTA(2,I) .GT. 100.) GO TO 20
           IF (PCTA(2,I) .LT. XCC(2,IT,I)) GO TO 10
           IN = IN + 1
           IR(IN) = I
           WRITE (1,102) NAM(ID), PCTA(2,I), XCC(1,IT,I), XCC(2,IT,I)
   10 CONTINUE
      ND = IN
      RETURN
   20 WRITE (1,104) I,ID,NL,IT,X(ID),SIGMA,XCC(1,IT,I),PCTA(1,I),
     1               PCTA(2,I), AGE
      WRITE (1,105) AGET(1), XD(1,I), AGET(2), XD(2,I)
      WRITE (1,103)
      STOP 'ERROR CONDITION IN CONDCK'
  101 FORMAT (/1X,'DISTRESS ',A8,', CURRENT VALUE=',G12.4/
     1         1X,'HAS PASSED CRITICAL VALUE OF ', G12.4)
  102 FORMAT (/1X,'FOR DISTRESS TYPE ',A8
     1        /1X,G12.4,' PERCENT OF AREA HAS VALUE GREATER THAN',G12.4,
     2        /1X,'(REHAB AT ',F5.1, ' PERCENT')
  103 FORMAT (/' FROM CONDCK:  AN OUT-OF-RANGE AREA HAS BEEN COMPUTED.',
     1        /' PROGRAM ABORT.')
  104 FORMAT (/' I,ID,NL,IT = ',4I5/' X(ID), SIGMA = ',2G14.6,
     2        /' CRITICAL X, PREVIOUS AREA, PRESENT AREA =',F6.2,2G14.6,
     3        /' AFTER ',F5.1,' YEARS. ')
  105 FORMAT (/' PREVIOUS AGE AND DISTRESS LEVEL = ',F7.3,G12.4,
     1        /' PRESENT  AGE AND DISTRESS LEVEL = ',F7.3,G12.4)
      END
C
      SUBROUTINE REHABL
      CHARACTER*8 NAM, RLABEL, LBLCST
      DIMENSION XT(6), LBLCST(10)
      INTEGER COSTKY, RKEY, RS
      COMMON /CURVAL/ X(40), CVX(40), DFDX(40), AGE
      COMMON /CTRL  / NIN, NOUT, NDERV, LSAVE, LOUT
      COMMON /INDAT / NAM(40), IDX(40), VAL(40), CV(40), IFN(40),
     1                NQ(40), IQ(10,40), IDEC(40), NI, NYR
      COMMON /RECRIT/ XCC(2,4,10), ICC(3,10), NCC
      COMMON /REHAB / RLABEL(4,31), RCOST(31), COSTKY(31), RKEY(6,31),
     1                IRB(31),IZR(50),NL(6),RS( 200),NDIM,NRB,LRN,NN
      COMMON /REHCHK/ ND, IR(6), LV(6), PCTA(2,6), XD(2,6), AGET(2),
     1                IRSEL, FAILT, IDF
      DATA LBLCST /' SQ. YD.', 9*'        ' /
C
C     WRITE OUT LAST SET OF CALCULATED FUNCTION VALUES.
      WRITE (1,105) AGE
      DO 20 I = 1, NI
          ID = IDX(I)
          IF (IFN(ID) .EQ. 0) GO TO 20
          WRITE (1,106) ID, NAM(ID), X(ID), CVX(ID)
   20 CONTINUE
C     INTERPOLATE FOR TIME OF FAILURE FOR ALL DISTRESSES WHICH ARE PAST
```

```
C     CRITICAL VALUE, AND SELECT THE EARLIEST TIME.  STORE IN -FAILT-.
C
      DO 30 IN = 1, ND
          I = IR(IN)
          IT = ICC(3,I)
          IF (PCTA(2,I) .GT. 0.) GO TO 25
          C = XCC(1,IT,I)
          XT(IN) = (C - XD(1,I))/(XD(2,I) - XD(1,I))
          GO TO 30
   25     C = XCC(2,IT,I)
          XT(IN) = (C - PCTA(1,I))/(PCTA(2,I) - PCTA(1,I))
   30 CONTINUE
C     XT(IN) IS THE -FRACTION- OF THE TIME PERIOD BETWEEN TWO ANALYSIS TIMES
C     AT WHICH THE PARTICULAR DISTRESS PASSED ITS CRITICAL VALUE.
C     NOW FIND THE SMALLEST VALUE OF XT; THIS WILL CORRESPOND TO THE DISTRESS
C     CRITERION WHICH WAS FIRST VIOLATED.  IRT SAVES THE INDEX ON THIS CRIT.
      SMALL = 100.
      DO 40 IN = 1, ND
          IF (XT(IN) .GT. SMALL) GO TO 40
          SMALL = XT(IN)
          ID = ICC(1, IR(IN))
          IRT = IR(IN)
   40 CONTINUE
      IDF = ID
      DELT = AGET(2) - AGET(1)
      FAILT = SMALL * DELT + AGET(1)
      WRITE (1,104) NAM (IDF), IDF
      WRITE (1,103) FAILT
C
C     INTERPOLATE -ALL- DISTRESS VALUES TO -FAILT- BEFORE DOING
C     REHAB SELECTION.  ASSUME CVX(ID) NOT CHANGING FAST ENOUGH TO
C     WARRANT INTERPOLATION.
C
      DO 60 I = 1, NCC
          ID = ICC(1,I)
          X(ID) = XD(1,I) + (FAILT-AGET(1))*(XD(2,I)-XD(1,I))/DELT
   60 CONTINUE
C     DETERMINE LEVELS OF -ALL- DISTRESSES TO SELECT APPROPRIATE REHAB
C     OPTION -IRSEL-.  SET THE TRIGGERING DISTRESS LEVEL WITHOUT RE-
C     CALCULATION (84/6/8).
C
      WRITE (1,107) FAILT
      DO 150 I=1, NCC
          IF (I .EQ. IRT) GO TO 140
          ID = ICC(1,I)
          NLV = ICC(2,I)
C         ASSUME ALL LEVELS FOR SPECIFIC DISTRESS WILL HAVE -AREA- TEST
C         IF ANY ONE DOES.  ASSUME -AREA- ALWAYS -INCREASES- WITH TIME.
          IF (XCC(2,1,I) .GT. 0.) GO TO 120
          DO 110 J = 1, NLV
              WRITE (1,108) ID, NAM(ID), X(ID), CVX(ID), XCC(1,J,I)
              LV(I) = J
```

```
              IF (IDEC(ID) .EQ. 0) THEN
                  IF (X(ID) .LT. XCC(1,J,I)) GO TO 150
                ELSE
                  IF (X(ID) .GT. XCC(1,J,I)) GO TO 150
                ENDIF
  110     CONTINUE
          LV(I) = NLV + 1
          GO TO 150
  120     DO 130 J = 1, NLV
              LV(I) = J
              PCTA(2,I) = 100.*FCRIT (X(ID), X(ID)*CVX(ID), XCC(1,J,I))
              WRITE (1,108)ID,NAM(ID),X(ID),CVX(ID),XCC(1,J,I),PCTA(2,I)
              IF (PCTA(2,I) .LT. XCC(2,J,I)) GO TO 150
  130     CONTINUE
          LV(I) = NLV + 1
          GO TO 150
C         SPECIAL CASE FOR THE TRIGGERING DISTRESS MODE.
  140     LV(I) = ICC(3,I) + 1
  150 CONTINUE
C     IF USING FEWER THAN -NN- REHAB LEVELS, MUST SET UNUSED ONES TO 1
      IF (NCC .EQ. NN) GO TO 170
      NP = NCC + 1
      DO 160 I = NP, NN
          LV(I) = 1
  160 CONTINUE
  170 CONTINUE
      LOC = LOCN (LV, NL, NN, NDIM)
      IRL = RS(LOC)
      IRSEL = IRL
      IZ = IZR(IRL)
      WRITE (1,101) (LV(J), J=1,NN)
      JZ = COSTKY(IZ)
      WRITE (1,102) IRL, (RLABEL(J,IZ), J=1,4), RCOST(IZ),LBLCST(JZ)
  101 FORMAT (/1X, 'LEVELS FOR DISTRESSES 1-6 =', 6I2)
  102 FORMAT (1X, 'REHAB OPTION ',I2,' SELECTED'/1X,4A8 /
     1        1X, 'AT A COST OF ', F5.2,' DOLLARS PER ', A8 )
  103 FORMAT ( 1X,'AT PAVEMENT AGE',F6.2,' YEARS')
  104 FORMAT (/1X, A8,' (ID=',I3,') HAS THE EARLIEST FAILURE TIME')
  105 FORMAT (/1X,'FROM REHABL - FUNCTION VALUES AND C.V. AT AGE=',
     1        F5.1,' YEARS')
  106 FORMAT (1X,I4,2X,A8,2X,G12.4,F8.4)
  107 FORMAT (1X,'FROM REHABL - DISTRESSES INTERPOLATED TO',F6.2,
     1        ' YEARS'/
     2    /'                                 REFERENCE  PCT PAVT AREA '
     3    /'                         COEFF.  DISTRESS   WITH DISTRESS '
     4    /' ID   NAME      VALUE     OF VAR.   LEVEL    ABOVE REFERENCE'
     5      )
  108 FORMAT (1X,I2,1X,A8,1X,G11.3,1X,F7.4,1X,F8.2,6X,F6.2)
      RETURN
      END
C
      FUNCTION FCRIT (YBAR, SIGMA, YCRIT)
```

```
C     COMPUTES THE AREA UNDER A NORMAL CURVE (YBAR, SIGMA) ABOVE
C     Y=YCRIT, USING  A NUMERICAL APPROXIMATION FOR THE INTEGRAL OF
C     THE NORMAL CURVE FROM NBS HANDBOOK OF MATH. FUNCTIONS.
C     (EQUATION 26.2.18).  MAXIMUM ERROR .LT. 2.5*10**(-4).
C
      DATA C1, C2, C3, C4 /.196854, .115194, .000344, .019527 /
      EX = (YCRIT - YBAR)/SIGMA
      X = ABS(EX)
      P = 1.
      IF (X .GT. 5.) GO TO 10
      T = 1.+X*(C1 + X*(C2 + X*(C3 + X*C4)))
      P =  1. - 0.5*T**(-4)
   10 IF (EX .LT. 0) P = 1. - P
      FCRIT = 1. - P
C     REMEMBER, FCRIT IS THE AREA -ABOVE- YCRIT.  P IS AN APPROXIMATION
C     TO THE INTEGRAL FROM -INF. TO YCRIT.
      RETURN
      END
```

```
      SUBROUTINE BC (NPASS)
      DIMENSION C(250), TC(250), MX(5), MY(2), BUF(50), DUMMY (250)
      INTEGER*2 IS(250), IBUF(50)
      CHARACTER*8 NAM
      COMMON /CTRL  / NIN, NOUT, NDERV, LSAVE, LOUT
      COMMON /INDAT / NAM(40), IDX(40), VAL(40), CV(40), IFN(40),
     1                NQ(40), IQ(10,40), IDEC(40), NI, NYR
      COMMON /TEST  / NTT, IDT(5), NTEST(11,5), ICONF(5), TESTC(5),
     1                AT(5), BT(5), CT(5), DT(5)
      DATA MAX /250/, MBUF /50/
C
C     READ THE DATA TO BE SORTED.
      REWIND LOUT
      WRITE (1,4) NPASS
      IF (NPASS .GT. MAX) WRITE (1,3) MAX
      NP = MIN0(MAX, NPASS)
      DO 40 I=1, NP
      READ (LOUT,END=60) MX, FT, MY, C(I), TC(I)
      WRITE (1,1) MX, FT, MY, C(I), TC(I)
   40 CONTINUE
   60 CONTINUE
      IM = NP
      CALL INDSORT (TC, DUMMY, IS, IM)
C
C     INDSORT RETURNS WITH INDEX ARRAY -IS- POINTING TO VALUES OF TC IN
C     INCREASING SORTED ORDER.
C     NOW DO B/C ANALYSIS AND RETAIN ONLY THE LAST -MBUF- VALUES WITH
C     DIFFERENTIAL B/C .GT. 1, USING A CIRCULAR BUFFER.
C
      IN = 0
      IL = 0
      ID = IS(1)
      DO 80 I = 2, IM
          IC = IS(I)
          DB = -(C(IC) - C(ID))
C         THE MINUS SIGN IS PRESENT BECAUSE THE BENEFIT IS THE -REDUCTION-
C         IN COST.
          DC  = TC(IC) - TC(ID)
          BCR = DB/DC
          IF (BCR .LT. 1.) GO TO 80
          ID = IC
          IN = IN + 1
          IL = IL + 1
          IF (IN .GT. MBUF) IN = 1
          IBUF(IN) = ID
          BUF(IN) = BCR
   80 CONTINUE
      ILAST = IN
      NLAST = MIN0 (IL, MBUF)
      WRITE (1,2) NLAST
C
```

```
C     NOW RETRIEVE FULL DATA FOR THE CASES RETAINED IN THE BUFFER.
C     -ILAST- POINTS TO THE LAST (HIGHEST TESTING COST) ENTRY,
C     SO ILAST + 1 IS THE FIRST ENTRY RETAINED IF MORE THAN -MBUF-
C     ALTERNATIVES SHOWED DIFFERENTIAL B/C GREATER THAN 1.
C
      WRITE (NOUT, '(1H1)')
      WRITE (NOUT,11) (IDT(I), I=1,NTT)
      WRITE (NOUT, '(1X)')
      DO 100 I = 1, NLAST
          K = I
          IF (IL .GT. MBUF) K = MOD(I + ILAST - 1, MBUF) + 1
          J = IBUF(K)
          BCR = BUF(K)
          READ (LOUT, REC=J, END=200)
     1         M1,M2,M3,M4,M5,FAILT,IDF,IRSEL, COST, TCOST
          WRITE (1,2) J,M1,M2,M3,M4,M5,FAILT,IDF,IRSEL,COST,TCOST,BCR
          WRITE (NOUT,12)
     1         M1,M2,M3,M4,M5,FAILT,NAM(IDF),IRSEL, COST, TCOST, BCR
  100 CONTINUE
  200 CONTINUE
      RETURN
    1 FORMAT (1X,'FROM BC1: ',3X,5I3,F7.3,2I3,2F10.4)
    2 FORMAT (1X,'FROM BC2: ',   6I3,F7.3,2I3,3F10.4)
    3 FORMAT (1X, 'INSUFFICIENT SPACE FOR ALL COSTS TO BE SORTED'
     1        /1X, 'RUN WILL CONTINUE USING ONLY', I5,' VALUES')
    4 FORMAT (1X,'FROM BC:  NPASS =', I5)
   11 FORMAT ('   NUMBER OF TESTS ON                          '
     1         ' UNIF. ANN. UNIF. ANN.   DIFF. '
     2        /'   MATERIAL PROPERTY   AGE AT  DISTRESS SELECTED '
     3         '   COSTS    TESTING    BENEFIT/'
     4        /'  IDENTIFIED BY ID NO. FAILURE CAUSING   REHAB   '
     5         ' 1000-S OF   COST        COST   '
     6        /'                       YEARS   FAILURE   OPTION  '
     7         '  DOLLARS   DOLLARS     RATIO  '
     8        /4X, 5I3)
   12 FORMAT (4X,5I3, 4X, F5.2, 3X,A8, 4X,I2,4X, F7.2,3X, 3PF9.2,
     1         3X,0PF7.3)

      END
      FUNCTION CMPFAC (INTFAC, XINT,XN)
C     CMPFAC - COMPOUND INTEREST FACTORS.
C     INPUT:  INTFAC  -  CHARACTER*2 STRING INDICATING WHICH
C                        FACTOR IS REQUIRED.  MAY BE ONE OF
C                        THE FOLLOWING:
C                        FP - SINGLE PAYMENT COMPOUND AMOUNT
C                        PF - SINGLE PAYMENT PRESENT WORTH
C                        AF - UNIFORM SERIES SINKING FUND
C                        AP - UNIFORM SERIES CAPITAL RECOVERY
C                        FA - UNIFORM SERIES COMPOUND AMOUNT
C                        PA - UNIFORM SERIES PRESENT WORTH
C                  USE, E.G., 'FP' IN CALLING SEQUENCE.
C             XINT    -  INTEREST RATE PER PERIOD (PERCENT)
```

```
C              XN       -  NUMBER OF PERIODS (CAN BE FRACTIONAL).
C     OUTPUT: CMPFAC   -  APPROPRIATE COMPOUND INTEREST FACTOR.
C
      CHARACTER*2 INTF(6), INTFAC
      DATA INTF /'FP', 'PF', 'AF', 'AP', 'FA', 'PA' /
C
      DO 10 I = 1, 6
      II = I
      IF (INTFAC .EQ. INTF(I)) GO TO 15
   10 CONTINUE
      FAC = -99.
C     INTFAC NOT ONE OF THE 6 PERMITTED VALUES.
      GO TO 99
   15 CONTINUE
      XI = XINT/100.
      T = (1. + XI)**XN
      GO TO (20, 25, 30, 35, 40, 45), II
   20 FAC = T
      GO TO 99
   25 FAC = 1./T
      GO TO 99
   30 FAC = XI/(T-1.)
      GO TO 99
   35 FAC = XI*T/(T-1.)
      GO TO 99
   40 FAC = (T-1.)/XI
      GO TO 99
   45 FAC = (T-1.)/(XI*T)
      GO TO 99
C
   99 CMPFAC = FAC
      RETURN
      END
      FUNCTION ACUFP (FP, TIME, XINT, XNP)
      DIMENSION FP(1), TIME(1)
      CHARACTER*2 PF, AP
      DATA PF, AP /'PF', 'AP'/
C
C     UNIFORM ANNUAL COST OF -NP- UNEQUAL FUTURE PAYMENTS -FP-
C     AT TIMES -TIME- (YEARS) BASED ON INTEREST RATE -XINT- (PERCENT).
C
      NP = XNP + 1. - 1.E-06
      PV = 0.
      DO 10 I = 1, NP
      T = TIME(I)
      IF (I .EQ. NP) T = TIME(I-1) + (XNP-(NP-1))*(TIME(I)-TIME(I-1))
          F1 = CMPFAC (PF, XINT, T)
          PV = PV + F1*FP(I)
   10 CONTINUE
      F2 = CMPFAC (AP, XINT, T)
C     USE THE LAST VALUE FOR T FROM PREVIOUS LOOP.
      ACUFP = F2*PV
```

```
      RETURN
      END
      SUBROUTINE INDSORT (A,B,IS,N)
      DIMENSION A(N), B(N)
      INTEGER*2 IS(N)
      INTEGER TOP, SML
      DO 80 I = 1,N
         IS(I) = I
   80 B(I) = A(I)
      TOP = 1
  100 SML = LOCSML (B,TOP,N)
      TMP = B(TOP)
      B(TOP) = B(SML)
      B(SML) = TMP
      ITMP = IS(TOP)
      IS(TOP) = IS(SML)
      IS(SML) = ITMP
      TOP = TOP + 1
      IF (TOP.LT.N) GOTO 100
      RETURN
      END
      FUNCTION LOCSML (A,IFR,ITO)
      DIMENSION A(1)
      LOCSML = IFR
      I = IFR + 1
  100 IF (I.GT.ITO) RETURN
      IF (A(I).LT.A(LOCSML)) LOCSML = I
      I = I + 1
      GOTO 100
      END
      FUNCTION TVAL (N, ICON, IERR)
C
C     -TVAL- RETURNS THE T-VALUE FOR ONE-SIDED CONFIDENCE LEVEL -ICON-
C     (MUST BE ONE OF 75, 90, 95, 99) AND NUMBER OF DEGREES OF FREEDOM
C     -N-.  IF N(=30 THEN THE VALUE IS RETRIEVED DIRECTLY.  IF N)30,
C     THE VALUE IS FOUND BY LOGARITHMIC INTERPOLATION AMONG THE VALUES
C     FOR N=(30,40,60,120).  NO INTERPOLATION ACROSS CONFIDENCE LEVEL.
C     ADDITIONAL CONFIDENCE LEVELS MAY BE ADDED LATER, FOR CONVENIENCE
C     OF USE WHEN TWO-SIDED CONFIDENCE LEVELS ARE DESIRED.
C     MODIFIED 84/4/17 TO RETURN NEGATIVE VALUES OF TVAL IF ICON .LT. 0.
C
      DIMENSION T75(30), T90(30), T95(30), T99(30),
     1          TL75(4), TL90(4), TL95(4), TL99(4),
     2          TL(4,4), TF(30,4), XFL(4), ICONF(4)
C
      EQUIVALENCE (T75(1),TF(1,1)), (T90(1),TF(1,2)),
     1             (T95(1),TF(1,3)), (T99(1),TF(1,4)),
     2             (TL75(1),TL(1,1)), (TL90(1),TL(1,2)),
     3             (TL95(1),TL(1,3)), (TL99(1),TL(1,4))
C
      DATA T75 /1.000,0.816,0.765,0.741,0.727,0.718,0.711,0.706,
     1          0.703,0.700,0.697,0.695,0.694,0.692,0.691,0.690,
```

```
     2          0.689,0.688,0.688,0.687,0.686,0.686,0.685,0.685,
     3          0.684,0.684,0.684,0.683,0.683,0.683/
      DATA T90 /3.078,1.886,1.638,1.533,1.476,1.440,1.415,1.397,
     1          1.383,1.372,1.363,1.356,1.350,1.345,1.341,1.337,
     2          1.333,1.330,1.328,1.325,1.323,1.321,1.319,1.318,
     3          1.316,1.315,1.314,1.313,1.311,1.310/
      DATA T95 /6.314,2.920,2.353,2.132,2.015,1.943,1.895,1.860,
     1          1.833,1.812,1.796,1.782,1.771,1.761,1.753,1.746,
     2          1.740,1.734,1.729,1.725,1.721,1.717,1.714,1.711,
     3          1.708,1.706,1.703,1.701,1.699,1.697/
      DATA T99/31.821,6.965,4.541,3.747,3.365,3.143,2.998,2.896,
     1          2.821,2.764,2.718,2.681,2.650,2.624,2.602,2.583,
     2          2.567,2.552,2.539,2.528,2.518,2.508,2.500,2.492,
     3          2.485,2.479,2.473,2.467,2.462,2.457/
      DATA TL75 /-.1656, -.1669, -.1681, -.1694/
      DATA TL90 / .1173,  .1149,  .1126,  .1103/
      DATA TL95 / .2297,  .2263,  .2230,  .2196/
      DATA TL99 / .3904,  .3844,  .3784,  .3725/
      DATA XFL  /1.4771, 1.6021, 1.7782, 2.0792/
      DATA NC, ICONF/ 4, 75, 90, 95, 99/
C
C     XFL ARE THE LOGS OF 30, 40, 60, AND 120, RESPECTIVELY, FOR WHICH
C     DEGREES OF FREEDOM THE LOGS OF THE -T- VALUES ARE GIVEN FOR THE
C     INDICATED CONFIDENCE LEVELS.
      IERR = 0
      IC = 0
      IF (N .LE. 0) GO TO 98
      DO 10 I = 1, NC
      IF (IABS(ICON) .NE. ICONF(I)) GO TO 10
      IC = I
      GO TO 15
   10 CONTINUE
      IF (IC .EQ. 0) GO TO 99
   15 IF (N .GT. 30) GO TO 20
      TVL = TF(N, IC)
      GO TO 90
   20 XNL = ALOG10(REAL(N))
      CALL INTERP (XFL, TL(1,IC), 4, XNL, TXL,1)
      TVL = EXP(2.302585*TXL)
   90 CONTINUE
      TVAL = SIGN (TVL, REAL(ICON))
      RETURN
   98 IERR = 1
      RETURN
   99 IERR = 2
      RETURN
      END
      SUBROUTINE INTERP (X, F, N, XR, FR, NR)
      DIMENSION X(N), F(N), XR(NR), FR(NR)
      DO 100 J = 1, NR
      IF (N .GT. 2) GO TO 10
      FI = F(1) + (XR(J) - X(1)) * (F(2) - F(1)) / (X(2) - X(1))
```

```
      GO TO 99
  10  CONTINUE
      IB = 1
      IF (N .EQ. 3) GO TO 30
      R = +1.
      IF (X(2) .LT. X(1)) R = -1.
      DO 15 I = 2, N
      IX = I
      IF ((X(I) - XR(J))*R .GT. 0.) GO TO 20
  15  CONTINUE
  20  IF ((2.*XR(J) - X(IX-1) - X(IX))*R .LT. 0.) IX = IX - 1
      IB = IX - 1
      IF (IB .LT. 1) IB = 1
      IF (IB .GT. (N-2)) IB = N-2
  30  FI = PARAB (XR(J), X(IB), F(IB) )
  99  FR(J) = FI
 100  CONTINUE
      RETURN
      END
      FUNCTION PARAB (XR, X, F)
      DIMENSION X(3), F(3)
      XL = X(2) - X(1)
      XU = X(3) - X(2)
      D = XL * XU * (X(3) - X(1))
      P1 = XL * (F(3) - F(2))
      P2 = XU * (F(2) - F(1))
      S1 = P1 * XL + P2 * XU
      S2 = P1 - P2
      T = XR - X(2)
      PARAB = F(2) + (S1 + S2 * T) * T / D
      RETURN
      END
```

```
      SUBROUTINE EVALFN (ID, IFN, X)
      DIMENSION X(40)
C     WRITE (1,1) ID,IFN
C   1 FORMAT (1X,'EVALFN CALLED WITH ID, IFN=', 2I4)
      X(ID) = YFUNC (IFN, X)
      RETURN
      END
      SUBROUTINE EVALDF (ID, IFN, NQ, IQ, X, DFDX)
      DIMENSION IQ(1), X(40), DFDX(40)
C     DIMENSION IQ(1) IS USED IN PLACE OF IQ(NQ) ABOVE BECAUSE
C     NQ CAN BE 0 OR NEG. AND HENCE < ASSUMED LOWER BOUND.  83/8/3 F77.
C     IF NQ .LT. 0, THEN NO DERIVATIVES ARE DESIRED FOR THIS FUNCTION,
C     EVEN IF A FUNCTIONAL DEPENDENCE IS SHOWN.
      COMMON /CURVAL/ DUMX(40), CVX(40), DUMD(40), AGE
      DATA DEL /1.E-2/
C     WRITE (1,1) ID, IFN, NQ, IQ
C   1 FORMAT (1X,'EVALDF CALLED WITH ID, IFN, NQ, IQ=', /(1X,18I4))
C     WRITE (1,2) X(ID)
C   2 FORMAT (1X,'CURRENT FUNCTION VALUE = ', G12.4)
      IF (NQ .LE. 0) RETURN
      DO 10 I = 1, NQ
          IV = IQ(I)
          DFDX(IV) = 0.
          IF (CVX(IV) .EQ. 0.) GO TO 10
          SAVE = X(IV)
          DELTA = DEL*X(IV)
          X(IV) = X(IV) + DELTA
          YP = YFUNC (IFN, X)
          DFDX(IV) = (YP-X(ID))/DELTA
          X(IV) = SAVE
C         WRITE (1,3) IV, X(IV), IFN, YP, DFDX(IV)
   10 CONTINUE
C   3 FORMAT (1X,'WITH VARIABLE',I3,' INCREMENTED TO ', G12.4/
C    1        1X,'FUNCTION #',I2,'=',G12.4,' AND DFDX =',G12.4)
      RETURN
      END
      SUBROUTINE EVALVR (ID, NQ, IQ)
      DIMENSION IQ(1)
C     DIMENSION IQ(1) USED IN PLACE OF IQ(NQ) BECAUSE
C     NQ CAN BE ZERO; < ASSUMED LOWER BOUND OF 1.  83/8/3 F77.
      COMMON /CTRL  / NIN, NOUT, NDERV, NSAVE, LOUT
      COMMON /CURVAL/ X(40), CVX(40), DFDX(40), AGE
      SUM = 0.
      IF (NQ .LE. 0) RETURN
      DO 10 I = 1, NQ
          IX = IQ(I)
          SUM = SUM + (DFDX(IX)*CVX(IX)*X(IX))**2
   10 CONTINUE
      IF (X(ID) .EQ. 0.) GO TO 20
      CVX(ID) = ABS(SQRT(SUM)/X(ID))
      RETURN
```

```
   20 WRITE (NOUT,101) ID, ID, SUM
      WRITE (    1,101) ID, ID, SUM
  101 FORMAT (1X,'FROM EVALVR:  COMPUTATION OF COEF. OF VARIATION FOR '
     1       /1X,'FUNCTION ID=',I3,' (X(',I3,')=0. VARIANCE =',E12.4,')'
     2       /1X,'WILL CAUSE A DIVISION BY ZERO.   ABORT.')
      STOP 'EVALVR'
      END
      FUNCTION YFUNC (IFN, X)
      DIMENSION X(40)
      GO TO (10,20,30,40,50,60,70,80,90,100,110,120,130,140,150), IFN
   10 YFUNC = FUNC1(X)
      RETURN
   20 YFUNC = FUNC2(X)
      RETURN
   30 YFUNC = FUNC3(X)
      RETURN
   40 YFUNC = FUNC4(X)
      RETURN
   50 YFUNC = FUNC5(X)
      RETURN
   60 YFUNC = FUNC6(X)
      RETURN
   70 YFUNC = FUNC7(X)
      RETURN
   80 YFUNC = FUNC8(X)
      RETURN
   90 YFUNC = FUNC9(X)
      RETURN
  100 YFUNC = FUNC10(X)
      RETURN
  110 YFUNC = FUNC11(X)
      RETURN
  120 YFUNC = FUNC12(X)
      RETURN
  130 YFUNC = FUNC13(X)
      RETURN
  140 YFUNC = FUNC14(X)
      RETURN
  150 YFUNC = FUNC15(X)
      RETURN
      END
      FUNCTION FUNC1 (X)
C     UNITS ON MODULUS CHANGED TO -KPSI- 06/17/1983.
C     WITCZAK REGRESSION FOR LOG(BASE 10) (ASPHALT MODULUS, KPSI).
      DIMENSION X(40)
      SUM= 5.553833+ .028829*(X(13)/X(15)**.17033)-.03476*X(12)
      SUM= SUM +.070377*X(14) +.931757*X(15)**(-.02774)
      P1= 1.3 +.49825*ALOG10(X(15))
      SUM = SUM + X(16)**P1*SQRT(X(11))*(5E-6-.00189*X(15)**(-1.1))
      FUNC1= SUM - 3.0
      RETURN
      END
```

```
      FUNCTION FUNC2 (X)
C     WATMODE REGRESSION FOR RUTTING.
C     ALL MODULI INPUT IN UNITS OF -KPSI- (83/06/17)
C     NOTE: ASPHALT MODULUS (X(20)) IS ASSUMED TO BE IN LOG10 FORM.
C     CUM ESAL NOW ASSUMED TO BE IN X(7) (84/4/18)
      DIMENSION X(40)
      CUMSAL = X(7)
      A= (X(24)+.5*X(25)+ X(26)/3.)*.10
      EA= 10.**(X(20)-3)
      ES= X(23)*0.1
      EN = CUMSAL*1.E-5
      ALN= ALOG(A)
C     ADD CORRECTION FOR HIGH TRAFFIC (.GT. 5.E5 ESAL)
      DIFF = 0.
      IF (EN .LE. 5.) GO TO 1
      DELTA = EN - 5.
      EN = 5.
      BETA = 1./A
      TAU = .02/BETA
      DIFF = BETA*(1. - EXP(-TAU*DELTA))
    1 R1= -1.0318+ 1.2067*A+(1.1639*EA-2.1788)*ALN
      R2= (.0456*ES- .4114*EA)*ALN - .0216*ES + .0803
      R3= .1896
      RUT= R1 + R2*EN + R3*ALOG(EN)
      IF (RUT .LT. 0.) RUT = 0.
      RUT = RUT + DIFF
C     CF = 1.2/A IS SMOOTH APPROX. TO STEP FUNCTION IN WATMODE.
C     THIS IS A CORRECTION FACTOR FOR OVER-PRED. OF RUT IN THIN PAVTS.
C     SMOOTHNESS IS NECESSARY FOR DERIVATIVES.
      CF = AMAX1(1.0, AMIN1(2.0, 1.2/A))
      RUT = RUT/CF
      FUNC2= RUT
      RETURN
      END
      FUNCTION FUNC3 (X)
      DIMENSION X(40)
C     THIS EVALUATES THE RADIAL STRAIN UNDER THE ASPHALT (WATMODE)
C     MODULI HERE ASSUMED TO BE IN UNITS OF -KPSI- (83/6/17)
C     AC MODULUS (X(20)) IS IN LOGARITHMIC FORM.
      AT = X(24)
      CT = AMAX1(X(25),X(26))
      EC = AMAX1(X(21),X(22))*0.1
      IF (X(21).LE.0. .OR.X(22).LE. 0. .OR.X(25).LE.0. .OR.X(26).LE.0.)
     1    GO TO 10
      CT = X(25) + 0.67*X(26)
      EC = (.75*X(21) + .25*X(22))*0.1
   10 CONTINUE
      E1 = 10.**(X(20) - 2.)
      ES = X(23)
      STRLN = .2395 - ALOG(AT)*(.0024*ES + .0585*E1) - .1413*AT
     1                - ALOG(EC)*(.5476    - .0305*AT) - .0168*EC*CT
      FUNC3 = EXP(STRLN)*1.E-03
```

```
      RETURN
      END
      FUNCTION FUNC4(X)
      DIMENSION X(40)
C     THIS EVALUATES THE NUMBER OF LOAD REPETITIONS TO FAILURE.
C     USING THE BRE-MODIFIED 1-10B RELATIONS FOR K1, K2.
C     ALL MODULI IN KPSI (SPECIFICALLY X(20), EAC, AND ERF) 83/6/20
      REAL K1, K2, K1RF
      DATA K1RF, ERF /7.87E-07, 5.0E+02/
      EAC = 10.**X(20)
      K1 = K1RF*(EAC/ERF)**(-4.)
      K2 = 1.75 - .252*ALOG10(K1)
      FAILNR = K1*X(31)**(-K2)
      FUNC4 = FAILNR
      RETURN
      END
      FUNCTION FUNC5(X)
      DIMENSION X(40)
C     THIS EVALUATES THE DAMAGE INDEX FOR GIVEN CUM. ESAL, NR TO FAIL.
      FAILNR = X(32)
      CUMSAL = X(7)
      DI = CUMSAL/FAILNR
      FUNC5 = DI
      RETURN
      END
      FUNCTION FUNC6(X)
      DIMENSION X(40)
C     THIS EVALUATES PERCENT CRACKED AREA, BASED ON 1-10B AASHO
C     ANAL. AND PRJ FIT TO (DI,AREA) FOR (1., 10.) AND (1.38, 45.).
C     CUM ESAL NOW ASSUMED TO BE IN X(7) (84/4/18).
      FAILNR = X(32)
      CUMSAL = X(7)
      DI = CUMSAL/FAILNR
      AC = 0.
      IF (DI .GT. 0.5) AC = 100.*(1. - (1. - EXP(-6.29/DI))**56.7)
      FUNC6 = AC
      RETURN
      END
      FUNCTION FUNC7(X)
      DIMENSION X(40)
      COMMON /CURTFC/ CURADT, CURTRK, CURSAL, CUMVEH, CUMTRK, CUMSAL
C     AASHO EQN FOR LOSS OF SERVICEABILITY.
C     CHANGED 84/4/12 TO RETURN POSITIVE VALUE (ONE DECREASING WITH TIME)
      SN = 0.44*X(24) + 0.14*X(25) + 0.11*X(26)
      R = X(27)
      SS = 5.049*ALOG(3.623*X(23)*0.1)
C     ABOVE EQN DERIVED FROM ASSUMED SS=3 AT E=5000, SS=10 AT E=20000.
C     AND AN ASSUMED FORM.  USE ONLY FOR PURPOSE OF TESTING THIS PGM.
C     NOTE:  SUBGRADE MODULUS (X(23)) IS IN UNITS OF -KPSI- (83/6/17).
      RHOLOG = 9.36*ALOG10(SN + 1.) + ALOG10(R) + .372*(SS-3.)
      BETA = 0.4 + 1094.*(SN+1.)**(-5.19)
C     NOTE: RHOLOG AND BETA ASSUME 18-KIP AXLES.
```

```
C     CUM ESAL NOW IN X(7) (84/4/18)
      GT = BETA*(ALOG10(X(7))-RHOLOG)
      PSI = 4.2 - 2.7*10.**GT
      FUNC7 = PSI
      RETURN
      END
      FUNCTION FUNC8(X)
      DIMENSION X(40)
C     SKID MODEL, USING WISCONSIN IGNEOUS SURFACING MATERIAL.  NOTE THAT
C     THERE IS -NO- DEPENDENCE ON ANY ASPHALTIC OR STRUCTURAL PROPERTY
C     IN THIS MODEL.
C     MODIFIED 84/4/12 TO RETURN A POSITIVE VALUE (ONE DECREASING WITH TIME).
C     CUM. TRUCK TRAFFIC NOW IN X(6)
      Z = X(6)
      SKIDNR = 119.5 - 11.67*ALOG10(Z)
      FUNC8 = SKIDNR
      RETURN
      END
      FUNCTION FUNC9(X)
      DIMENSION X(40)
      COMMON /CURVAL/ DUMMY(40), CVX(40), DFDX(40), AGE
C     AASHO EQUATION FOR PSI=F(RUT,CRKG,SLOPE VAR.)
C     REPLACE SV BY K1*VAR(R.D.), VAR(R.D.)=K2*R.D.
C     S.V.= 556.*(ETA**2)*(R.D.)**2
C     APPROXIMATE ETA (=C.V. OF VERT. DISPL.) BY X(17)*C.V.(E (A.C.))
C     FROM SEVERAL VESYS RUNS, X(17) IS APPROXIMATELY 1.2
C     IN THIS PSI CALCULATION.
C     MODIFIED 84/4/12 TO RETURN A POSITIVE VALUE, DECREASING WITH TIME.
      ETA = X(17)*CVX(20)*X(20)*2.3026
      SV = 556.*(ETA*X(30))**2
C     ASSUME INITIAL PSI = 4.2, HENCE INITIAL SV = 1.72
      PSI = 5.03 - 1.91*ALOG10(1. + SV + 1.72) - 1.38*X(30)**2
C     IGNORE THE SMALL CONTRIBUTION OF AREAL CRACKING FOR THE MOMENT.
      FUNC9 = PSI
      RETURN
      END
      FUNCTION FUNC10(X)
      DIMENSION X(40)
      COMMON /CURVAL/ DUMMY(40), CVX(40), DFDX(40), AGE
C     ASSUMES:  X(1) = INITIAL ADT.
C               X(2) = PERCENT/YEAR INCREASE IN ADT.
C               X(3) = PCT TRUCKS.
C               X(4) = AVG. ESAL/TRUCK
C               X(5) = CURRENT ADT
C               X(6) = CUMULATIVE TRUCKS
C               X(7) = CUMULATIVE ESAL
      R = 1. + X(2)/100.
      FUNC10 = X(1)*R**(AGE-1.)
      RETURN
      END
      FUNCTION FUNC11(X)
      DIMENSION X(40)
```

```
      COMMON /CURVAL/ DUMMY(40), CVX(40), DFDX(40), AGE
      R = 1. + X(2)/100.
      IF (X(2) .NE. 0.) THEN
          CUMVEH = X(1)*(R**AGE - 1.)/(R - 1.) * 365.25
          ELSE
          CUMVEH = X(1)*AGE*365.25
      ENDIF
      FUNC11 = CUMVEH*X(3)/100.
      RETURN
      END
      FUNCTION FUNC12(X)
      DIMENSION X(40)
C     ASSUMES THAT CUMULATIVE TRUCKS IS IN X(6)
C     AND OBTAINS CUM. ESAL FROM X(6) AND ESAL/TRK (X(4)).
      FUNC12 = X(6) * X(4)
      RETURN
      END
      FUNCTION FUNC13(X)
      DIMENSION X(40)
C     THIS MODELS THE VARIATION OF C1 AND C2 IN SKID RELATION
C     SN=C1*(TRUX/1E6)**C2 WITH MOH'S HARDNESS (H) AND LOS ANGELES
C     ABRASION (LA).  BASED ON STUDY BY HVQ.  NOT FOR GENERAL USE,
C     AS RELATIONS ARE NOT HIGHLY RELIABLE.
C
C     X(27) = MOH'S HARDNESS
C     X(28) = L.A. ABRASION.
C     X(6)  = CUMULATIVE TRUCKS.
C
      C1 = 0.52 * X(28) + 27.13
      C2 = 0.1E-3 * (-0.34 + 0.76*X(27)) * C1 + (-0.38 + 0.014*X(27))
      SN = C1 * (X(6) * 1.E-6)**C2
      FUNC13 = SN
      RETURN
      END
      FUNCTION FUNC14(X)
      STOP 'FUNCTION 14'
      END
      FUNCTION FUNC15(X)
      STOP 'FUNCTION 15'
      END
```

APPENDIX E

EXAMPLE FOR CODING DECISION CRITERIA FOR SELECTING MAINTENANCE AND REHABILITATION OPTIONS

Appendix E is a detailed discussion for the input of decision criteria defining maintenance and rehabilitation options for various levels, extents and combinations of distresses. The following provides a detailed discussion of an example.

Assume that there exist M distresses or other criteria (e.g., traffic level) that determine the choice of rehabilitation procedure for a particular project; not all of these need be capable of triggering the rehabilitation (for example, traffic level). Assume further that there exist N different rehabilitation options or strategies.

1. For each of M distress types:
    a. The identification number of the corresponding model that calculates the distress.
    b. The number N of distress criteria.
    c. Which, if any, of the distress criteria will trigger maintenance if exceeded.
    d. The N distress criteria (values of severity) or pairs of values (severity and extent in percent area), which mark the boundaries between the N + 1 (=NL) levels of distress).
2. For each rehabilitation option:
    a. A code or identification number;
    b. A set of M digits (keys) which will be described below;
    c. A unit cost and a unit key; and
    d. A description of the option (< 30 letters).

The only restriction on the number of levels for each distress is that the product of all the numbers must be less than the size NDIM of an array in the program (currently 300); for example, four distresses may have two levels and two distresses may have three levels for a product of 144 ($=2^4 \times 3^2$). NDIM can be adjusted to fit the available space.

As an example of the data required for Part 1, and to clarify the distinction between severity and extent, consider the following:

> If the distress considered is mean rut depth, there might be only two levels of importance: less than 0.5 inch, and greater than 0.5 inch. Here N would be 1, the single value would be 0.5, and there would be N + 1 = NL = 2 levels. If on the other hand one defines calculated percent areal cracking as the percent area for which the calculated damage index DI is greater than 1.0, then for areal cracking one might have 3 levels of importance: area < 1 percent, area between 1 percent and 20 percent, and area greater than 20 percent. Here N = 2, there are N + 1 = NL = 3 levels, and there are 2 pairs of values: {1.,1.} and {1.,20.} where the second value in each pair is the percent area (or extent) for which the distress exceeds in severity the first value of the pair (here, damage index).

At each time point in the simulation of pavement performance, calculated distresses are compared with the criteria input by the user, and a level d_i is assigned for each distress. If any distress exceeds a trigger level for rehabilitation, a subroutine is called which obtains the appropriate rehabilitation procedure by treating each d_i as an index in an array, and retrieving from the array the code number of the corresponding option. These will have been pre-stored on the basis of the M keys mentioned in Item 2b above.

The assignment of keys for each rehabilitation option requires that the user set up a decision tree or chart as he would if he were manually assigning the option, based on the calculated distress levels (for example, refer to Table 52 in Appendix C). Then for each option, the M keys correspond to the distress levels for each of the M distresses which would lead to the selection of that option, except for one simplification: If for any case, the option is chosen without respect to a given distress i, a 0 for the key corresponding to that distress ensures that for all NL_i values for that index, the corresponding code number is stored in the array. It may still occur that an option will appear more than once, for distinct areas of the decision chart, and require a second set of keys; however, the number of such repetitions will in general be much smaller than the number of possible combinations of distress for which that option will be prescribed.

A specific example will serve to clarify the above. The decision tree shown in Tables 51 and 52 (Appendix C) will be used as a reasonably typical example.

(Note that Skid Resistance and PSI are decreasing functions of time. The reversed comparisons required in such cases are enabled by a special input variable discussed in the input guide.) We see that the product of the NL_i is 144, well below the current limit of 300. If we were to write the decision tree in full, there would be 144 separate combinations to consider; fortunately we do not need to do this, as normally a few distresses will dominate the picture.

Referring to Table 52, we see that fatigue cracking >20 percent (in area) overrides all other considerations; i.e., no matter what the other distress levels are, the outcome of the decision process is the same. Hence, we use the 0 key value for all distresses except fatigue cracking, and our keys for the corresponding rehabilitation option number 1 are 300000. There are 2x2x3x2x2 = 48 possible combinations of the indices corresponding to the 0's, so 48 of the 144 locations in the (6 dimensional) array are filled with the value 1. (The program does not actually use a 6-dimensional array, but calculates the corresponding position in a singly dimensioned array, making possible changes in the values NL_i without programming changes).

Next on our decision chart is: 1 percent <fatigue <20 percent; PSI < 2.0. Therefore, our keys are 200300, and the program puts the option number, 2, in 1x2x2x1x2x2 = 16 locations. Next is 1 percent < fatigue <20 percent; rutting (d_2) <.5. Here we might say the keys are 220000, and put a 3 in 2x3x2x2 = 24 locations. But, one observes, some of those 24 overlap the 16 already filled with 2. The program, however, checks each location before storing into it. At the beginning, a code corresponding to a default, or "do-nothing" alternative, is stored in all array locations. If anything other than the "do nothing" choice is already present when the program checks an array location, that location is not changed. So, the keys above (220000) were correct, but in fact only 16 of the 24 locations will have a 3 stored in them.

This illustrates the importance of the order in which the tests on the different distresses are made in the decision chart. If in the above example rutting had been checked before roughness, 24 locations would have had option 3 and only 8 would have had option 2 (keeping the code number associated with the same option description as before).

APPENDIX F

EXAMPLES: INPUT AND OUTPUT FOR PROGRAM COSTOP1

Appendix F contains some of the example problems discussed and presented in Chapter 7. Table 53 is a listing of these individual problems.

Table 53 Summary of Problems Contained in Appendix F

Problem No.	Problem Description
1-A, 1-B, 1-C	Analysis of Testing Programs for Bitumen Content, Percent Air Voids, Percent Passing the No. 200 Sieve, Asphalt Viscosity and Asphalt Concrete Thickness for States A, B, and C, respectively.
2-A, 2-B, 2-C	Analysis of Testing Programs for Extractions, Asphalt Viscosity, and Asphalt Concrete Thickness for States A, B, and C, respectively.
3-A.1, 3-A.2	Analysis of Testing Programs for Extractions, Asphalt Viscosity, and Asphalt Concrete Thickness Using State A for Different Highway Classifications, (Low Traffic, and High Traffic Roadways, respectively).
4-C.1, 4-C.2, 4-C.3, 4-C.4, 4-C.5	Analysis of Testing Frequencies for Individual Tests Including Asphalt Viscosity, Bitumen Content, Percent Passing the No. 200 Sieve, Percent Air Voids, and Asphalt Concrete Thickness, respectively, using State C.

```
                                                     PROBLEM 1-A

EXAMPLE:  ANALYSIS OF ASPHALT CONCRETE TESTS IN STATE "A".

RUN DESCRIPTION:
----------------

USE PERFORMANCE MODELS TO CALCULATE DISTRESS.  OPTIMUM TESTING PROGRAM FOR
ASPHALT LABORATORY.  (PCT. AC, PCT. VOID, PCT. 200, AC VISCOS, AC THICK)


INPUT DATA (COSTS)
(THOUSANDS OF DOLLARS/LANE MILE
--------------------------------

INITIAL CONSTRUCTION       90.0
ANNUAL MAINTENANCE COST      .0
ANNUAL USER COST             .0
USER COST OF REHAB.          .0

COST OF MONEY (INTEREST)   12.5 PERCENT


INPUT DATA (GEOMETRICAL)
------------------------
LANE WIDTH (FEET)          12.0


INPUT DATA (TRAFFIC)
--------------------

 ABBREV.  ID                            COEF.         FULL
  NAME    NO.   VALUE        UNITS     OF VAR.        NAME

INIT ADT   1      .60E+04 VEH/DAY        .00     INITIAL AVG. DAILY TRAFFIC
PCTPERYR   2      5.0     PERCENT        .00     PERCENT PER YR GROWTH IN ADT
PCTTRK     3      .10E+02 PERCENT        .00     PERCENT OF TRUCKS IN TRAFFIC
ESAL/TRK   4      .30     ESAL           .00     18-KIP EQUIV. SINGLE AXLES/TRK


INPUT DATA (MATERIALS)
----------------------

 ABBREV.  ID                            COEF.         FULL
  NAME    NO.   VALUE        UNITS     OF VAR.        NAME

PCT AC    11      6.0     PERCENT        .06     PERCENT BITUMEN (BY WEIGHT)
PCT VOID  12      3.0     PERCENT        .40     PERCENT AIR VOIDS IN MIX
PCT 200   13      3.0     PERCENT        .25     PCT AGGREG. PASSING #200 SEIVE
VISCOS    14      3.2     10^6 POISE     .10     VISCOSITY OF BITUMEN-70 DEG F
LOAD FQ   15      .10E+02 HZ             .10     FREQUENCY OF REPEATED LOADINGS
AC TEMP   16      .85E+02 DEG F          .10     TEMPERATURE OF AC (MID-DEPTH)
```

```
EACVARML  17      1.0     DIM-LESS        .00     MULT. ON CALC. VAR. OF E(AC)
E BASE    21      .30E+02 KPSI            .25     RESILIENT MODULUS OF BASE
E SUBB    22      .20E+02 KPSI            .25     RESILIENT MODULUS OF SUBBASE
E SUBGR   23      .15E+02 KPSI            .30     RESILIENT MODULUS OF SUBGRADE
THK AC    24      4.5     INCHES          .05     THICKNESS OF AC LAYER
THK BASE  25      8.0     INCHES          .10     THICKNESS OF BASE
THK SUBB  26      .12E+02 INCHES          .15     THICKNESS OF SUBBASE

SPECIFICATION OF INDEPENDENT VARIABLES
FOR INDICATED MODELS
-------------------------------------

 ABBREV.               ID  FN  DEPENDENT ON
  NAME      UNITS      NO. NO. ID    NAME        FULL NAME

CURADT   VEH/DAY        5  10                    CURRENT AVG. DAILY TRAFFIC
                                1  INIT ADT      INITIAL AVG. DAILY TRAFFIC
                                2  PCTPERYR      PERCENT PER YR GROWTH IN ADT

CUMTRK   TRUCKS         6  11                    CUMULATIVE TRUCKS TO PRESENT
                                1  INIT ADT      INITIAL AVG. DAILY TRAFFIC
                                2  PCTPERYR      PERCENT PER YR GROWTH IN ADT
                                3  PCTTRK        PERCENT OF TRUCKS IN TRAFFIC

CUMESAL  ESAL           7  12                    CUMULATIVE ESAL   TO PRESENT
                                4  ESAL/TRK      18-KIP EQUIV. SINGLE AXLES/TRK
                                6  CUMTRK        CUMULATIVE TRUCKS TO PRESENT

LOG E AC KPSI (LOG)    20  -1                    LOG (BASE 10) OF AC MODULUS
                               11  PCT AC        PERCENT BITUMEN (BY WEIGHT)
                               12  PCT VOID      PERCENT AIR VOIDS IN MIX
                               13  PCT 200       PCT AGGREG. PASSING #200 SEIVE
                               14  VISCOS        VISCOSITY OF BITUMEN-70 DEG F
                               15  LOAD FQ       FREQUENCY OF REPEATED LOADINGS
                               16  AC TEMP       TEMPERATURE OF AC (MID-DEPTH)

RUT DEP  INCHES        30   2                    AVG RUT DEPTH-BOTH WHEEL PATH
                                7  CUMESAL       CUMULATIVE ESAL   TO PRESENT
                               20  LOG E AC      LOG (BASE 10) OF AC MODULUS
                               21  E BASE        RESILIENT MODULUS OF BASE
                               22  E SUBB        RESILIENT MODULUS OF SUBBASE
                               23  E SUBGR       RESILIENT MODULUS OF SUBGRADE
                               24  THK AC        THICKNESS OF AC LAYER
                               25  THK BASE      THICKNESS OF BASE
                               26  THK SUBB      THICKNESS OF SUBBASE

RAD STRN INCHES/INCH   31  -3                    RADIAL STRAIN, BOTTOM OF AC.
                               20  LOG E AC      LOG (BASE 10) OF AC MODULUS
                               21  E BASE        RESILIENT MODULUS OF BASE
                               23  E SUBGR       RESILIENT MODULUS OF SUBGRADE
                               24  THK AC        THICKNESS OF AC LAYER
                               25  THK BASE      THICKNESS OF BASE
```

```
NRTOFAIL DIM-LESS      32  -4                  NR 18-KIP ESAL TO 10 PCT CRKG
                               31  RAD STRN    RADIAL STRAIN, BOTTOM OF AC.

DMG INDX DIM-LESS      33   5                  FRACTION OF FATIGUE LIFE USED
                                7  CUMESAL     CUMULATIVE ESAL   TO PRESENT
                               32  NRTOFAIL    NR 18-KIP ESAL TO 10 PCT CRKG

PSI      DIM-LESS      34   9                  PRESENT SERVICABILITY INDEX
                               20  LOG E AC    LOG (BASE 10) OF AC MODULUS
                               30  RUT DEP     AVG RUT DEPTH-BOTH WHEEL PATH

SKID NR. DIM-LESS      35   8                  SKID NUMBER
                                6  CUMTRK      CUMULATIVE TRUCKS TO PRESENT



INPUT CRITERIA AFFECTING
MAINT OR REHAB DECISIONS
------------------------

          ASSIGNED ASSIGNED      DEFINITION OF ASSIGNED
CRITERION  ID NO.  LEVEL NO.        CRITERION LEVEL

 DMG INDX     33         3     GREATER THAN       1.00 FOR MORE THAN 20.0 PCT AREA
                         2     GREATER THAN       1.00 FOR MORE THAN  1.0 PCT AREA
 PSI          34         3     LESS THAN          2.00 (MEAN VALUE)
                         2     LESS THAN          3.00 (MEAN VALUE)
 RUT DEP      30         2     GREATER THAN        .50 (MEAN VALUE)
 SKID NR.     35         2     LESS THAN         43.00 (MEAN VALUE)
 CURADT        5         2     GREATER THAN    1000.00 (MEAN VALUE)

INPUT MAINTENANCE OR
REHABILITATION PROCEDURES
-------------------------

  NR   KEYS    COST   COST             DESCRIPTION
              (DOL.) UNITS

   1  300000   6.00  SQ. YD.      4"    OVERLAY
   2  230000   4.50  SQ. YD.      MILL 1" + 2" OVERLAY
   3  202000   5.00  SQ. YD.      1.5" LEVELUP + 1.5" OVERLAY
   4  200200   2.75  SQ. YD.      MEMBRANE + 1.5" OVERLAY
   5  130000   3.50  SQ. YD.      MILL 1" +   1.5"   OVERLAY
   6  102000   3.00  SQ. YD.      1" LEVELUP + 1" OVERLAY
   7  120200   2.50  SQ. YD.      MILL 0.5" + 1" OVERLAY
   8  110210   1.25  SQ. YD.      CHIP SEAL
   9  110220   1.75  SQ. YD.      AC FRICTION COURSE.
  31  000000    .00               DO NOTHING
```

```
PARAMETERS DETERMINING VARIABLE VALUES
AS A FUNCTION OF NUMBER OF TESTS
-------------------------------------

                          CONF.    PARAMETERS FOR        COST PER
              TYPE OF     LEVEL  FUNCTIONAL VARIATION      TEST
 ID   NAME   VARIATION    (PCT)    A     B     C     D   (DOLLARS)

 11  PCT AC     STAT        95    .00   .00   .00   .00      90.
 12  PCT VOID   STAT        95    .00   .00   .00   .00      60.
 13  PCT 200    STAT       -95    .00   .00   .00   .00      85.
 14  VISCOS     STAT       -95    .00   .00   .00   .00     100.
 24  THK AC     STAT       -90    .00   .00   .00   .00     100.


VALUES OF TESTED VARIABLES USED IN SIMULATIONS
(CALCULATED FROM NUMBER OF TESTS)
---------------------------------------------

             NR OF   VALUE   NR OF   VALUE   NR OF   VALUE   NR OF  VALUE
 ID   NAME   TESTS   (C.V.)  TESTS   (C.V.)  TESTS   (C.V.)  TESTS  (C.V.)

 11  PCT AC     3    6.6069    6    6.2961    9    6.2232
                      .0545            .0572           .0578
 12  PCT VOID   3    5.0230    6    3.9871    9    3.7440
                      .2389            .3010           .3205
 13  PCT 200    3    1.7356    6    2.3830    9    2.5350
                      .4321            .3147           .2959
 14  VISCOS     3    2.6605    6    2.9368
                      .1203            .1090
 24  THK AC     3    4.2550    6    4.3644    9    4.3952
                      .0529            .0516           .0512

  NUMBER OF TESTS ON                                  UNIF. ANN. UNIF. ANN.   DIFF.
  MATERIAL PROPERTY   AGE AT  DISTRESS SELECTED         COSTS     TESTING   BENEFIT/
 IDENTIFIED BY ID NO. FAILURE CAUSING    REHAB       1000-S OF     COST       COST
                       YEARS  FAILURE    OPTION        DOLLARS    DOLLARS     RATIO
    11  12  13  14  24

     3   6   3   3   3   4.86   PSI         5           29.80      425.90     1.414
     6   3   3   3   3   4.94   PSI         5           29.39      446.13    20.092
     6   6   3   3   3   4.96   PSI         5           29.31      495.84     1.664
     9   3   3   3   3   4.97   PSI         5           29.28      520.76     1.274
     6   3   3   3   6   5.00   PSI         5           29.12      526.62    27.206
     6   6   3   3   6   5.02   PSI         5           29.02      575.34     2.101
     9   3   3   3   6   5.03   PSI         5           28.99      600.04     1.081
     9   6   3   3   6   5.05   PSI         5           28.88      648.24     2.198
     9   6   3   3   9   5.07   PSI         5           28.80      729.90     1.065
```

```
                                                                  PROBLEM 1-B

EXAMPLE:  ANALYSIS OF ASPHALT CONCRETE TESTS IN STATE "B".


RUN DESCRIPTION:
----------------

USE PERFORMANCE MODELS TO CALCULATE DISTRESS.  OPTIMUM TESTING PROGRAM FOR
ASPHALT LABORATORY.  (PCT. AC, PCT. VOID, PCT. 200, AC VISCOS, AC THICK)


INPUT DATA (COSTS)
(THOUSANDS OF DOLLARS/LANE MILE
--------------------------------

INITIAL CONSTRUCTION         90.0
ANNUAL MAINTENANCE COST        .0
ANNUAL USER COST               .0
USER COST OF REHAB.            .0

COST OF MONEY (INTEREST)     12.5 PERCENT


INPUT DATA (GEOMETRICAL)
------------------------
LANE WIDTH (FEET)            12.0


INPUT DATA (TRAFFIC)
--------------------

 ABBREV.  ID                                COEF.          FULL
  NAME    NO.   VALUE         UNITS        OF VAR.         NAME

INIT ADT   1       .60E+04 VEH/DAY           .00      INITIAL AVG. DAILY TRAFFIC
PCTPERYR   2      5.0      PERCENT           .00      PERCENT PER YR GROWTH IN ADT
PCTTRK     3       .10E+02 PERCENT           .00      PERCENT OF TRUCKS IN TRAFFIC
ESAL/TRK   4       .30     ESAL              .00      18-KIP EQUIV. SINGLE AXLES/TRK


INPUT DATA (MATERIALS)
----------------------

 ABBREV.  ID                                COEF.          FULL
  NAME    NO.   VALUE         UNITS        OF VAR.         NAME

PCT AC    11      5.0      PERCENT           .06      PERCENT BITUMEN (BY WEIGHT)
PCT VOID  12      5.0      PERCENT           .40      PERCENT AIR VOIDS IN MIX
PCT 200   13      6.0      PERCENT           .25      PCT AGGREG. PASSING #200 SEIVE
VISCOS    14      5.0      10^6 POISE        .10      VISCOSITY OF BITUMEN-70 DEG F
LOAD FQ   15       .10E+02 HZ                .10      FREQUENCY OF REPEATED LOADINGS
AC TEMP   16       .75E+02 DEG F             .10      TEMPERATURE OF AC (MID-DEPTH)
```

```
EACVARML  17      1.0      DIM-LESS        .00     MULT. ON CALC. VAR. OF E(AC).
E BASE    21      .30E+02  KPSI            .25     RESILIENT MODULUS OF BASE
E SUBB    22      .20E+02  KPSI            .25     RESILIENT MODULUS OF SUBBASE
E SUBGR   23      .15E+02  KPSI            .30     RESILIENT MODULUS OF SUBGRADE
THK AC    24      4.5      INCHES          .05     THICKNESS OF AC LAYER
THK BASE  25      8.0      INCHES          .10     THICKNESS OF BASE
THK SUBB  26      .12E+02  INCHES          .15     THICKNESS OF SUBBASE

SPECIFICATION OF INDEPENDENT VARIABLES
FOR INDICATED MODELS
--------------------------------------

 ABBREV.                ID  FN  DEPENDENT ON
  NAME     UNITS        NO. NO. ID    NAME       FULL NAME

CURADT   VEH/DAY         5  10                   CURRENT AVG. DAILY TRAFFIC
                                 1  INIT ADT     INITIAL AVG. DAILY TRAFFIC
                                 2  PCTPERYR     PERCENT PER YR GROWTH IN ADT

CUMTRK   TRUCKS          6  11                   CUMULATIVE TRUCKS TO PRESENT
                                 1  INIT ADT     INITIAL AVG. DAILY TRAFFIC
                                 2  PCTPERYR     PERCENT PER YR GROWTH IN ADT
                                 3  PCTTRK       PERCENT OF TRUCKS IN TRAFFIC

CUMESAL  ESAL            7  12                   CUMULATIVE ESAL   TO PRESENT
                                 4  ESAL/TRK     18-KIP EQUIV. SINGLE AXLES/TRK
                                 6  CUMTRK       CUMULATIVE TRUCKS TO PRESENT

LOG E AC KPSI (LOG)     20  -1                   LOG (BASE 10) OF AC MODULUS
                                11  PCT AC       PERCENT BITUMEN (BY WEIGHT)
                                12  PCT VOID     PERCENT AIR VOIDS IN MIX
                                13  PCT 200      PCT AGGREG. PASSING #200 SEIVE
                                14  VISCOS       VISCOSITY OF BITUMEN-70 DEG F
                                15  LOAD FQ      FREQUENCY OF REPEATED LOADINGS
                                16  AC TEMP      TEMPERATURE OF AC (MID-DEPTH)

RUT DEP  INCHES         30   2                   AVG RUT DEPTH-BOTH WHEEL PATH
                                 7  CUMESAL      CUMULATIVE ESAL   TO PRESENT
                                20  LOG E AC     LOG (BASE 10) OF AC MODULUS
                                21  E BASE       RESILIENT MODULUS OF BASE
                                22  E SUBB       RESILIENT MODULUS OF SUBBASE
                                23  E SUBGR      RESILIENT MODULUS OF SUBGRADE
                                24  THK AC       THICKNESS OF AC LAYER
                                25  THK BASE     THICKNESS OF BASE
                                26  THK SUBB     THICKNESS OF SUBBASE

RAD STRN INCHES/INCH    31  -3                   RADIAL STRAIN, BOTTOM OF AC.
                                20  LOG E AC     LOG (BASE 10) OF AC MODULUS
                                21  E BASE       RESILIENT MODULUS OF BASE
                                23  E SUBGR      RESILIENT MODULUS OF SUBGRADE
                                24  THK AC       THICKNESS OF AC LAYER
                                25  THK BASE     THICKNESS OF BASE
```

```
NRTOFAIL DIM-LESS       32  -4                           NR 18-KIP ESAL TO 10 PCT CRKG
                                  31  RAD STRN           RADIAL STRAIN, BOTTOM OF AC.

DMG INDX DIM-LESS       33   5                           FRACTION OF FATIGUE LIFE USED
                                   7  CUMESAL            CUMULATIVE ESAL   TO PRESENT
                                  32  NRTOFAIL           NR 18-KIP ESAL TO 10 PCT CRKG

PSI      DIM-LESS       34   9                           PRESENT SERVICABILITY INDEX
                                  20  LOG E AC           LOG (BASE 10) OF AC MODULUS
                                  30  RUT DEP            AVG RUT DEPTH-BOTH WHEEL PATH

SKID NR. DIM-LESS       35   8                           SKID NUMBER
                                   6  CUMTRK             CUMULATIVE TRUCKS TO PRESENT
1


 INPUT CRITERIA AFFECTING
 MAINT OR REHAB DECISIONS
 ------------------------

          ASSIGNED ASSIGNED      DEFINITION OF ASSIGNED
 CRITERION  ID NO.  LEVEL NO.        CRITERION LEVEL

  RUT DEP     30         3      GREATER THAN        .50 FOR MORE THAN 50.0 PCT AREA
                         2      GREATER THAN        .25 FOR MORE THAN 50.0 PCT AREA
  PSI         34         2      LESS THAN          2.00 (MEAN VALUE)
  DMG INDX    33         2      GREATER THAN       1.00 FOR MORE THAN 50.0 PCT AREA
  CURADT       5         3      GREATER THAN    5000.00 (MEAN VALUE)
                         2      GREATER THAN    1000.00 (MEAN VALUE)

 INPUT MAINTENANCE OR
 REHABILITATION PROCEDURES
 -------------------------

   NR   KEYS     COST   COST              DESCRIPTION
                (DOL.) UNITS

    1  300000    5.50   SQ. YD.       3"   OVERLAY
    2  220100    3.25   SQ. YD.       MILL 1" + 1" OVERLAY
    3  220200    4.00   SQ. YD.       MILL 1" + 1.5" OVERLAY
    4  220300    4.75   SQ. YD.       MILL 1" + 2" OVERLAY
    5  212100    3.50   SQ. YD.       SEAL COAT + 1"   OVERLAY
    6  212200    4.50   SQ. YD.       MEMBRANE + 1.5" OVERLAY
    7  212300    5.25   SQ. YD.       MEMBRANE + 2" OVERLAY
    8  120100    3.00   SQ. YD.       MILL 0.5" + 1" OVERLAY
    9  120200    3.75   SQ. YD.       MILL 0.5" + 1.5" OVERLAY
   10  120300    4.50   SQ. YD.       MILL 0.5" + 2" OVERLAY
   11  112100    1.50   SQ. YD.       SEAL COAT
   12  112200    3.50   SQ. YD.       SEAL COAT + 1" OVERLAY
   13  112300    4.25   SQ. YD.       SEAL COAT + 1.5" OVERLAY
   31  000000     .00                 DO NOTHING
```

```
PARAMETERS DETERMINING VARIABLE VALUES
AS A FUNCTION OF NUMBER OF TESTS
--------------------------------------

                            CONF.    PARAMETERS FOR          COST PER
              TYPE OF       LEVEL  FUNCTIONAL VARIATION        TEST
 ID   NAME    VARIATION     (PCT)    A       B       C      D    (DOLLARS)

 11  PCT AC      STAT         95     .00     .00     .00    .00      80.
 12  PCT VOID    STAT         95     .00     .00     .00    .00      60.
 13  PCT 200     STAT        -95     .00     .00     .00    .00     100.
 14  VISCOS      STAT        -95     .00     .00     .00    .00     125.
 24  THK AC      STAT        -90     .00     .00     .00    .00     105.

VALUES OF TESTED VARIABLES USED IN SIMULATIONS
(CALCULATED FROM NUMBER OF TESTS)
----------------------------------------------

                NR OF   VALUE    NR OF   VALUE    NR OF   VALUE    NR OF   VALUE
 ID   NAME      TESTS   (C.V.)   TESTS   (C.V.)   TESTS   (C.V.)   TESTS   (C.V.)

 11  PCT AC      12     5.1555    15     5.1364    18     5.1230
                         .0582            .0584            .0586
 12  PCT VOID    15     5.9094    18     5.8202    21     5.7529
                         .3384            .3436            .3477
 13  PCT 200     12     5.2223    15     5.3180    18     5.3848
                         .2872            .2821            .2786
 14  VISCOS       9     4.6900    12     4.7408    15     4.7727
                         .1066            .1055            .1048
 24  THK AC      15     4.4219    18     4.4293    21     4.4349
                         .0509            .0508            .0507
1
  NUMBER OF TESTS ON                                   UNIF. ANN. UNIF. ANN.   DIFF.
  MATERIAL PROPERTY    AGE AT  DISTRESS SELECTED        COSTS      TESTING    BENEFIT/
 IDENTIFIED BY ID NO. FAILURE CAUSING    REHAB       1000-S OF     COST       COST
                       YEARS   FAILURE   OPTION       DOLLARS     DOLLARS     RATIO
    11 12 13 14 24

    12 18 12  9 15     8.48   RUT DEP      1          20.64      1175.60     3.195
    12 21 12  9 15     8.52   RUT DEP      1          20.56      1207.66     2.334
    12 18 12 12 15     8.54   RUT DEP      1          20.52      1244.22     1.070
    12 21 15  9 15     8.56   RUT DEP      1          20.50      1263.91     1.020
    12 21 12 12 15     8.59   RUT DEP      1          20.45      1275.94     4.496
    15 21 12 12 15     8.61   RUT DEP      1          20.40      1320.72     1.014
    12 21 15 12 15     8.62   RUT DEP      1          20.39      1331.78     1.201
    15 21 15 12 15     8.65   RUT DEP      1          20.34      1376.35     1.014
    12 21 15 15 15     8.66   RUT DEP      1          20.32      1401.36     1.005
    15 21 15 15 15     8.69   RUT DEP      1          20.27      1445.68     1.014
```

```
                                                                PROBLEM 1-C

EXAMPLE:  ANALYSIS OF ASPHALT CONCRETE TESTS IN STATE "C".  1/11/85


RUN DESCRIPTION:
----------------

USE PERFORMANCE MODELS TO CALCULATE DISTRESS.  OPTIMUM TESTING PROGRAM FOR
ASPHALT LABORATORY.  ( PCT. AC, PCT. VOIDS, PCT. 200, AC VISCOS., AC THICK)


INPUT DATA (COSTS)
(THOUSANDS OF DOLLARS/LANE MILE
--------------------------------

INITIAL CONSTRUCTION        90.0
ANNUAL MAINTENANCE COST       .0
ANNUAL USER COST              .0
USER COST OF REHAB.           .0

COST OF MONEY (INTEREST)    12.5 PERCENT


INPUT DATA (GEOMETRICAL)
------------------------
LANE WIDTH (FEET)           12.0


INPUT DATA (TRAFFIC)
--------------------

 ABBREV.  ID                               COEF.          FULL
  NAME    NO.   VALUE        UNITS        OF VAR.         NAME

INIT ADT   1       .60E+04 VEH/DAY          .00      INITIAL AVG. DAILY TRAFFIC
PCTPERYR   2      5.0      PERCENT          .00      PERCENT PER YR GROWTH IN ADT
PCTTRK     3       .10E+02 PERCENT          .00      PERCENT OF TRUCKS IN TRAFFIC
ESAL/TRK   4       .30     ESAL             .00      18-KIP EQUIV. SINGLE AXLES/TRK


INPUT DATA (MATERIALS)
----------------------

 ABBREV.  ID                               COEF.          FULL
  NAME    NO.   VALUE        UNITS        OF VAR.         NAME

PCT AC    11      6.0      PERCENT          .06      PERCENT BITUMEN (BY WEIGHT)
PCT VOID  12      2.5      PERCENT          .40      PERCENT AIR VOIDS IN MIX
PCT 200   13      6.0      PERCENT          .25      PCT AGGREG. PASSING #200 SEIVE
VISCOS    14      5.0      10^6 POISE       .10      VISCOSITY OF BITUMEN-70 DEG F
LOAD FQ   15       .10E+02 HZ               .10      FREQUENCY OF REPEATED LOADINGS
AC TEMP   16       .75E+02 DEG F            .10      TEMPERATURE OF AC (MID-DEPTH)
```

```
EACVARML  17      1.0     DIM-LESS       .00    MULTIPLIER ON CALC. VAR. OF E(
E BASE    21      .30E+02 KPSI           .25    RESILIENT MODULUS OF BASE
E SUBB    22      .20E+02 KPSI           .25    RESILIENT MODULUS OF SUBBASE
E SUBGR   23      .15E+02 KPSI           .30    RESILIENT MODULUS OF SUBGRADE
THK AC    24      4.5      INCHES        .05    THICKNESS OF AC LAYER
THK BASE  25      8.0      INCHES        .10    THICKNESS OF BASE
THK SUBB  26      .12E+02 INCHES         .15    THICKNESS OF SUBBASE

SPECIFICATION OF INDEPENDENT VARIABLES
FOR INDICATED MODELS
--------------------------------------

 ABBREV.                 ID  FN  DEPENDENT ON
  NAME     UNITS         NO. NO. ID     NAME      FULL NAME

CURADT   VEH/DAY          5  10                   CURRENT AVG. DAILY TRAFFIC
                                  1  INIT ADT     INITIAL AVG. DAILY TRAFFIC
                                  2  PCTPERYR     PERCENT PER YR GROWTH IN ADT

CUMTRK   TRUCKS           6  11                   CUMULATIVE TRUCKS TO PRESENT
                                  1  INIT ADT     INITIAL AVG. DAILY TRAFFIC
                                  2  PCTPERYR     PERCENT PER YR GROWTH IN ADT
                                  3  PCTTRK       PERCENT OF TRUCKS IN TRAFFIC

CUMESAL  ESAL             7  12                   CUMULATIVE ESAL   TO PRESENT
                                  4  ESAL/TRK     18-KIP EQUIV. SINGLE AXLES/TRK
                                  6  CUMTRK       CUMULATIVE TRUCKS TO PRESENT

LOG E AC KPSI (LOG)      20  -1                   LOG (BASE 10) OF AC MODULUS
                                 11  PCT AC       PERCENT BITUMEN (BY WEIGHT)
                                 12  PCT VOID     PERCENT AIR VOIDS IN MIX
                                 13  PCT 200      PCT AGGREG. PASSING #200 SEIVE
                                 14  VISCOS.      VISCOSITY OF BITUMEN-70 DEG F
                                 15  LOAD FQ      FREQUENCY OF REPEATED LOADINGS
                                 16  AC TEMP      TEMPERATURE OF AC (MID-DEPTH)

RUT DEP  INCHES          30   2                   AVG RUT DEPTH-BOTH WHEEL PATH
                                  7  CUMESAL      CUMULATIVE ESAL   TO PRESENT
                                 20  LOG E AC     LOG (BASE 10) OF AC MODULUS
                                 21  E BASE       RESILIENT MODULUS OF BASE
                                 22  E SUBB       RESILIENT MODULUS OF SUBBASE
                                 23  E SUBGR      RESILIENT MODULUS OF SUBGRADE
                                 24  THK AC       THICKNESS OF AC LAYER
                                 25  THK BASE     THICKNESS OF BASE
                                 26  THK SUBB     THICKNESS OF SUBBASE

RAD STRN INCHES/INCH     31  -3                   RADIAL STRAIN, BOTTOM OF AC.
                                 20  LOG E AC     LOG (BASE 10) OF AC MODULUS
                                 21  E BASE       RESILIENT MODULUS OF BASE
                                 23  E SUBGR      RESILIENT MODULUS OF SUBGRADE
                                 24  THK AC       THICKNESS OF AC LAYER
                                 25  THK BASE     THICKNESS OF BASE
```

```
NRTOFAIL DIM-LESS       32  -4                     NR 18-KIP ESAL TO 10 PCT CRKG
                                 31  RAD STRN      RADIAL STRAIN, BOTTOM OF AC.

DMG INDX DIM-LESS       33   5                     FRACTION OF FATIGUE LIFE USED
                                  7  CUMESAL       CUMULATIVE ESAL   TO PRESENT
                                 32  NRTOFAIL      NR 18-KIP ESAL TO 10 PCT CRKG
1



INPUT CRITERIA AFFECTING
MAINT OR REHAB DECISIONS
------------------------

         ASSIGNED ASSIGNED      DEFINITION OF ASSIGNED
CRITERION  ID NO.  LEVEL NO.       CRITERION LEVEL

 DMG INDX     33        3      GREATER THAN      1.00 FOR MORE THAN 50.0 PCT AREA
                        2      GREATER THAN      1.00 FOR MORE THAN  1.0 PCT AREA
 RUT DEP      30        2      GREATER THAN       .50 (MEAN VALUE)
 CURADT        5        2      GREATER THAN   1000.00 (MEAN VALUE)

INPUT MAINTENANCE OR
REHABILITATION PROCEDURES
-------------------------

  NR   KEYS    COST   COST            DESCRIPTION
              (DOL.) UNITS

   1  300000    5.50  SQ. YD.      SEAL COAT + 2.5" OVERLAY
   2  221000    4.75  SQ. YD.      MILL 1", SEAL COAT, 1.5" OVERLAY
   3  222000    6.25  SQ. YD.      MILL 1", SEAL COAT, 2.5" OVERLAY
   4  121000    3.50  SQ. YD.      MILL 0.5" + 1.5" OVERLAY
   5  122000    5.00  SQ. YD.      MILL 0.5" + 2.5" OVERLAY
  31  000000     .00               DO NOTHING

PARAMETERS DETERMINING VARIABLE VALUES
AS A FUNCTION OF NUMBER OF TESTS
-------------------------------------

                         CONF.    PARAMETERS FOR        COST PER
             TYPE OF     LEVEL  FUNCTIONAL VARIATION      TEST
 ID   NAME   VARIATION   (PCT)   A      B      C      D    (DOLLARS)

 11  PCT AC      STAT      95    .00    .00    .00    .00      80.
 12  PCT VOID    STAT      95    .00    .00    .00    .00      70.
 13  PCT 200     STAT     -95    .00    .00    .00    .00       0.
 14  VISCOS      STAT     -95    .00    .00    .00    .00     150.
 24  THK AC      STAT     -90    .00    .00    .00    .00     105.


 VALUES OF TESTED VARIABLES USED IN SIMULATIONS
```

```
(CALCULATED FROM NUMBER OF TESTS)
----------------------------------------------

              NR OF   VALUE   NR OF   VALUE   NR OF   VALUE   NR OF   VALUE
 ID   NAME    TESTS   (C.V.)  TESTS   (C.V.)  TESTS   (C.V.)  TESTS   (C.V.)

 11  PCT AC    15     6.1637   18     6.1476   21     6.1355
                       .0584           .0586           .0587
 12  PCT VOID  15     2.9547   18     2.9101   21     2.8764
                       .3384           .3436           .3477
 13  PCT 200   12     5.2223   15     5.3180   18     5.3848
                       .2872           .2821           .2786
 14  VISCOS     9     4.6900   12     4.7408   15     4.7727
                       .1066           .1055           .1048
 24  THK AC    15     4.4219   18     4.4293   21     4.4349
                       .0509           .0508           .0507
1
  NUMBER OF TESTS ON                                   UNIF. ANN. UNIF. ANN.   DIFF.
  MATERIAL PROPERTY   AGE AT  DISTRESS SELECTED     COSTS      TESTING     BENEFIT/
 IDENTIFIED BY ID NO. FAILURE CAUSING   REHAB     1000-S OF    COST        COST
                      YEARS   FAILURE   OPTION     DOLLARS    DOLLARS      RATIO
    11 12 13 14 24

    15 18 18  9 15     9.08   RUT DEP     5         19.43     1024.85      1.144
    15 15 18 12 15     9.12   RUT DEP     5         19.37     1067.98      1.317
    15 18 18 12 15     9.15   RUT DEP     5         19.33     1105.83      1.144
```

```
                                                         PROBLEM 2-A

EXAMPLE:  ANALYSIS OF ASPHALT CONCRETE TESTS IN STATE "A".

RUN DESCRIPTION:
----------------

USE PERFORMANCE MODELS TO CALCULATE DISTRESS.  OPTIMUM TESTING PROGRAM FOR
ASPHALT LABORATORY.  (PCT. VOID, AC VISCOS, AC THICK)


INPUT DATA (COSTS)
(THOUSANDS OF DOLLARS/LANE MILE
--------------------------------

INITIAL CONSTRUCTION        90.0
ANNUAL MAINTENANCE COST       .0
ANNUAL USER COST              .0
USER COST OF REHAB.           .0

COST OF MONEY (INTEREST)    12.5 PERCENT


INPUT DATA (GEOMETRICAL)
------------------------
LANE WIDTH (FEET)           12.0


INPUT DATA (TRAFFIC)
--------------------

 ABBREV.  ID                             COEF.          FULL
  NAME    NO.   VALUE        UNITS      OF VAR.         NAME

INIT ADT   1       .60E+04 VEH/DAY        .00      INITIAL AVG. DAILY TRAFFIC
PCTPERYR   2      5.0      PERCENT        .00      PERCENT PER YR GROWTH IN ADT
PCTTRK     3       .10E+02 PERCENT        .00      PERCENT OF TRUCKS IN TRAFFIC
ESAL/TRK   4       .30     ESAL           .00      18-KIP EQUIV. SINGLE AXLES/TRK


INPUT DATA (MATERIALS)
----------------------

 ABBREV.  ID                             COEF.          FULL
  NAME    NO.   VALUE        UNITS      OF VAR.         NAME

PCT AC    11      6.0      PERCENT        .06      PERCENT BITUMEN (BY WEIGHT)
PCT VOID  12      3.0      PERCENT        .40      PERCENT AIR VOIDS IN MIX
PCT 200   13      3.0      PERCENT        .25      PCT AGGREG. PASSING #200 SEIVE
VISCOS    14      3.2      10^6 POISE     .10      VISCOSITY OF BITUMEN-70 DEG F
LOAD FQ   15       .10E+02 HZ             .10      FREQUENCY OF REPEATED LOADINGS
AC TEMP   16       .85E+02 DEG F          .10      TEMPERATURE OF AC (MID-DEPTH)
```

```
EACVARML  17       1.0      DIM-LESS        .00     MULTIPLIER ON CALC. VAR. OF E(
E BASE    21       .30E+02 KPSI             .25     RESILIENT MODULUS OF BASE
E SUBB    22       .20E+02 KPSI             .25     RESILIENT MODULUS OF SUBBASE
E SUBGR   23       .15E+02 KPSI             .30     RESILIENT MODULUS OF SUBGRADE
THK AC    24       4.5      INCHES          .05     THICKNESS OF AC LAYER
THK BASE  25       8.0      INCHES          .10     THICKNESS OF BASE
THK SUBB  26       .12E+02 INCHES           .15     THICKNESS OF SUBBASE

SPECIFICATION OF INDEPENDENT VARIABLES
FOR INDICATED MODELS
-------------------------------------

 ABBREV.                  ID  FN  DEPENDENT ON
  NAME      UNITS         NO. NO. ID     NAME       FULL NAME

CURADT    VEH/DAY          5  10                    CURRENT AVG. DAILY TRAFFIC
                                   1   INIT ADT     INITIAL AVG. DAILY TRAFFIC
                                   2   PCTPERYR     PERCENT PER YR GROWTH IN ADT

CUMTRK    TRUCKS           6  11                    CUMULATIVE TRUCKS TO PRESENT
                                   1   INIT ADT     INITIAL AVG. DAILY TRAFFIC
                                   2   PCTPERYR     PERCENT PER YR GROWTH IN ADT
                                   3   PCTTRK       PERCENT OF TRUCKS IN TRAFFIC

CUMESAL   ESAL             7  12                    CUMULATIVE ESAL   TO PRESENT
                                   4   ESAL/TRK     18-KIP EQUIV. SINGLE AXLES/TRK
                                   6   CUMTRK       CUMULATIVE TRUCKS TO PRESENT

LOG E AC KPSI (LOG)       20  -1                    LOG (BASE 10) OF AC MODULUS
                                  11   PCT AC       PERCENT BITUMEN (BY WEIGHT)
                                  12   PCT VOID     PERCENT AIR VOIDS IN MIX
                                  13   PCT 200      PCT AGGREG. PASSING #200 SEIVE
                                  14   VISCOS       VISCOSITY OF BITUMEN-70 DEG F
                                  15   LOAD FQ      FREQUENCY OF REPEATED LOADINGS
                                  16   AC TEMP      TEMPERATURE OF AC (MID-DEPTH)

RUT DEP   INCHES          30   2                    AVG RUT DEPTH-BOTH WHEEL PATH
                                   7   CUMESAL      CUMULATIVE ESAL   TO PRESENT
                                  20   LOG E AC     LOG (BASE 10) OF AC MODULUS
                                  21   E BASE       RESILIENT MODULUS OF BASE
                                  22   E SUBB       RESILIENT MODULUS OF SUBBASE
                                  23   E SUBGR      RESILIENT MODULUS OF SUBGRADE
                                  24   THK AC       THICKNESS OF AC LAYER
                                  25   THK BASE     THICKNESS OF BASE
                                  26   THK SUBB     THICKNESS OF SUBBASE

RAD STRN INCHES/INCH      31  -3                    RADIAL STRAIN, BOTTOM OF AC.
                                  20   LOG E AC     LOG (BASE 10) OF AC MODULUS
                                  21   E BASE       RESILIENT MODULUS OF BASE
                                  23   E SUBGR      RESILIENT MODULUS OF SUBGRADE
                                  24   THK AC       THICKNESS OF AC LAYER
                                  25   THK BASE     THICKNESS OF BASE
```

```
NRTOFAIL DIM-LESS       32  -4                      NR 18-KIP ESAL TO 10 PCT CRKG
                                 31  RAD STRN       RADIAL STRAIN, BOTTOM OF AC.

DMG INDX DIM-LESS       33   5                      FRACTION OF FATIGUE LIFE USED
                                  7  CUMESAL        CUMULATIVE ESAL   TO PRESENT
                                 32  NRTOFAIL       NR 18-KIP ESAL TO 10 PCT CRKG

PSI      DIM-LESS       34   9                      PRESENT SERVICABILITY INDEX
                                 20  LOG E AC       LOG (BASE 10) OF AC MODULUS
                                 30  RUT DEP        AVG RUT DEPTH-BOTH WHEEL PATH

SKID NR. DIM-LESS       35   8                      SKID NUMBER
                                  6  CUMTRK         CUMULATIVE TRUCKS TO PRESENT
1



 INPUT CRITERIA AFFECTING
 MAINT OR REHAB DECISIONS
 ------------------------

          ASSIGNED ASSIGNED      DEFINITION OF ASSIGNED
 CRITERION  ID NO.  LEVEL NO.        CRITERION LEVEL

  DMG INDX     33         3      GREATER THAN       1.00 FOR MORE THAN 20.0 PCT AREA
                          2      GREATER THAN       1.00 FOR MORE THAN  1.0 PCT AREA
  PSI          34         3      LESS THAN          2.00 (MEAN VALUE)
                          2      LESS THAN          3.00 (MEAN VALUE)
  RUT DEP      30         2      GREATER THAN        .50 (MEAN VALUE)
  SKID NR.     35         2      LESS THAN         43.00 (MEAN VALUE)
  CURADT        5         2      GREATER THAN    1000.00 (MEAN VALUE)

 INPUT MAINTENANCE OR
 REHABILITATION PROCEDURES
 -------------------------

   NR    KEYS     COST   COST              DESCRIPTION
                 (DOL.) UNITS

     1  300000    6.00   SQ. YD.       4"   OVERLAY
     2  230000    4.50   SQ. YD.       MILL 1" + 2" OVERLAY
     3  202000    5.00   SQ. YD.       1.5" LEVELUP + 1.5" OVERLAY
     4  200200    2.75   SQ. YD.       MEMBRANE + 1.5" OVERLAY
     5  130000    3.50   SQ. YD.       MILL 1" +   1.5"   OVERLAY
     6  102000    3.00   SQ. YD.       1" LEVELUP + 1" OVERLAY
     7  120200    2.50   SQ. YD.       MILL 0.5" + 1" OVERLAY
     8  110210    1.25   SQ. YD.       CHIP SEAL
     9  110220    1.75   SQ. YD.       AC FRICTION COURSE.
    31  000000     .00                 DO NOTHING
```

```
PARAMETERS DETERMINING VARIABLE VALUES
AS A FUNCTION OF NUMBER OF TESTS
--------------------------------------

                            CONF.     PARAMETERS FOR        COST PER
               TYPE OF      LEVEL  FUNCTIONAL VARIATION       TEST
 ID   NAME    VARIATION     (PCT)    A      B      C      D   (DOLLARS)

 12  PCT VOID   STAT         95     .00    .00    .00    .00     60.
 14  VISCOS     STAT        -95     .00    .00    .00    .00    100.
 24  THK AC     STAT        -90     .00    .00    .00    .00     80.

VALUES OF TESTED VARIABLES USED IN SIMULATIONS
(CALCULATED FROM NUMBER OF TESTS)
----------------------------------------------

                NR OF   VALUE    NR OF   VALUE    NR OF   VALUE    NR OF   VALUE
 ID   NAME      TESTS   (C.V.)   TESTS   (C.V.)   TESTS   (C.V.)   TESTS   (C.V.)

 12  PCT VOID     3     5.0230     6     3.9871     9     3.7440    12     3.6222
                         .2389            .3010            .3205            .3313
 14  VISCOS       3     2.6605     6     2.9368
                         .1203            .1090
 24  THK AC       3     4.2550     6     4.3644     9     4.3952    12     4.4115
                         .0529            .0516            .0512            .0510
1
  NUMBER OF TESTS ON                                 UNIF. ANN. UNIF. ANN.   DIFF.
  MATERIAL PROPERTY     AGE AT  DISTRESS SELECTED      COSTS     TESTING    BENEFIT/
 IDENTIFIED BY ID NO.  FAILURE  CAUSING   REHAB     1000-S OF    COST       COST
                        YEARS   FAILURE   OPTION     DOLLARS    DOLLARS     RATIO
    12  14  24

     6   3   3   0   0    5.09   PSI         5        28.70      249.51     2.380
     3   3   6   0   0    5.13   PSI         5        28.51      264.50    13.034
     6   3   6   0   0    5.16   PSI         5        28.38      312.83     2.627
     6   3   9   0   0    5.18   PSI         5        28.29      377.64     1.355
```

```
                                                              PROBLEM 2-B

EXAMPLE:  ANALYSIS OF ASPHALT CONCRETE TESTS IN STATE "B".


RUN DESCRIPTION:
----------------

USE PERFORMANCE MODELS TO CALCULATE DISTRESS.  OPTIMUM TESTING PROGRAM FOR
ASPHALT LABORATORY.  (PCT. VOID, AC VISCOS, AC THICK)


INPUT DATA (COSTS)
(THOUSANDS OF DOLLARS/LANE MILE
--------------------------------

INITIAL CONSTRUCTION        90.0
ANNUAL MAINTENANCE COST       .0
ANNUAL USER COST              .0
USER COST OF REHAB.           .0

COST OF MONEY (INTEREST)    12.5 PERCENT


INPUT DATA (GEOMETRICAL)
------------------------
LANE WIDTH (FEET)           12.0


INPUT DATA (TRAFFIC)
--------------------

 ABBREV.  ID                               COEF.         FULL
  NAME    NO.   VALUE        UNITS        OF VAR.        NAME

INIT ADT   1      .60E+04 VEH/DAY           .00     INITIAL AVG. DAILY TRAFFIC
PCTPERYR   2     5.0      PERCENT           .00     PERCENT PER YR GROWTH IN ADT
PCTTRK     3      .10E+02 PERCENT           .00     PERCENT OF TRUCKS IN TRAFFIC
ESAL/TRK   4      .30     ESAL              .00     18-KIP EQUIV. SINGLE AXLES/TRK


INPUT DATA (MATERIALS)
----------------------

 ABBREV.  ID                               COEF.         FULL
  NAME    NO.   VALUE        UNITS        OF VAR.        NAME

PCT AC    11     5.0      PERCENT           .06     PERCENT BITUMEN (BY WEIGHT)
PCT VOID  12     5.0      PERCENT           .40     PERCENT AIR VOIDS IN MIX
PCT 200   13     6.0      PERCENT           .25     PCT AGGREG. PASSING #200 SEIVE
VISCOS    14     5.0      10^6 POISE        .10     VISCOSITY OF BITUMEN-70 DEG F
LOAD FQ   15      .10E+02 HZ                .10     FREQUENCY OF REPEATED LOADINGS
AC TEMP   16      .75E+02 DEG F             .10     TEMPERATURE OF AC (MID-DEPTH)
```

```
EACVARML  17      1.0      DIM-LESS       .00    MULT. ON CALC. VAR. OF E(AC).
E BASE    21      .30E+02 KPSI            .25    RESILIENT MODULUS OF BASE
E SUBB    22      .20E+02 KPSI            .25    RESILIENT MODULUS OF SUBBASE
E SUBGR   23      .15E+02 KPSI            .30    RESILIENT MODULUS OF SUBGRADE
THK AC    24      4.5      INCHES         .05    THICKNESS OF AC LAYER
THK BASE  25      8.0      INCHES         .10    THICKNESS OF BASE
THK SUBB  26      .12E+02 INCHES          .15    THICKNESS OF SUBBASE

SPECIFICATION OF INDEPENDENT VARIABLES
FOR INDICATED MODELS
-------------------------------------

 ABBREV.                ID  FN  DEPENDENT ON
  NAME     UNITS        NO. NO. ID    NAME       FULL NAME

CURADT   VEH/DAY         5  10                   CURRENT AVG. DAILY TRAFFIC
                                 1  INIT ADT     INITIAL AVG. DAILY TRAFFIC
                                 2  PCTPERYR     PERCENT PER YR GROWTH IN ADT

CUMTRK   TRUCKS          6  11                   CUMULATIVE TRUCKS TO PRESENT
                                 1  INIT ADT     INITIAL AVG. DAILY TRAFFIC
                                 2  PCTPERYR     PERCENT PER YR GROWTH IN ADT
                                 3  PCTTRK       PERCENT OF TRUCKS IN TRAFFIC

CUMESAL  ESAL            7  12                   CUMULATIVE ESAL   TO PRESENT
                                 4  ESAL/TRK     18-KIP EQUIV. SINGLE AXLES/TRK
                                 6  CUMTRK       CUMULATIVE TRUCKS TO PRESENT

LOG E AC KPSI (LOG)     20  -1                   LOG (BASE 10) OF AC MODULUS
                                11  PCT AC       PERCENT BITUMEN (BY WEIGHT)
                                12  PCT VOID     PERCENT AIR VOIDS IN MIX
                                13  PCT 200      PCT AGGREG. PASSING #200 SEIVE
                                14  VISCOS       VISCOSITY OF BITUMEN-70 DEG F
                                15  LOAD FQ      FREQUENCY OF REPEATED LOADINGS
                                16  AC TEMP      TEMPERATURE OF AC (MID-DEPTH)

RUT DEP  INCHES         30   2                   AVG RUT DEPTH-BOTH WHEEL PATH
                                 7  CUMESAL      CUMULATIVE ESAL   TO PRESENT
                                20  LOG E AC     LOG (BASE 10) OF AC MODULUS
                                21  E BASE       RESILIENT MODULUS OF BASE
                                22  E SUBB       RESILIENT MODULUS OF SUBBASE
                                23  E SUBGR      RESILIENT MODULUS OF SUBGRADE
                                24  THK AC       THICKNESS OF AC LAYER
                                25  THK BASE     THICKNESS OF BASE
                                26  THK SUBB     THICKNESS OF SUBBASE

RAD STRN INCHES/INCH    31  -3                   RADIAL STRAIN, BOTTOM OF AC.
                                20  LOG E AC     LOG (BASE 10) OF AC MODULUS
                                21  E BASE       RESILIENT MODULUS OF BASE
                                23  E SUBGR      RESILIENT MODULUS OF SUBGRADE
                                24  THK AC       THICKNESS OF AC LAYER
                                25  THK BASE     THICKNESS OF BASE
```

```
NRTOFAIL DIM-LESS       32   -4                          NR 18-KIP ESAL TO 10 PCT CRKG
                                  31   RAD STRN          RADIAL STRAIN, BOTTOM OF AC.

DMG INDX DIM-LESS       33    5                          FRACTION OF FATIGUE LIFE USED
                                   7   CUMESAL           CUMULATIVE ESAL   TO PRESENT
                                  32   NRTOFAIL          NR 18-KIP ESAL TO 10 PCT CRKG

PSI      DIM-LESS       34    9                          PRESENT SERVICABILITY INDEX
                                  20   LOG E AC          LOG (BASE 10) OF AC MODULUS
                                  30   RUT DEP           AVG RUT DEPTH-BOTH WHEEL PATH

SKID NR. DIM-LESS       35    8                          SKID NUMBER
                                   6   CUMTRK            CUMULATIVE TRUCKS TO PRESENT
1



 INPUT CRITERIA AFFECTING
 MAINT OR REHAB DECISIONS
 ------------------------

          ASSIGNED ASSIGNED      DEFINITION OF ASSIGNED
 CRITERION  ID NO.  LEVEL NO.        CRITERION LEVEL

  RUT DEP     30         3      GREATER THAN        .50 FOR MORE THAN 50.0 PCT AREA
                         2      GREATER THAN        .25 FOR MORE THAN 50.0 PCT AREA
  PSI         34         2      LESS THAN          2.00 (MEAN VALUE)
  DMG INDX    33         2      GREATER THAN       1.00 FOR MORE THAN 50.0 PCT AREA
  CURADT       5         3      GREATER THAN    5000.00 (MEAN VALUE)
                         2      GREATER THAN    1000.00 (MEAN VALUE)

 INPUT MAINTENANCE OR
 REHABILITATION PROCEDURES
 -------------------------

   NR    KEYS     COST   COST            DESCRIPTION
                 (DOL.) UNITS

    1  300000     5.50   SQ. YD.      3"   OVERLAY
    2  220100     3.25   SQ. YD.      MILL 1" + 1" OVERLAY
    3  220200     4.00   SQ. YD.      MILL 1" + 1.5" OVERLAY
    4  220300     4.75   SQ. YD.      MILL 1" + 2" OVERLAY
    5  212100     3.50   SQ. YD.      SEAL COAT + 1"   OVERLAY
    6  212200     4.50   SQ. YD.      MEMBRANE + 1.5" OVERLAY
    7  212300     5.25   SQ. YD.      MEMBRANE + 2" OVERLAY
    8  120100     3.00   SQ. YD.      MILL 0.5" + 1" OVERLAY
    9  120200     3.75   SQ. YD.      MILL 0.5" + 1.5" OVERLAY
   10  120300     4.50   SQ. YD.      MILL 0.5" + 2" OVERLAY
   11  112100     1.50   SQ. YD.      SEAL COAT
   12  112200     3.50   SQ. YD.      SEAL COAT + 1" OVERLAY
   13  112300     4.25   SQ. YD.      SEAL COAT + 1.5" OVERLAY
   31  000000      .00                DO NOTHING
```

```
PARAMETERS DETERMINING VARIABLE VALUES
AS A FUNCTION OF NUMBER OF TESTS
--------------------------------------

                         CONF.     PARAMETERS FOR         COST PER
            TYPE OF      LEVEL   FUNCTIONAL VARIATION       TEST
 ID   NAME  VARIATION    (PCT)     A      B      C      D   (DOLLARS)

 12  PCT VOID   STAT       95     .00    .00    .00    .00     60.
 14  VISCOS     STAT      -95     .00    .00    .00    .00    125.
 24  THK AC     STAT      -90     .00    .00    .00    .00    105.


VALUES OF TESTED VARIABLES USED IN SIMULATIONS
(CALCULATED FROM NUMBER OF TESTS)
----------------------------------------------

                NR OF  VALUE    NR OF  VALUE    NR OF  VALUE    NR OF  VALUE
 ID    NAME     TESTS  (C.V.)   TESTS  (C.V.)   TESTS  (C.V.)   TESTS  (C.V.)

 12  PCT VOID   15     5.9094   18     5.8202   21     5.7529   24     5.6997
                        .3384           .3436           .3477           .3509
 14  VISCOS      6     4.5887    9     4.6900   12     4.7408   15     4.7727
                        .1090           .1066           .1055           .1048
 24  THK AC     12     4.4115   15     4.4219   18     4.4293   21     4.4349
                        .0510           .0509           .0508           .0507
1
  NUMBER OF TESTS ON                                    UNIF. ANN. UNIF. ANN.   DIFF.
  MATERIAL PROPERTY    AGE AT  DISTRESS SELECTED     COSTS     TESTING     BENEFIT/
 IDENTIFIED BY ID NO.  FAILURE CAUSING    REHAB     1000-S OF    COST        COST
                       YEARS   FAILURE    OPTION     DOLLARS    DOLLARS      RATIO
    12 14 24

    18  6 12   0   0    8.80   RUT DEP      1         20.09      598.51      2.922
    21  6 12   0   0    8.85   RUT DEP      1         20.02      631.55      2.171
    15  9 12   0   0    8.88   RUT DEP      1         19.97      633.13     32.454
    18  9 12   0   0    8.94   RUT DEP      1         19.88      665.30      2.912
    21  9 12   0   0    8.98   RUT DEP      1         19.80      697.87      2.158
    24  9 12   0   0    9.02   RUT DEP      1         19.75      730.72      1.656
    21 12 12   0   0    9.05   RUT DEP      1         19.70      766.41      1.405
    24 12 12   0   0    9.09   RUT DEP      1         19.65      798.98      1.641
    24 12 15   0   0    9.13   RUT DEP      1         19.58      856.42      1.231
```

```
                                                                    PROBLEM 2-C

EXAMPLE:  ANALYSIS OF ASPHALT CONCRETE TESTS IN STATE "C".


RUN DESCRIPTION:
----------------

USE PERFORMANCE MODELS TO CALCULATE DISTRESS.  OPTIMUM TESTING PROGRAM FOR
ASPHALT LABORATORY.  ( PCT. VOIDS, AC VISCOS., AC THICK)


INPUT DATA (COSTS)
(THOUSANDS OF DOLLARS/LANE MILE
--------------------------------

INITIAL CONSTRUCTION        90.0
ANNUAL MAINTENANCE COST       .0
ANNUAL USER COST              .0
USER COST OF REHAB.           .0

COST OF MONEY (INTEREST)    12.5 PERCENT


INPUT DATA (GEOMETRICAL)
------------------------
LANE WIDTH (FEET)           12.0


INPUT DATA (TRAFFIC)
--------------------

 ABBREV.  ID                                COEF.         FULL
  NAME    NO.   VALUE         UNITS        OF VAR.        NAME

INIT ADT   1      .60E+04 VEH/DAY            .00      INITIAL AVG. DAILY TRAFFIC
PCTPERYR   2     5.0      PERCENT            .00      PERCENT PER YR GROWTH IN ADT
PCTTRK     3      .10E+02 PERCENT            .00      PERCENT OF TRUCKS IN TRAFFIC
ESAL/TRK   4      .30     ESAL               .00      18-KIP EQUIV. SINGLE AXLES/TRK


INPUT DATA (MATERIALS)
----------------------

 ABBREV.  ID                                COEF.         FULL
  NAME    NO.   VALUE         UNITS        OF VAR.        NAME

PCT AC    11     6.0      PERCENT            .06      PERCENT BITUMEN (BY WEIGHT)
PCT VOID  12     2.5      PERCENT            .40      PERCENT AIR VOIDS IN MIX
PCT 200   13     6.0      PERCENT            .25      PCT AGGREG. PASSING #200 SEIVE
VISCOS    14     5.0      10^6 POISE         .10      VISCOSITY OF BITUMEN-70 DEG F
LOAD FQ   15      .10E+02 HZ                 .10      FREQUENCY OF REPEATED LOADINGS
AC TEMP   16      .75E+02 DEG F              .10      TEMPERATURE OF AC (MID-DEPTH)
```

```
EACVARML  17       1.0      DIM-LESS         .00      MULTIPLIER ON CALC. VAR. OF E(
E BASE    21       .30E+02 KPSI              .25      RESILIENT MODULUS OF BASE
E SUBB    22       .20E+02 KPSI              .25      RESILIENT MODULUS OF SUBBASE
E SUBGR   23       .15E+02 KPSI              .30      RESILIENT MODULUS OF SUBGRADE
THK AC    24       4.5      INCHES           .05      THICKNESS OF AC LAYER
THK BASE  25       8.0      INCHES           .10      THICKNESS OF BASE
THK SUBB  26       .12E+02 INCHES            .15      THICKNESS OF SUBBASE

SPECIFICATION OF INDEPENDENT VARIABLES
FOR INDICATED MODELS
--------------------------------------

 ABBREV.                 ID  FN  DEPENDENT ON
  NAME     UNITS         NO. NO. ID    NAME       FULL NAME

CURADT   VEH/DAY          5  10                   CURRENT AVG. DAILY TRAFFIC
                                  1  INIT ADT     INITIAL AVG. DAILY TRAFFIC
                                  2  PCTPERYR     PERCENT PER YR GROWTH IN ADT

CUMTRK   TRUCKS           6  11                   CUMULATIVE TRUCKS TO PRESENT
                                  1  INIT ADT     INITIAL AVG. DAILY TRAFFIC
                                  2  PCTPERYR     PERCENT PER YR GROWTH IN ADT
                                  3  PCTTRK       PERCENT OF TRUCKS IN TRAFFIC

CUMESAL  ESAL             7  12                   CUMULATIVE ESAL   TO PRESENT
                                  4  ESAL/TRK     18-KIP EQUIV. SINGLE AXLES/TRK
                                  6  CUMTRK       CUMULATIVE TRUCKS TO PRESENT

LOG E AC KPSI (LOG)      20  -1                   LOG (BASE 10) OF AC MODULUS
                                 11  PCT AC       PERCENT BITUMEN (BY WEIGHT)
                                 12  PCT VOID     PERCENT AIR VOIDS IN MIX
                                 13  PCT 200      PCT AGGREG. PASSING #200 SEIVE
                                 14  VISCOS.      VISCOSITY OF BITUMEN-70 DEG F
                                 15  LOAD FQ      FREQUENCY OF REPEATED LOADINGS
                                 16  AC TEMP      TEMPERATURE OF AC (MID-DEPTH)

RUT DEP  INCHES          30   2                   AVG RUT DEPTH-BOTH WHEEL PATH
                                  7  CUMESAL      CUMULATIVE ESAL   TO PRESENT
                                 20  LOG E AC     LOG (BASE 10) OF AC MODULUS
                                 21  E BASE       RESILIENT MODULUS OF BASE
                                 22  E SUBB       RESILIENT MODULUS OF SUBBASE
                                 23  E SUBGR      RESILIENT MODULUS OF SUBGRADE
                                 24  THK AC       THICKNESS OF AC LAYER
                                 25  THK BASE     THICKNESS OF BASE
                                 26  THK SUBB     THICKNESS OF SUBBASE

RAD STRN INCHES/INCH     31  -3                   RADIAL STRAIN, BOTTOM OF AC.
                                 20  LOG E AC     LOG (BASE 10) OF AC MODULUS
                                 21  E BASE       RESILIENT MODULUS OF BASE
                                 23  E SUBGR      RESILIENT MODULUS OF SUBGRADE
                                 24  THK AC       THICKNESS OF AC LAYER
                                 25  THK BASE     THICKNESS OF BASE
```

```
NRTOFAIL DIM-LESS       32  -4                       NR 18-KIP ESAL TO 10 PCT CRKG
                                  31  RAD STRN     RADIAL STRAIN, BOTTOM OF AC.

DMG INDX DIM-LESS       33   5                       FRACTION OF FATIGUE LIFE USED
                                   7  CUMESAL      CUMULATIVE ESAL   TO PRESENT
                                  32  NRTOFAIL     NR 18-KIP ESAL TO 10 PCT CRKG
1



 INPUT CRITERIA AFFECTING
 MAINT OR REHAB DECISIONS
 ------------------------

         ASSIGNED ASSIGNED       DEFINITION OF ASSIGNED
CRITERION  ID NO.  LEVEL NO.          CRITERION LEVEL

 DMG INDX     33         3      GREATER THAN      1.00 FOR MORE THAN 50.0 PCT AREA
                         2      GREATER THAN      1.00 FOR MORE THAN  1.0 PCT AREA
 RUT DEP      30         2      GREATER THAN       .50 (MEAN VALUE)
 CURADT        5         2      GREATER THAN   1000.00 (MEAN VALUE)

 INPUT MAINTENANCE OR
 REHABILITATION PROCEDURES
 -------------------------

   NR   KEYS     COST   COST              DESCRIPTION
                (DOL.) UNITS

    1  300000    5.50   SQ. YD.       SEAL COAT + 2.5" OVERLAY
    2  221000    4.75   SQ. YD.       MILL 1", SEAL COAT, 1.5" OVERLAY
    3  222000    6.25   SQ. YD.       MILL 1", SEAL COAT, 2.5" OVERLAY
    4  121000    3.50   SQ. YD.       MILL 0.5" + 1.5" OVERLAY
    5  122000    5.00   SQ. YD.       MILL 0.5" + 2.5" OVERLAY
   31  000000     .00               . DO NOTHING

 PARAMETERS DETERMINING VARIABLE VALUES
 AS A FUNCTION OF NUMBER OF TESTS
 --------------------------------------

                         CONF.     PARAMETERS FOR        COST PER
              TYPE OF    LEVEL  FUNCTIONAL VARIATION       TEST
  ID   NAME   VARIATION  (PCT)    A       B      C      D   (DOLLARS)

  12  PCT VOID    STAT     95     .00    .00    .00    .00      70.
  14  VISCOS      STAT    -95     .00    .00    .00    .00     150.
  24  THK AC      STAT    -90     .00    .00    .00    .00     105.

 VALUES OF TESTED VARIABLES USED IN SIMULATIONS
 (CALCULATED FROM NUMBER OF TESTS)
 ----------------------------------------------
```

```
              NR OF  VALUE   NR OF  VALUE   NR OF  VALUE   NR OF  VALUE
  ID  NAME    TESTS  (C.V.)  TESTS  (C.V.)  TESTS  (C.V.)  TESTS  (C.V.)

  12 PCT VOID  15    2.9547   18    2.9101   21    2.8764   24    2.8499
                      .3384          .3436          .3477          .3509
  14 VISCOS     6    4.5887    9    4.6900   12    4.7408   15    4.7727
                      .1090          .1066          .1055          .1048
  24 THK AC    12    4.4115   15    4.4219   18    4.4293   21    4.4349
                      .0510          .0509          .0508          .0507
1
   NUMBER OF TESTS ON                                 UNIF. ANN. UNIF. ANN.   DIFF.
   MATERIAL PROPERTY   AGE AT  DISTRESS SELECTED   COSTS    TESTING     BENEFIT/
  IDENTIFIED BY ID NO. FAILURE CAUSING   REHAB    1000-S OF   COST        COST
                       YEARS   FAILURE   OPTION    DOLLARS   DOLLARS      RATIO
     12 14 24

     18  6 12  0  0     9.35   RUT DEP     5        19.05     640.48      1.108
     15  6 15  0  0     9.37   RUT DEP     5        19.02     659.46      1.268
     15  9 12  0  0     9.46   RUT DEP     5        18.90     681.00      5.908
     18  9 12  0  0     9.49   RUT DEP     5        18.85     718.79      1.102
     15  9 15  0  0     9.51   RUT DEP     5        18.83     737.55      1.245
     15 12 12  0  0     9.53   RUT DEP     5        18.80     761.58      1.283
     18 12 12  0  0     9.56   RUT DEP     5        18.76     799.07      1.102
     15 12 15  0  0     9.58   RUT DEP     5        18.74     817.68      1.236
     18 12 15  0  0     9.61   RUT DEP     5        18.69     854.97      1.099
```

```
                                                                PROBLEM 3-A.1

EXAMPLE:  ANALYSIS OF LOW TRAFFIC ASPHALT CONCRETE TESTS IN STATE "A".

RUN DESCRIPTION:
----------------

USE PERFORMANCE MODELS TO CALCULATE DISTRESS.  OPTIMUM TESTING PROGRAM FOR
ASPHALT LABORATORY.  (PCT. VOID, AC VISCOS, AC THICK)


INPUT DATA (COSTS)
(THOUSANDS OF DOLLARS/LANE MILE
--------------------------------

INITIAL CONSTRUCTION        35.0
ANNUAL MAINTENANCE COST       .0
ANNUAL USER COST              .0
USER COST OF REHAB.           .0

COST OF MONEY (INTEREST)    12.5 PERCENT


INPUT DATA (GEOMETRICAL)
------------------------
LANE WIDTH (FEET)           12.0


INPUT DATA (TRAFFIC)
--------------------

 ABBREV.  ID                               COEF.          FULL
  NAME    NO.   VALUE        UNITS        OF VAR.         NAME

INIT ADT   1       .50E+03 VEH/DAY          .00      INITIAL AVG. DAILY TRAFFIC
PCTPERYR   2       5.0     PERCENT          .00      PERCENT PER YR GROWTH IN ADT
PCTTRK     3       .10E+02 PERCENT          .00      PERCENT OF TRUCKS IN TRAFFIC
ESAL/TRK   4       .30     ESAL             .00      18-KIP EQUIV. SINGLE AXLES/TRK


INPUT DATA (MATERIALS)
----------------------

 ABBREV.  ID                               COEF.          FULL
  NAME    NO.   VALUE        UNITS        OF VAR.         NAME

PCT AC    11       6.0     PERCENT          .06      PERCENT BITUMEN (BY WEIGHT)
PCT VOID  12       3.0     PERCENT          .40      PERCENT AIR VOIDS IN MIX
PCT 200   13       3.0     PERCENT          .25      PCT AGGREG. PASSING #200 SEIVE
VISCOS    14       3.2     10^6 POISE       .10      VISCOSITY OF BITUMEN-70 DEG F
LOAD FQ   15       .10E+02 HZ               .10      FREQUENCY OF REPEATED LOADINGS
AC TEMP   16       .85E+02 DEG F            .10      TEMPERATURE OF AC (MID-DEPTH)
```

```
EACVARML  17      1.0     DIM-LESS         .00     MULTIPLIER ON CALC. VAR. OF E(
E BASE    21      .30E+02 KPSI             .25     RESILIENT MODULUS OF BASE
E SUBB    22      .20E+02 KPSI             .25     RESILIENT MODULUS OF SUBBASE
E SUBGR   23      .15E+02 KPSI             .30     RESILIENT MODULUS OF SUBGRADE
THK AC    24      1.5      INCHES          .05     THICKNESS OF AC LAYER
THK BASE  25      8.0      INCHES          .10     THICKNESS OF BASE
THK SUBB  26      .12E+02 INCHES           .15     THICKNESS OF SUBBASE

SPECIFICATION OF INDEPENDENT VARIABLES
FOR INDICATED MODELS
-------------------------------------

 ABBREV.                 ID  FN  DEPENDENT ON
  NAME      UNITS        NO. NO. ID     NAME       FULL NAME

CURADT   VEH/DAY          5  10                    CURRENT AVG. DAILY TRAFFIC
                                  1  INIT ADT      INITIAL AVG. DAILY TRAFFIC
                                  2  PCTPERYR      PERCENT PER YR GROWTH IN ADT

CUMTRK   TRUCKS           6  11                    CUMULATIVE TRUCKS TO PRESENT
                                  1  INIT ADT      INITIAL AVG. DAILY TRAFFIC
                                  2  PCTPERYR      PERCENT PER YR GROWTH IN ADT
                                  3  PCTTRK        PERCENT OF TRUCKS IN TRAFFIC

CUMESAL  ESAL             7  12                    CUMULATIVE ESAL   TO PRESENT
                                  4  ESAL/TRK      18-KIP EQUIV. SINGLE AXLES/TRK
                                  6  CUMTRK        CUMULATIVE TRUCKS TO PRESENT

LOG E AC KPSI (LOG)      20  -1                    LOG (BASE 10) OF AC MODULUS
                                 11  PCT AC        PERCENT BITUMEN (BY WEIGHT)
                                 12  PCT VOID      PERCENT AIR VOIDS IN MIX
                                 13  PCT 200       PCT AGGREG. PASSING #200 SEIVE
                                 14  VISCOS        VISCOSITY OF BITUMEN-70 DEG F
                                .15  LOAD FQ       FREQUENCY OF REPEATED LOADINGS
                                 16  AC TEMP       TEMPERATURE OF AC (MID-DEPTH)

RUT DEP  INCHES          30   2                    AVG RUT DEPTH-BOTH WHEEL PATH
                                  7  CUMESAL       CUMULATIVE ESAL   TO PRESENT
                                 20  LOG E AC      LOG (BASE 10) OF AC MODULUS
                                 21  E BASE        RESILIENT MODULUS OF BASE
                                 22  E SUBB        RESILIENT MODULUS OF SUBBASE
                                 23  E SUBGR       RESILIENT MODULUS OF SUBGRADE
                                 24  THK AC        THICKNESS OF AC LAYER
                                 25  THK BASE      THICKNESS OF BASE
                                 26  THK SUBB      THICKNESS OF SUBBASE

RAD STRN INCHES/INCH     31  -3                    RADIAL STRAIN, BOTTOM OF AC.
                                 20  LOG E AC      LOG (BASE 10) OF AC MODULUS
                                 21  E BASE        RESILIENT MODULUS OF BASE
                                 23  E SUBGR       RESILIENT MODULUS OF SUBGRADE
                                 24  THK AC        THICKNESS OF AC LAYER
                                 25  THK BASE      THICKNESS OF BASE
```

```
NRTOFAIL DIM-LESS       32   -4                   NR 18-KIP ESAL TO 10 PCT CRKG
                                  31  RAD STRN    RADIAL STRAIN, BOTTOM OF AC.

DMG INDX DIM-LESS       33    5                   FRACTION OF FATIGUE LIFE USED
                                   7  CUMESAL     CUMULATIVE ESAL   TO PRESENT
                                  32  NRTOFAIL    NR 18-KIP ESAL TO 10 PCT CRKG

PSI      DIM-LESS       34    9                   PRESENT SERVICABILITY INDEX
                                  20  LOG E AC    LOG (BASE 10) OF AC MODULUS
                                  30  RUT DEP     AVG RUT DEPTH-BOTH WHEEL PATH

SKID NR. DIM-LESS       35    8                   SKID NUMBER
                                   6  CUMTRK      CUMULATIVE TRUCKS TO PRESENT
1



 INPUT CRITERIA AFFECTING
 MAINT OR REHAB DECISIONS
 ------------------------

           ASSIGNED ASSIGNED      DEFINITION OF ASSIGNED
 CRITERION  ID NO.  LEVEL NO.        CRITERION LEVEL

  DMG INDX    33        3     GREATER THAN      1.00 FOR MORE THAN 20.0 PCT AREA
                        2     GREATER THAN      1.00 FOR MORE THAN  1.0 PCT AREA
  PSI         34        3     LESS THAN         2.00 (MEAN VALUE)
                        2     LESS THAN         3.00 (MEAN VALUE)
  RUT DEP     30        2     GREATER THAN       .50 (MEAN VALUE)
  SKID NR.    35        2     LESS THAN        43.00 (MEAN VALUE)
  CURADT       5        2     GREATER THAN   1000.00 (MEAN VALUE)

 INPUT MAINTENANCE OR
 REHABILITATION PROCEDURES
 -------------------------

   NR   KEYS    COST   COST            DESCRIPTION
               (DOL.) UNITS

    1  300000   6.00  SQ. YD.      4"   OVERLAY
    2  230000   4.50  SQ. YD.      MILL 1" + 2" OVERLAY
    3  202000   5.00  SQ. YD.      1.5" LEVELUP + 1.5" OVERLAY
    4  200200   2.75  SQ. YD.      MEMBRANE + 1.5" OVERLAY
    5  130000   3.50  SQ. YD.      MILL 1" +   1.5"   OVERLAY
    6  102000   3.00  SQ. YD.      1" LEVELUP + 1" OVERLAY
    7  120200   2.50  SQ. YD.      MILL 0.5" + 1" OVERLAY
    8  110210   1.25  SQ. YD.      CHIP SEAL
    9  110220   1.75  SQ. YD.      AC FRICTION COURSE.
   31  000000    .00               DO NOTHING
```

```
 PARAMETERS DETERMINING VARIABLE VALUES
 AS A FUNCTION OF NUMBER OF TESTS
 --------------------------------------

                             CONF.      PARAMETERS FOR          COST PER
               TYPE OF       LEVEL  FUNCTIONAL VARIATION          TEST
  ID   NAME    VARIATION     (PCT)     A       B       C       D      (DOLLARS)

  12  PCT VOID    STAT         95     .00     .00     .00     .00        60.
  14  VISCOS      STAT        -95     .00     .00     .00     .00       100.
  24  THK AC      STAT        -90     .00     .00     .00     .00        80.

 VALUES OF TESTED VARIABLES USED IN SIMULATIONS
 (CALCULATED FROM NUMBER OF TESTS)
 ----------------------------------------------

                NR OF   VALUE    NR OF   VALUE    NR OF   VALUE    NR OF   VALUE
  ID    NAME    TESTS   (C.V.)   TESTS   (C.V.)   TESTS   (C.V.)   TESTS   (C.V.)

  12   PCT VOID   3     5.0230     6     3.9871     9     3.7440    12     3.6222
                         .2389            .3010            .3205            .3313
  14   VISCOS     3     2.6605     6     2.9368
                         .1203            .1090
  24   THK AC     3     1.4183     6     1.4548     9     1.4651    12     1.4705
                         .0529            .0516            .0512            .0510
1
   NUMBER OF TESTS ON                                  UNIF. ANN.  UNIF. ANN.    DIFF.
   MATERIAL PROPERTY    AGE AT  DISTRESS SELECTED        COSTS      TESTING     BENEFIT/
  IDENTIFIED BY ID NO.  FAILURE CAUSING    REHAB      1000-S OF      COST         COST
                        YEARS   FAILURE    OPTION      DOLLARS      DOLLARS       RATIO
     12  14  24

      3   3   6   0   0   27.43   PSI           2         4.72        124.94       2.232
```

```
                                                                PROBLEM 3-A.2

EXAMPLE:  ANALYSIS OF HIGH TRAFFIC ASPHALT CONCRETE TESTS IN STATE "A".


RUN DESCRIPTION:
----------------

USE PERFORMANCE MODELS TO CALCULATE DISTRESS.  OPTIMUM TESTING PROGRAM FOR
ASPHALT LABORATORY.  (PCT. VOID, AC VISCOS, AC THICK)


INPUT DATA (COSTS)
(THOUSANDS OF DOLLARS/LANE MILE
--------------------------------

INITIAL CONSTRUCTION       160.0
ANNUAL MAINTENANCE COST       .0
ANNUAL USER COST              .0
USER COST OF REHAB.           .0

COST OF MONEY (INTEREST)   12.5 PERCENT


INPUT DATA (GEOMETRICAL)
------------------------
LANE WIDTH (FEET)          12.0


INPUT DATA (TRAFFIC)
--------------------

 ABBREV.  ID                            COEF.        FULL
  NAME    NO.   VALUE        UNITS     OF VAR.       NAME

INIT ADT   1       .25E+05 VEH/DAY        .00     INITIAL AVG. DAILY TRAFFIC
PCTPERYR   2      5.0      PERCENT        .00     PERCENT PER YR GROWTH IN ADT
PCTTRK     3       .10E+02 PERCENT        .00     PERCENT OF TRUCKS IN TRAFFIC
ESAL/TRK   4       .30     ESAL           .00     18-KIP EQUIV. SINGLE AXLES/TRK


INPUT DATA (MATERIALS)
----------------------

 ABBREV.  ID                            COEF.        FULL
  NAME    NO.   VALUE        UNITS     OF VAR.       NAME

PCT AC    11      6.0      PERCENT        .06     PERCENT BITUMEN (BY WEIGHT)
PCT VOID  12      3.0      PERCENT        .40     PERCENT AIR VOIDS IN MIX
PCT 200   13      3.0      PERCENT        .25     PCT AGGREG. PASSING #200 SEIVE
VISCOS    14      3.2      10^6 POISE     .10     VISCOSITY OF BITUMEN-70 DEG F
LOAD FQ   15       .10E+02 HZ             .10     FREQUENCY OF REPEATED LOADINGS
AC TEMP   16       .85E+02 DEG F          .10     TEMPERATURE OF AC (MID-DEPTH)
```

```
EACVARML  17       1.0      DIM-LESS        .00     MULTIPLIER ON CALC. VAR. OF E(
E BASE    21       .30E+02 KPSI             .25     RESILIENT MODULUS OF BASE
E SUBB    22       .20E+02 KPSI             .25     RESILIENT MODULUS OF SUBBASE
E SUBGR   23       .15E+02 KPSI             .30     RESILIENT MODULUS OF SUBGRADE
THK AC    24       .10E+02 INCHES           .05     THICKNESS OF AC LAYER
THK BASE  25       .12E+02 INCHES           .10     THICKNESS OF BASE
THK SUBB  26       .12E+02 INCHES           .15     THICKNESS OF SUBBASE

SPECIFICATION OF INDEPENDENT VARIABLES
FOR INDICATED MODELS
--------------------------------------

 ABBREV.                 ID  FN  DEPENDENT ON
  NAME      UNITS        NO. NO. ID    NAME      FULL NAME

CURADT   VEH/DAY          5  10                  CURRENT AVG. DAILY TRAFFIC
                                  1  INIT ADT    INITIAL AVG. DAILY TRAFFIC
                                  2  PCTPERYR    PERCENT PER YR GROWTH IN ADT

CUMTRK   TRUCKS           6  11                  CUMULATIVE TRUCKS TO PRESENT
                                  1  INIT ADT    INITIAL AVG. DAILY TRAFFIC
                                  2  PCTPERYR    PERCENT PER YR GROWTH IN ADT
                                  3  PCTTRK      PERCENT OF TRUCKS IN TRAFFIC

CUMESAL  ESAL             7  12                  CUMULATIVE ESAL   TO PRESENT
                                  4  ESAL/TRK    18-KIP EQUIV. SINGLE AXLES/TRK
                                  6  CUMTRK      CUMULATIVE TRUCKS TO PRESENT

LOG E AC KPSI (LOG)      20  -1                  LOG (BASE 10) OF AC MODULUS
                                 11  PCT AC      PERCENT BITUMEN (BY WEIGHT)
                                 12  PCT VOID    PERCENT AIR VOIDS IN MIX
                                 13  PCT 200     PCT AGGREG. PASSING #200 SEIVE
                                 14  VISCOS      VISCOSITY OF BITUMEN-70 DEG F
                                 15  LOAD FQ     FREQUENCY OF REPEATED LOADINGS
                                 16  AC TEMP     TEMPERATURE OF AC (MID-DEPTH)

RUT DEP  INCHES          30   2                  AVG RUT DEPTH-BOTH WHEEL PATH
                                  7  CUMESAL     CUMULATIVE ESAL   TO PRESENT
                                 20  LOG E AC    LOG (BASE 10) OF AC MODULUS
                                 21  E BASE      RESILIENT MODULUS OF BASE
                                 22  E SUBB      RESILIENT MODULUS OF SUBBASE
                                 23  E SUBGR     RESILIENT MODULUS OF SUBGRADE
                                 24  THK AC      THICKNESS OF AC LAYER
                                 25  THK BASE    THICKNESS OF BASE
                                 26  THK SUBB    THICKNESS OF SUBBASE

RAD STRN INCHES/INCH     31  -3                  RADIAL STRAIN, BOTTOM OF AC.
                                 20  LOG E AC    LOG (BASE 10) OF AC MODULUS
                                 21  E BASE      RESILIENT MODULUS OF BASE
                                 23  E SUBGR     RESILIENT MODULUS OF SUBGRADE
                                 24  THK AC      THICKNESS OF AC LAYER
                                 25  THK BASE    THICKNESS OF BASE
```

```
NRTOFAIL DIM-LESS       32  -4                     NR 18-KIP ESAL TO 10 PCT CRKG
                                 31  RAD STRN      RADIAL STRAIN, BOTTOM OF AC.

DMG INDX DIM-LESS       33   5                     FRACTION OF FATIGUE LIFE USED
                                  7  CUMESAL       CUMULATIVE ESAL   TO PRESENT
                                 32  NRTOFAIL      NR 18-KIP ESAL TO 10 PCT CRKG

PSI      DIM-LESS       34   9                     PRESENT SERVICABILITY INDEX
                                 20  LOG E AC      LOG (BASE 10) OF AC MODULUS
                                 30  RUT DEP       AVG RUT DEPTH-BOTH WHEEL PATH

SKID NR. DIM-LESS       35   8                     SKID NUMBER
                                  6  CUMTRK        CUMULATIVE TRUCKS TO PRESENT
1


 INPUT CRITERIA AFFECTING
 MAINT OR REHAB DECISIONS
 ------------------------

           ASSIGNED ASSIGNED       DEFINITION OF ASSIGNED
 CRITERION  ID NO.  LEVEL NO.         CRITERION LEVEL

  DMG INDX    33         3      GREATER THAN      1.00 FOR MORE THAN 20.0 PCT AREA
                         2      GREATER THAN      1.00 FOR MORE THAN  1.0 PCT AREA
  PSI         34         3      LESS THAN         2.00 (MEAN VALUE)
                         2      LESS THAN         3.00 (MEAN VALUE)
  RUT DEP     30         2      GREATER THAN       .50 (MEAN VALUE)
  SKID NR.    35         2      LESS THAN        43.00 (MEAN VALUE)
  CURADT       5         2      GREATER THAN   1000.00 (MEAN VALUE)

 INPUT MAINTENANCE OR
 REHABILITATION PROCEDURES
 -------------------------

   NR   KEYS     COST   COST            DESCRIPTION
                (DOL.) UNITS

    1  300000    6.00  SQ. YD.      4"   OVERLAY
    2  230000    4.50  SQ. YD.      MILL 1" + 2" OVERLAY
    3  202000    5.00  SQ. YD.      1.5" LEVELUP + 1.5" OVERLAY
    4  200200    2.75  SQ. YD.      MEMBRANE + 1.5" OVERLAY
    5  130000    3.50  SQ. YD.      MILL 1" +   1.5"   OVERLAY
    6  102000    3.00  SQ. YD.      1" LEVELUP + 1" OVERLAY
    7  120200    2.50  SQ. YD.      MILL 0.5" + 1" OVERLAY
    8  110210    1.25  SQ. YD.      CHIP SEAL
    9  110220    1.75  SQ. YD.      AC FRICTION COURSE.
   31  000000     .00               DO NOTHING


 PARAMETERS DETERMINING VARIABLE VALUES
 AS A FUNCTION OF NUMBER OF TESTS
```

```
---------------------------------------

                         CONF.     PARAMETERS FOR        COST PER
           TYPE OF       LEVEL   FUNCTIONAL VARIATION      TEST
ID   NAME  VARIATION     (PCT)     A      B      C      D    (DOLLARS)

12  PCT VOID    STAT       95     .00    .00    .00    .00      60.
14  VISCOS      STAT      -95     .00    .00    .00    .00     100.
24  THK AC      STAT      -90     .00    .00    .00    .00      80.


VALUES OF TESTED VARIABLES USED IN SIMULATIONS
(CALCULATED FROM NUMBER OF TESTS)
-----------------------------------------------

                NR OF   VALUE    NR OF   VALUE    NR OF   VALUE    NR OF   VALUE
ID    NAME      TESTS   (C.V.)   TESTS   (C.V.)   TESTS   (C.V.)   TESTS   (C.V.)

12   PCT VOID   12      3.6222   15      3.5456   18      3.4921   21      3.4517
                         .3313            .3384            .3436            .3477
14   VISCOS      9      3.0016   12      3.0341   15      3.0545   18      3.0688
                         .1066            .1055            .1048            .1043
24   THK AC      3      9.4556    6      9.6987    9      9.7672
                         .0529            .0516            .0512
1
 NUMBER OF TESTS ON                                   UNIF. ANN. UNIF. ANN.   DIFF.
 MATERIAL PROPERTY    AGE AT  DISTRESS SELECTED        COSTS     TESTING    BENEFIT/
IDENTIFIED BY ID NO.  FAILURE CAUSING   REHAB       1000-S OF    COST        COST
                      YEARS   FAILURE   OPTION       DOLLARS    DOLLARS      RATIO
   12  14  24

   15   9   3   0   0    2.15   PSI          5      100.25     1141.66     10.388
   18   9   3   0   0    2.16   PSI          5       99.59     1234.49      7.081
   15  12   3   0   0    2.17   PSI          5       99.45     1299.36      2.265
   21   9   3   0   0    2.17   PSI          5       99.10     1328.21     11.883
   18  12   3   0   0    2.18   PSI          5       98.80     1390.45      4.914
   21  12   3   0   0    2.19   PSI          5       98.31     1482.70      5.241
   21  15   3   0   0    2.21   PSI          5       97.82     1639.47      3.129
   21  18   3   0   0    2.21   PSI          5       97.48     1797.35      2.151
```

```
                                                            PROBLEM 4-C.1

EXAMPLE:  ANALYSIS OF ASPHALT CONCRETE VISCOSITY TESTS IN STATE "C".


RUN DESCRIPTION:
----------------

USE PERFORMANCE MODELS TO CALCULATE DISTRESS.  OPTIMUM TESTING PROGRAM FOR
ASPHALT LABORATORY.  ( AC VISCOS. )


INPUT DATA (COSTS)
(THOUSANDS OF DOLLARS/LANE MILE
--------------------------------

INITIAL CONSTRUCTION        90.0
ANNUAL MAINTENANCE COST       .0
ANNUAL USER COST              .0
USER COST OF REHAB.           .0

COST OF MONEY (INTEREST)    12.5 PERCENT


INPUT DATA (GEOMETRICAL)
------------------------
LANE WIDTH (FEET)           12.0


INPUT DATA (TRAFFIC)
--------------------

 ABBREV.  ID                               COEF.          FULL
  NAME    NO.   VALUE        UNITS        OF VAR.         NAME

INIT ADT   1      .60E+04 VEH/DAY           .00      INITIAL AVG. DAILY TRAFFIC
PCTPERYR   2     5.0      PERCENT           .00      PERCENT PER YR GROWTH IN ADT
PCTTRK     3      .10E+02 PERCENT           .00      PERCENT OF TRUCKS IN TRAFFIC
ESAL/TRK   4      .30     ESAL              .00      18-KIP EQUIV. SINGLE AXLES/TRK


INPUT DATA (MATERIALS)
----------------------

 ABBREV.  ID                               COEF.          FULL
  NAME    NO.   VALUE        UNITS        OF VAR.         NAME

PCT AC    11     6.0      PERCENT           .06      PERCENT BITUMEN (BY WEIGHT)
PCT VOID  12     2.5      PERCENT           .40      PERCENT AIR VOIDS IN MIX
PCT 200   13     6.0      PERCENT           .25      PCT AGGREG. PASSING #200 SEIVE
VISCOS    14     5.0      10^6 POISE        .10      VISCOSITY OF BITUMEN-70 DEG F
LOAD FQ   15      .10E+02 HZ                .10      FREQUENCY OF REPEATED LOADINGS
AC TEMP   16      .75E+02 DEG F             .10      TEMPERATURE OF AC (MID-DEPTH)
```

```
EACVARML  17       1.0      DIM-LESS        .00      MULTIPLIER ON CALC. VAR. OF E(
E BASE    21       .30E+02 KPSI             .25      RESILIENT MODULUS OF BASE
E SUBB    22       .20E+02 KPSI             .25      RESILIENT MODULUS OF SUBBASE
E SUBGR   23       .15E+02 KPSI             .30      RESILIENT MODULUS OF SUBGRADE
THK AC    24       4.5      INCHES          .05      THICKNESS OF AC LAYER
THK BASE  25       8.0      INCHES          .10      THICKNESS OF BASE
THK SUBB  26       .12E+02 INCHES           .15      THICKNESS OF SUBBASE

SPECIFICATION OF INDEPENDENT VARIABLES
FOR INDICATED MODELS
--------------------------------------

 ABBREV.                  ID  FN  DEPENDENT ON
  NAME     UNITS          NO. NO. ID    NAME      FULL NAME

CURADT   VEH/DAY           5  10                  CURRENT AVG. DAILY TRAFFIC
                                   1  INIT ADT    INITIAL AVG. DAILY TRAFFIC
                                   2  PCTPERYR    PERCENT PER YR GROWTH IN ADT

CUMTRK   TRUCKS            6  11                  CUMULATIVE TRUCKS TO PRESENT
                                   1  INIT ADT    INITIAL AVG. DAILY TRAFFIC
                                   2  PCTPERYR    PERCENT PER YR GROWTH IN ADT
                                   3  PCTTRK      PERCENT OF TRUCKS IN TRAFFIC

CUMESAL  ESAL              7  12                  CUMULATIVE ESAL   TO PRESENT
                                   4  ESAL/TRK    18-KIP EQUIV. SINGLE AXLES/TRK
                                   6  CUMTRK      CUMULATIVE TRUCKS TO PRESENT

LOG E AC KPSI (LOG)       20  -1                  LOG (BASE 10) OF AC MODULUS
                                  11  PCT AC      PERCENT BITUMEN (BY WEIGHT)
                                  12  PCT VOID    PERCENT AIR VOIDS IN MIX
                                  13  PCT 200     PCT AGGREG. PASSING #200 SEIVE
                                  14  VISCOS      VISCOSITY OF BITUMEN-70 DEG F
                                  15  LOAD FQ     FREQUENCY OF REPEATED LOADINGS
                                  16  AC TEMP     TEMPERATURE OF AC (MID-DEPTH)

RUT DEP  INCHES           30   2                  AVG RUT DEPTH-BOTH WHEEL PATH
                                   7  CUMESAL     CUMULATIVE ESAL   TO PRESENT
                                  20  LOG E AC    LOG (BASE 10) OF AC MODULUS
                                  21  E BASE      RESILIENT MODULUS OF BASE
                                  22  E SUBB      RESILIENT MODULUS OF SUBBASE
                                  23  E SUBGR     RESILIENT MODULUS OF SUBGRADE
                                  24  THK AC      THICKNESS OF AC LAYER
                                  25  THK BASE    THICKNESS OF BASE
                                  26  THK SUBB    THICKNESS OF SUBBASE

RAD STRN INCHES/INCH      31  -3                  RADIAL STRAIN, BOTTOM OF AC.
                                  20  LOG E AC    LOG (BASE 10) OF AC MODULUS
                                  21  E BASE      RESILIENT MODULUS OF BASE
                                  23  E SUBGR     RESILIENT MODULUS OF SUBGRADE
                                  24  THK AC      THICKNESS OF AC LAYER
                                  25  THK BASE    THICKNESS OF BASE
```

```
NRTOFAIL DIM-LESS       32   -4                     NR 18-KIP ESAL TO 10 PCT CRKG
                                  31   RAD STRN     RADIAL STRAIN, BOTTOM OF AC.

DMG INDX DIM-LESS       33    5                     FRACTION OF FATIGUE LIFE USED
                                   7   CUMESAL      CUMULATIVE ESAL   TO PRESENT
                                  32   NRTOFAIL     NR 18-KIP ESAL TO 10 PCT CRKG
1



INPUT CRITERIA AFFECTING
MAINT OR REHAB DECISIONS
------------------------

          ASSIGNED ASSIGNED       DEFINITION OF ASSIGNED
CRITERION  ID NO.  LEVEL NO.         CRITERION LEVEL

 DMG INDX     33          3      GREATER THAN      1.00 FOR MORE THAN 50.0 PCT AREA
                          2      GREATER THAN      1.00 FOR MORE THAN  1.0 PCT AREA
 RUT DEP     30           2      GREATER THAN       .50 (MEAN VALUE)
 CURADT        5          2      GREATER THAN   1000.00 (MEAN VALUE)

INPUT MAINTENANCE OR
REHABILITATION PROCEDURES
-------------------------

  NR    KEYS     COST   COST              DESCRIPTION
                (DOL.) UNITS

   1  300000    5.50   SQ. YD.       SEAL COAT + 2.5" OVERLAY
   2  221000    4.75   SQ. YD.       MILL 1", SEAL COAT, 1.5" OVERLAY
   3  222000    6.25   SQ. YD.       MILL 1", SEAL COAT, 2.5" OVERLAY
   4  121000    3.50   SQ. YD.       MILL 0.5" + 1.5" OVERLAY
   5  122000    5.00   SQ. YD.       MILL 0.5" + 2.5" OVERLAY
  31  000000     .00                 DO NOTHING

PARAMETERS DETERMINING VARIABLE VALUES
AS A FUNCTION OF NUMBER OF TESTS
--------------------------------------

                           CONF.     PARAMETERS FOR          COST PER
                TYPE OF    LEVEL  FUNCTIONAL VARIATION         TEST
 ID    NAME    VARIATION   (PCT)     A      B      C      D    (DOLLARS)

 14   VISCOS     STAT      -95      .00    .00    .00    .00     150.

VALUES OF TESTED VARIABLES USED IN SIMULATIONS
(CALCULATED FROM NUMBER OF TESTS)
-----------------------------------------------

               NR OF   VALUE   NR OF   VALUE   NR OF   VALUE   NR OF   VALUE
```

```
 ID   NAME     TESTS  (C.V.)  TESTS  (C.V.)  TESTS  (C.V.)  TESTS  (C.V.)

 14  VISCOS      9    4.6900   12    4.7408   15    4.7727   18    4.7949
                       .1066          .1055          .1048          .1043
1
 NUMBER OF TESTS ON                                UNIF. ANN. UNIF. ANN.   DIFF.
 MATERIAL PROPERTY   AGE AT  DISTRESS SELECTED      COSTS     TESTING    BENEFIT/
IDENTIFIED BY ID NO. FAILURE CAUSING   REHAB     1000-S OF    COST        COST
                     YEARS   FAILURE   OPTION     DOLLARS    DOLLARS      RATIO
   14

   12   0   0   0   0   10.28   RUT DEP     5       17.90       320.54      1.072
```

```
                                                                  PROBLEM 4-C.2

EXAMPLE:  ANALYSIS OF PERCENT ASPHALT TESTS IN STATE "C".  84/6/7.

RUN DESCRIPTION:
----------------

USE PERFORMANCE MODELS TO CALCULATE DISTRESS.  OPTIMUM TESTING PROGRAM FOR
ASPHALT LABORATORY.  (PCT. ASPHALT)


INPUT DATA (COSTS)
(THOUSANDS OF DOLLARS/LANE MILE
--------------------------------

INITIAL CONSTRUCTION        90.0
ANNUAL MAINTENANCE COST       .0
ANNUAL USER COST              .0
USER COST OF REHAB.           .0

COST OF MONEY (INTEREST)    12.5 PERCENT


INPUT DATA (GEOMETRICAL)
------------------------
LANE WIDTH (FEET)           12.0


INPUT DATA (TRAFFIC)
--------------------

 ABBREV.  ID                             COEF.          FULL
  NAME    NO.   VALUE        UNITS      OF VAR.         NAME

INIT ADT   1      .60E+04 VEH/DAY          .00     INITIAL AVG. DAILY TRAFFIC
PCTPERYR   2     5.0      PERCENT          .00     PERCENT PER YR GROWTH IN ADT
PCTTRK     3      .10E+02 PERCENT          .00     PERCENT OF TRUCKS IN TRAFFIC
ESAL/TRK   4      .30     ESAL             .00     18-KIP EQUIV. SINGLE AXLES/TRK


INPUT DATA (MATERIALS)
----------------------

 ABBREV.  ID                             COEF.          FULL
  NAME    NO.   VALUE        UNITS      OF VAR.         NAME

PCT AC    11     6.0      PERCENT          .06     PERCENT BITUMEN (BY WEIGHT)
PCT VOID  12     2.5      PERCENT          .40     PERCENT AIR VOIDS IN MIX
PCT 200   13     6.0      PERCENT          .25     PCT AGGREG. PASSING #200 SEIVE
VISCOS    14     5.0      10^6 POISE       .10     VISCOSITY OF BITUMEN-70 DEG F
LOAD FQ   15      .10E+02 HZ               .10     FREQUENCY OF REPEATED LOADINGS
AC TEMP   16      .75E+02 DEG F            .10     TEMPERATURE OF AC (MID-DEPTH)
```

```
EACVARML  17     1.0     DIM-LESS        .00     MULT. ON CALC. VAR. OF E(AC)
E BASE    21     .30E+02 KPSI            .25     RESILIENT MODULUS OF BASE
E SUBB    22     .20E+02 KPSI            .25     RESILIENT MODULUS OF SUBBASE
E SUBGR   23     .15E+02 KPSI            .30     RESILIENT MODULUS OF SUBGRADE
THK AC    24     4.5     INCHES          .05     THICKNESS OF AC LAYER
THK BASE  25     8.0     INCHES          .10     THICKNESS OF BASE
THK SUBB  26     .12E+02 INCHES          .15     THICKNESS OF SUBBASE

SPECIFICATION OF INDEPENDENT VARIABLES
FOR INDICATED MODELS
---------------------------------------

 ABBREV.                ID  FN  DEPENDENT ON
  NAME     UNITS        NO. NO. ID    NAME       FULL NAME

CURADT   VEH/DAY         5  10                   CURRENT AVG. DAILY TRAFFIC
                                 1  INIT ADT     INITIAL AVG. DAILY TRAFFIC
                                 2  PCTPERYR     PERCENT PER YR GROWTH IN ADT

CUMTRK   TRUCKS          6  11                   CUMULATIVE TRUCKS TO PRESENT
                                 1  INIT ADT     INITIAL AVG. DAILY TRAFFIC
                                 2  PCTPERYR     PERCENT PER YR GROWTH IN ADT
                                 3  PCTTRK       PERCENT OF TRUCKS IN TRAFFIC

CUMESAL  ESAL            7  12                   CUMULATIVE ESAL   TO PRESENT
                                 4  ESAL/TRK     18-KIP EQUIV. SINGLE AXLES/TRK
                                 6  CUMTRK       CUMULATIVE TRUCKS TO PRESENT

LOG E AC KPSI (LOG)     20  -1                   LOG (BASE 10) OF AC MODULUS
                                11  PCT AC       PERCENT BITUMEN (BY WEIGHT)
                                12  PCT VOID     PERCENT AIR VOIDS IN MIX
                                13  PCT 200      PCT AGGREG. PASSING #200 SEIVE
                                14  VISCOS       VISCOSITY OF BITUMEN-70 DEG F
                                15  LOAD FQ      FREQUENCY OF REPEATED LOADINGS
                                16  AC TEMP      TEMPERATURE OF AC (MID-DEPTH)

RUT DEP  INCHES         30   2                   AVG RUT DEPTH-BOTH WHEEL PATH
                                 7  CUMESAL      CUMULATIVE ESAL   TO PRESENT
                                20  LOG E AC     LOG (BASE 10) OF AC MODULUS
                                21  E BASE       RESILIENT MODULUS OF BASE
                                22  E SUBB       RESILIENT MODULUS OF SUBBASE
                                23  E SUBGR      RESILIENT MODULUS OF SUBGRADE
                                24  THK AC       THICKNESS OF AC LAYER
                                25  THK BASE     THICKNESS OF BASE
                                26  THK SUBB     THICKNESS OF SUBBASE

RAD STRN INCHES/INCH    31  -3                   RADIAL STRAIN, BOTTOM OF AC.
                                20  LOG E AC     LOG (BASE 10) OF AC MODULUS
                                21  E BASE       RESILIENT MODULUS OF BASE
                                23  E SUBGR      RESILIENT MODULUS OF SUBGRADE
                                24  THK AC       THICKNESS OF AC LAYER
                                25  THK BASE     THICKNESS OF BASE
```

```
NRTOFAIL DIM-LESS       32   -4                     NR 18-KIP ESAL TO 10 PCT CRKG
                                31  RAD STRN        RADIAL STRAIN, BOTTOM OF AC.

DMG INDX DIM-LESS       33    5                     FRACTION OF FATIGUE LIFE USED
                                 7  CUMESAL         CUMULATIVE ESAL   TO PRESENT
                                32  NRTOFAIL        NR 18-KIP ESAL TO 10 PCT CRKG



INPUT CRITERIA AFFECTING
MAINT OR REHAB DECISIONS
------------------------

          ASSIGNED ASSIGNED      DEFINITION OF ASSIGNED
CRITERION  ID NO.  LEVEL NO.        CRITERION LEVEL

 DMG INDX     33         3      GREATER THAN      1.00 FOR MORE THAN 50.0 PCT AREA
                         2      GREATER THAN      1.00 FOR MORE THAN  1.0 PCT AREA
 RUT DEP      30         2      GREATER THAN       .50 (MEAN VALUE)
 CURADT        5         2      GREATER THAN   1000.00 (MEAN VALUE)

INPUT MAINTENANCE OR
REHABILITATION PROCEDURES
-------------------------

  NR    KEYS     COST   COST             DESCRIPTION
                (DOL.) UNITS

   1  300000     5.50  SQ. YD.      SEAL COAT + 2.5" OVERLAY
   2  221000     4.75  SQ. YD.      MILL 1", SEAL COAT, 1.5" OVERLAY
   3  222000     6.25  SQ. YD.      MILL 1", SEAL COAT, 2.5" OVERLAY
   4  121000     3.50  SQ. YD.      MILL 0.5" + 1.5" OVERLAY
   5  122000     5.00  SQ. YD.      MILL 0.5" + 2.5" OVERLAY
  31  000000      .00               DO NOTHING

PARAMETERS DETERMINING VARIABLE VALUES
AS A FUNCTION OF NUMBER OF TESTS
--------------------------------------

                         CONF.     PARAMETERS FOR        COST PER
             TYPE OF     LEVEL  FUNCTIONAL VARIATION       TEST
 ID   NAME   VARIATION   (PCT)    A     B     C     D    (DOLLARS)

 11  PCT AC     STAT       95    .00   .00   .00   .00      80.
```

```
VALUES OF TESTED VARIABLES USED IN SIMULATIONS
(CALCULATED FROM NUMBER OF TESTS)
---------------------------------------------

                NR OF  VALUE   NR OF  VALUE   NR OF  VALUE   NR OF  VALUE
 ID    NAME     TESTS  (C.V.)  TESTS  (C.V.)  TESTS  (C.V.)  TESTS  (C.V.)

 11  PCT AC       6    6.2961    9    6.2232   12    6.1866   15    6.1637
                        .0572          .0578          .0582          .0584

  NUMBER OF TESTS ON                                UNIF. ANN. UNIF. ANN.   DIFF.
  MATERIAL PROPERTY    AGE AT  DISTRESS SELECTED     COSTS     TESTING    BENEFIT/
 IDENTIFIED BY ID NO. FAILURE CAUSING   REHAB     1000-S OF    COST       COST
                       YEARS   FAILURE   OPTION    DOLLARS    DOLLARS     RATIO
    11

     9   0   0   0   0    10.34   RUT DEP      5       17.83      127.83      2.794
    12   0   0   0   0    10.39   RUT DEP      5       17.77      169.99      1.394
```

```
                                                                PROBLEM 4-C.3

EXAMPLE:  ANALYSIS OF GRADATION TESTS IN STATE "C".  84/1/183.


RUN DESCRIPTION:
----------------


USE PERFORMANCE MODELS TO CALCULATE DISTRESS.  OPTIMUM TESTING PROGRAM FOR
ASPHALT LABORATORY.  ( PCT. 200 )


INPUT DATA (COSTS)
(THOUSANDS OF DOLLARS/LANE MILE
--------------------------------

INITIAL CONSTRUCTION        90.0
ANNUAL MAINTENANCE COST       .0
ANNUAL USER COST              .0
USER COST OF REHAB.           .0

COST OF MONEY (INTEREST)    12.5 PERCENT


INPUT DATA (GEOMETRICAL)
------------------------
LANE WIDTH (FEET)           12.0


INPUT DATA (TRAFFIC)
--------------------

 ABBREV.  ID                                COEF.         FULL
  NAME    NO.   VALUE       UNITS          OF VAR.        NAME

INIT ADT   1      .60E+04 VEH/DAY            .00     INITIAL AVG. DAILY TRAFFIC
PCTPERYR   2     5.0      PERCENT            .00     PERCENT PER YR GROWTH IN ADT
PCTTRK     3      .10E+02 PERCENT            .00     PERCENT OF TRUCKS IN TRAFFIC
ESAL/TRK   4      .30     ESAL               .00     18-KIP EQUIV. SINGLE AXLES/TRK


INPUT DATA (MATERIALS)
----------------------

 ABBREV.  ID                                COEF.         FULL
  NAME    NO.   VALUE       UNITS          OF VAR.        NAME

PCT AC    11      6.0     PERCENT            .06     PERCENT BITUMEN (BY WEIGHT)
PCT VOID  12      2.5     PERCENT            .40     PERCENT AIR VOIDS IN MIX
PCT 200   13      6.0     PERCENT            .25     PCT AGGREG. PASSING #200 SEIVE
VISCOS    14      5.0     10'6 POISE         .10     VISCOSITY OF BITUMEN-70 DEG F
LOAD FQ   15      .10E+02 HZ                 .10     FREQUENCY OF REPEATED LOADINGS
AC TEMP   16      .75E+02 DEG F              .10     TEMPERATURE OF AC (MID-DEPTH)
```

```
EACVARML  17      1.0      DIM-LESS        .00     MULTIPLIER ON CALC. VAR. OF E(
E BASE    21      .30E+02 KPSI             .25     RESILIENT MODULUS OF BASE
E SUBB    22      .20E+02 KPSI             .25     RESILIENT MODULUS OF SUBBASE
E SUBGR   23      .15E+02 KPSI             .30     RESILIENT MODULUS OF SUBGRADE
THK AC    24      4.5      INCHES          .05     THICKNESS OF AC LAYER
THK BASE  25      8.0      INCHES          .10     THICKNESS OF BASE
THK SUBB  26      .12E+02 INCHES           .15     THICKNESS OF SUBBASE

SPECIFICATION OF INDEPENDENT VARIABLES
FOR INDICATED MODELS
-------------------------------------

 ABBREV.               ID  FN  DEPENDENT ON
  NAME     UNITS       NO. NO. ID.    NAME       FULL NAME

CURADT   VEH/DAY        5  10                    CURRENT AVG. DAILY TRAFFIC
                                1  INIT ADT      INITIAL AVG. DAILY TRAFFIC
                                2  PCTPERYR      PERCENT PER YR GROWTH IN ADT

CUMTRK   TRUCKS         6  11                    CUMULATIVE TRUCKS TO PRESENT
                                1  INIT ADT      INITIAL AVG. DAILY TRAFFIC
                                2  PCTPERYR      PERCENT PER YR GROWTH IN ADT
                                3  PCTTRK        PERCENT OF TRUCKS IN TRAFFIC

CUMESAL  ESAL           7  12                    CUMULATIVE ESAL   TO PRESENT
                                4  ESAL/TRK      18-KIP EQUIV. SINGLE AXLES/TRK
                                6  CUMTRK        CUMULATIVE TRUCKS TO PRESENT

LOG E AC KPSI (LOG)    20  -1                    LOG (BASE 10) OF AC MODULUS
                               11  PCT AC        PERCENT BITUMEN (BY WEIGHT)
                               12  PCT VOID      PERCENT AIR VOIDS IN MIX
                               13  PCT 200       PCT AGGREG. PASSING #200 SEIVE
                               14  VISCOS        VISCOSITY OF BITUMEN-70 DEG F
                               15  LOAD FQ       FREQUENCY OF REPEATED LOADINGS
                               16  AC TEMP       TEMPERATURE OF AC (MID-DEPTH)

RUT DEP  INCHES        30   2                    AVG RUT DEPTH-BOTH WHEEL PATH
                                7  CUMESAL       CUMULATIVE ESAL   TO PRESENT
                               20  LOG E AC      LOG (BASE 10) OF AC MODULUS
                               21  E BASE        RESILIENT MODULUS OF BASE
                               22  E SUBB        RESILIENT MODULUS OF SUBBASE
                               23  E SUBGR       RESILIENT MODULUS OF SUBGRADE
                               24  THK AC        THICKNESS OF AC LAYER
                               25  THK BASE      THICKNESS OF BASE
                               26  THK SUBB      THICKNESS OF SUBBASE

RAD STRN INCHES/INCH   31  -3                    RADIAL STRAIN, BOTTOM OF AC.
                               20  LOG E AC      LOG (BASE 10) OF AC MODULUS
                               21  E BASE        RESILIENT MODULUS OF BASE
                               23  E SUBGR       RESILIENT MODULUS OF SUBGRADE
                               24  THK AC        THICKNESS OF AC LAYER
                               25  THK BASE      THICKNESS OF BASE
```

```
NRTOFAIL DIM-LESS       32  -4                    NR 18-KIP ESAL TO 10 PCT CRKG
                                31  RAD STRN      RADIAL STRAIN, BOTTOM OF AC.

DMG INDX DIM-LESS       33   5                    FRACTION OF FATIGUE LIFE USED
                                 7  CUMESAL       CUMULATIVE ESAL   TO PRESENT
                                32  NRTOFAIL      NR 18-KIP ESAL TO 10 PCT CRKG
1



 INPUT CRITERIA AFFECTING
 MAINT OR REHAB DECISIONS
 ------------------------

          ASSIGNED ASSIGNED      DEFINITION OF ASSIGNED
 CRITERION  ID NO.  LEVEL NO.       CRITERION LEVEL

  DMG INDX    33        3      GREATER THAN      1.00 FOR MORE THAN 50.0 PCT AREA
                        2      GREATER THAN      1.00 FOR MORE THAN  1.0 PCT AREA
  RUT DEP     30        2      GREATER THAN       .50 (MEAN VALUE)
  CURADT       5        2      GREATER THAN   1000.00 (MEAN VALUE)

 INPUT MAINTENANCE OR
 REHABILITATION PROCEDURES
 -------------------------

   NR   KEYS    COST   COST              DESCRIPTION
               (DOL.) UNITS

    1  300000   5.50   SQ. YD.      SEAL COAT + 2.5" OVERLAY
    2  221000   4.75   SQ. YD.      MILL 1", SEAL COAT, 1.5" OVERLAY
    3  222000   6.25   SQ. YD.      MILL 1", SEAL COAT, 2.5" OVERLAY
    4  121000   3.50   SQ. YD.      MILL 0.5" + 1.5" OVERLAY
    5  122000   5.00   SQ. YD.      MILL 0.5" + 2.5" OVERLAY
   31  000000    .00                DO NOTHING

 PARAMETERS DETERMINING VARIABLE VALUES
 AS A FUNCTION OF NUMBER OF TESTS
 --------------------------------------

                          CONF.     PARAMETERS FOR          COST PER
              TYPE OF     LEVEL  FUNCTIONAL VARIATION         TEST
  ID   NAME   VARIATION   (PCT)    A      B      C      D    (DOLLARS)

  13  PCT 200    STAT      -95    .00    .00    .00    .00     100.

 VALUES OF TESTED VARIABLES USED IN SIMULATIONS
 (CALCULATED FROM NUMBER OF TESTS)
 ----------------------------------------------

                  NR OF   VALUE   NR OF   VALUE   NR OF   VALUE   NR OF   VALUE
```

```
 ID   NAME    TESTS  (C.V.)  TESTS  (C.V.)  TESTS  (C.V.)  TESTS  (C.V.)

 13  PCT 200    9    5.0700   12    5.2223   15    5.3180   18    5.3848
                      .2959          .2872          .2821          .2786
1
  NUMBER OF TESTS ON                                UNIF. ANN. UNIF. ANN.   DIFF.
  MATERIAL PROPERTY   AGE AT  DISTRESS SELECTED   COSTS     TESTING    BENEFIT/
 IDENTIFIED BY ID NO. FAILURE CAUSING   REHAB    1000-S OF   COST        COST
                      YEARS   FAILURE   OPTION    DOLLARS   DOLLARS      RATIO
    13

    12   0   0   0   0    10.34   RUT DEP      5      17.82      212.99      1.326
```

```
                                                                PROBLEM 4-C.4

EXAMPLE:  ANALYSIS OF AC PCT AIR VOIDS TESTS IN STATE "C".


RUN DESCRIPTION:
----------------

USE PERFORMANCE MODELS TO CALCULATE DISTRESS.  OPTIMUM TESTING PROGRAM FOR
ASPHALT LABORATORY.  ( PCT. VOIDS )


INPUT DATA (COSTS)
(THOUSANDS OF DOLLARS/LANE MILE
--------------------------------

INITIAL CONSTRUCTION        90.0
ANNUAL MAINTENANCE COST       .0
ANNUAL USER COST              .0
USER COST OF REHAB.           .0

COST OF MONEY (INTEREST)    12.5 PERCENT


INPUT DATA (GEOMETRICAL)
------------------------
LANE WIDTH (FEET)           12.0


INPUT DATA (TRAFFIC)
--------------------

 ABBREV.  ID                            COEF.          FULL
  NAME    NO.   VALUE       UNITS      OF VAR.         NAME

INIT ADT   1      .60E+04 VEH/DAY        .00     INITIAL AVG. DAILY TRAFFIC
PCTPERYR   2     5.0      PERCENT        .00     PERCENT PER YR GROWTH IN ADT
PCTTRK     3      .10E+02 PERCENT        .00     PERCENT OF TRUCKS IN TRAFFIC
ESAL/TRK   4      .30     ESAL           .00     18-KIP EQUIV. SINGLE AXLES/TRK


INPUT DATA (MATERIALS)
----------------------

 ABBREV.  ID                            COEF.          FULL
  NAME    NO.   VALUE       UNITS      OF VAR.         NAME

PCT AC    11     6.0      PERCENT        .06     PERCENT BITUMEN (BY WEIGHT)
PCT VOID  12     2.5      PERCENT        .40     PERCENT AIR VOIDS IN MIX
PCT 200   13     6.0      PERCENT        .25     PCT AGGREG. PASSING #200 SEIVE
VISCOS    14     5.0      10^6 POISE     .10     VISCOSITY OF BITUMEN-70 DEG F
LOAD FQ   15      .10E+02 HZ             .10     FREQUENCY OF REPEATED LOADINGS
AC TEMP   16      .75E+02 DEG F          .10     TEMPERATURE OF AC (MID-DEPTH)
```

```
EACVARML  17      1.0     DIM-LESS       .00     MULTIPLIER ON CALC. VAR. OF E(
E BASE    21      .30E+02 KPSI           .25     RESILIENT MODULUS OF BASE
E SUBB    22      .20E+02 KPSI           .25     RESILIENT MODULUS OF SUBBASE
E SUBGR   23      .15E+02 KPSI           .30     RESILIENT MODULUS OF SUBGRADE
THK AC    24      4.5     INCHES         .05     THICKNESS OF AC LAYER
THK BASE  25      8.0     INCHES         .10     THICKNESS OF BASE
THK SUBB  26      .12E+02 INCHES         .15     THICKNESS OF SUBBASE

SPECIFICATION OF INDEPENDENT VARIABLES
FOR INDICATED MODELS
--------------------------------------

 ABBREV.               ID  FN  DEPENDENT ON
  NAME     UNITS       NO. NO. ID    NAME      FULL NAME

CURADT   VEH/DAY        5  10                  CURRENT AVG. DAILY TRAFFIC
                                1  INIT ADT    INITIAL AVG. DAILY TRAFFIC
                                2  PCTPERYR    PERCENT PER YR GROWTH IN ADT

CUMTRK   TRUCKS         6  11                  CUMULATIVE TRUCKS TO PRESENT
                                1  INIT ADT    INITIAL AVG. DAILY TRAFFIC
                                2  PCTPERYR    PERCENT PER YR GROWTH IN ADT
                                3  PCTTRK      PERCENT OF TRUCKS IN TRAFFIC

CUMESAL  ESAL           7  12                  CUMULATIVE ESAL   TO PRESENT
                                4  ESAL/TRK    18-KIP EQUIV. SINGLE AXLES/TRK
                                6  CUMTRK      CUMULATIVE TRUCKS TO PRESENT

LOG E AC KPSI (LOG)    20  -1                  LOG (BASE 10) OF AC MODULUS
                               11  PCT AC      PERCENT BITUMEN (BY WEIGHT)
                               12  PCT VOID    PERCENT AIR VOIDS IN MIX
                               13  PCT 200     PCT AGGREG. PASSING #200 SEIVE
                               14  VISCOS      VISCOSITY OF BITUMEN-70 DEG F
                               15  LOAD FQ     FREQUENCY OF REPEATED LOADINGS
                               16  AC TEMP     TEMPERATURE OF AC (MID-DEPTH)

RUT DEP  INCHES        30   2                  AVG RUT DEPTH-BOTH WHEEL PATH
                                7  CUMESAL     CUMULATIVE ESAL   TO PRESENT
                               20  LOG E AC    LOG (BASE 10) OF AC MODULUS
                               21  E BASE      RESILIENT MODULUS OF BASE
                               22  E SUBB      RESILIENT MODULUS OF SUBBASE
                               23  E SUBGR     RESILIENT MODULUS OF SUBGRADE
                               24  THK AC      THICKNESS OF AC LAYER
                               25  THK BASE    THICKNESS OF BASE
                               26  THK SUBB    THICKNESS OF SUBBASE

RAD STRN INCHES/INCH   31  -3                  RADIAL STRAIN, BOTTOM OF AC.
                               20  LOG E AC    LOG (BASE 10) OF AC MODULUS
                               21  E BASE      RESILIENT MODULUS OF BASE
                               23  E SUBGR     RESILIENT MODULUS OF SUBGRADE
                               24  THK AC      THICKNESS OF AC LAYER
                               25  THK BASE    THICKNESS OF BASE
```

```
NRTOFAIL DIM-LESS       32   -4                    NR 18-KIP ESAL TO 10 PCT CRKG
                                31  RAD STRN       RADIAL STRAIN, BOTTOM OF AC.

DMG INDX DIM-LESS       33    5                    FRACTION OF FATIGUE LIFE USED
                                 7  CUMESAL        CUMULATIVE ESAL   TO PRESENT
                                32  NRTOFAIL       NR 18-KIP ESAL TO 10 PCT CRKG
1



 INPUT CRITERIA AFFECTING
 MAINT OR REHAB DECISIONS
 ------------------------

           ASSIGNED ASSIGNED      DEFINITION OF ASSIGNED
 CRITERION  ID NO.  LEVEL NO.        CRITERION LEVEL

  DMG INDX     33         3      GREATER THAN      1.00 FOR MORE THAN 50.0 PCT AREA
                          2      GREATER THAN      1.00 FOR MORE THAN  1.0 PCT AREA
  RUT DEP      30         2      GREATER THAN       .50 (MEAN VALUE)
  CURADT        5         2      GREATER THAN   1000.00 (MEAN VALUE)

 INPUT MAINTENANCE OR
 REHABILITATION PROCEDURES
 -------------------------

   NR    KEYS     COST   COST             DESCRIPTION
                 (DOL.) UNITS

    1  300000    5.50   SQ. YD.       SEAL COAT + 2.5" OVERLAY
    2  221000    4.75   SQ. YD.       MILL 1", SEAL COAT, 1.5" OVERLAY
    3  222000    6.25   SQ. YD.       MILL 1", SEAL COAT, 2.5" OVERLAY
    4  121000    3.50   SQ. YD.       MILL 0.5" + 1.5" OVERLAY
    5  122000    5.00   SQ. YD.       MILL 0.5" + 2.5" OVERLAY
   31  000000     .00                 DO NOTHING

 PARAMETERS DETERMINING VARIABLE VALUES
 AS A FUNCTION OF NUMBER OF TESTS
 --------------------------------------

                              CONF.     PARAMETERS FOR        COST PER
                 TYPE OF      LEVEL  FUNCTIONAL VARIATION       TEST
  ID    NAME   VARIATION    (PCT)    A      B      C      D    (DOLLARS)

  12  PCT VOID   STAT         95     .00    .00    .00    .00     70.

 VALUES OF TESTED VARIABLES USED IN SIMULATIONS
 (CALCULATED FROM NUMBER OF TESTS)
 ----------------------------------------------

                         NR OF   VALUE   NR OF   VALUE   NR OF   VALUE   NR OF   VALUE
```

```
ID   NAME     TESTS  (C.V.)  TESTS  (C.V.)  TESTS  (C.V.)  TESTS  (C.V.)

12  PCT VOID    9     3.1200   12    3.0185   15     2.9547   18     2.9101
                      .3205          .3313           .3384           .3436
1
 NUMBER OF TESTS ON                                UNIF. ANN. UNIF. ANN.   DIFF.
 MATERIAL PROPERTY   AGE AT  DISTRESS SELECTED    COSTS     TESTING     BENEFIT/
IDENTIFIED BY ID NO. FAILURE CAUSING   REHAB    1000-S OF    COST        COST
                     YEARS   FAILURE   OPTION    DOLLARS    DOLLARS      RATIO
   12

   12   0   0   0   0    10.28   RUT DEP      5       17.89       149.55      2.268
   15   0   0   0   0    10.33   RUT DEP      5       17.84       186.50      1.416
```

```
                                                                PROBLEM 4-C.5

EXAMPLE:  ANALYSIS OF ASPHALT CONCRETE THICKNESS TESTS IN STATE "C".


RUN DESCRIPTION:
----------------

USE PERFORMANCE MODELS TO CALCULATE DISTRESS.  OPTIMUM TESTING PROGRAM FOR
ASPHALT LABORATORY.  ( AC THICK )


INPUT DATA (COSTS)
(THOUSANDS OF DOLLARS/LANE MILE
--------------------------------

INITIAL CONSTRUCTION        90.0
ANNUAL MAINTENANCE COST       .0
ANNUAL USER COST              .0
USER COST OF REHAB.           .0

COST OF MONEY (INTEREST)    12.5 PERCENT


INPUT DATA (GEOMETRICAL)
-----------------------
LANE WIDTH (FEET)           12.0


INPUT DATA (TRAFFIC)
--------------------

 ABBREV.  ID                             COEF.         FULL
  NAME    NO.   VALUE       UNITS       OF VAR.        NAME

INIT ADT   1       .60E+04 VEH/DAY        .00     INITIAL AVG. DAILY TRAFFIC
PCTPERYR   2      5.0      PERCENT        .00     PERCENT PER YR GROWTH IN ADT
PCTTRK     3       .10E+02 PERCENT        .00     PERCENT OF TRUCKS IN TRAFFIC
ESAL/TRK.  4       .30     ESAL           .00     18-KIP EQUIV. SINGLE AXLES/TRK


INPUT DATA (MATERIALS)
---------------------

 ABBREV.  ID                             COEF.         FULL
  NAME    NO.   VALUE       UNITS       OF VAR.        NAME

PCT AC    11      6.0      PERCENT        .06     PERCENT BITUMEN (BY WEIGHT)
PCT VOID  12      2.5      PERCENT        .40     PERCENT AIR VOIDS IN MIX
PCT 200   13      6.0      PERCENT        .25     PCT AGGREG. PASSING #200 SEIVE
VISCOS    14      5.0      10^6 POISE     .10     VISCOSITY OF BITUMEN-70 DEG F
LOAD FQ   15       .10E+02 HZ             .10     FREQUENCY OF REPEATED LOADINGS
AC TEMP   16       .75E+02 DEG F          .10     TEMPERATURE OF AC (MID-DEPTH)
```

```
EACVARML  17       1.0      DIM-LESS         .00     MULTIPLIER ON CALC. VAR. OF E(
E BASE.   21       .30E+02 KPSI              .25     RESILIENT MODULUS OF BASE
E SUBB    22       .20E+02 KPSI              .25     RESILIENT MODULUS OF SUBBASE
E SUBGR   23       .15E+02 KPSI              .30     RESILIENT MODULUS OF SUBGRADE
THK AC    24       4.5      INCHES           .05     THICKNESS OF AC LAYER
THK BASE  25       8.0      INCHES           .10     THICKNESS OF BASE
THK SUBB  26       .12E+02 INCHES            .15     THICKNESS OF SUBBASE

SPECIFICATION OF INDEPENDENT VARIABLES
FOR INDICATED MODELS
-------------------------------------

 ABBREV.                 ID  FN  DEPENDENT ON
  NAME      UNITS        NO. NO. ID    NAME        FULL NAME

CURADT    VEH/DAY         5  10                    CURRENT AVG. DAILY TRAFFIC
                                  1  INIT ADT      INITIAL AVG. DAILY TRAFFIC
                                  2  PCTPERYR      PERCENT PER YR GROWTH IN ADT

CUMTRK    TRUCKS          6  11                    CUMULATIVE TRUCKS TO PRESENT
                                  1  INIT ADT      INITIAL AVG. DAILY TRAFFIC
                                  2  PCTPERYR      PERCENT PER YR GROWTH IN ADT
                                  3  PCTTRK        PERCENT OF TRUCKS IN TRAFFIC

CUMESAL   ESAL            7  12                    CUMULATIVE ESAL   TO PRESENT
                                  4  ESAL/TRK      18-KIP EQUIV. SINGLE AXLES/TRK
                                  6  CUMTRK        CUMULATIVE TRUCKS TO PRESENT

LOG E AC KPSI (LOG)      20  -1                    LOG (BASE 10) OF AC MODULUS
                                 11  PCT AC        PERCENT BITUMEN (BY WEIGHT)
                                 12  PCT VOID      PERCENT AIR VOIDS IN MIX
                                 13  PCT 200       PCT AGGREG. PASSING #200 SEIVE
                                 14  VISCOS        VISCOSITY OF BITUMEN-70 DEG F
                                 15  LOAD FQ       FREQUENCY OF REPEATED LOADINGS
                                 16  AC TEMP       TEMPERATURE OF AC (MID-DEPTH)

RUT DEP   INCHES         30   2                    AVG RUT DEPTH-BOTH WHEEL PATH
                                  7  CUMESAL       CUMULATIVE ESAL   TO PRESENT
                                 20  LOG E AC      LOG (BASE 10) OF AC MODULUS
                                 21  E BASE        RESILIENT MODULUS OF BASE
                                 22  E SUBB        RESILIENT MODULUS OF SUBBASE
                                 23  E SUBGR       RESILIENT MODULUS OF SUBGRADE
                                 24  THK AC        THICKNESS OF AC LAYER
                                 25  THK BASE      THICKNESS OF BASE
                                 26  THK SUBB      THICKNESS OF SUBBASE

RAD STRN INCHES/INCH     31  -3                    RADIAL STRAIN, BOTTOM OF AC.
                                 20  LOG E AC      LOG (BASE 10) OF AC MODULUS
                                 21  E BASE        RESILIENT MODULUS OF BASE
                                 23  E SUBGR       RESILIENT MODULUS OF SUBGRADE
                                 24  THK AC        THICKNESS OF AC LAYER
                                 25  THK BASE      THICKNESS OF BASE
```

```
 NRTOFAIL DIM-LESS      32  -4                  NR 18-KIP ESAL TO 10 PCT CRKG
                                31  RAD STRN    RADIAL STRAIN, BOTTOM OF AC.

 DMG INDX DIM-LESS      33   5                  FRACTION OF FATIGUE LIFE USED
                                 7  CUMESAL     CUMULATIVE ESAL    TO PRESENT
                                32  NRTOFAIL    NR 18-KIP ESAL TO 10 PCT CRKG
1


 INPUT CRITERIA AFFECTING
 MAINT OR REHAB DECISIONS
 ------------------------

          ASSIGNED ASSIGNED       DEFINITION OF ASSIGNED
 CRITERION  ID NO. LEVEL NO.         CRITERION LEVEL

  DMG INDX    33         3    GREATER THAN       1.00 FOR MORE THAN 50.0 PCT AREA
                         2    GREATER THAN       1.00 FOR MORE THAN  1.0 PCT AREA
  RUT DEP     30         2    GREATER THAN        .50 (MEAN VALUE)
  CURADT       5         2    GREATER THAN    1000.00 (MEAN VALUE)

 INPUT MAINTENANCE OR
 REHABILITATION PROCEDURES
 -------------------------

   NR   KEYS    COST  COST               DESCRIPTION
               (DOL.) UNITS

    1  300000   5.50  SQ. YD.       SEAL COAT + 2.5" OVERLAY
    2  221000   4.75  SQ. YD.       MILL 1", SEAL COAT, 1.5" OVERLAY
    3  222000   6.25  SQ. YD.       MILL 1", SEAL COAT, 2.5" OVERLAY
    4  121000   3.50  SQ. YD.       MILL 0.5" + 1.5" OVERLAY
    5  122000   5.00  SQ. YD.       MILL 0.5" + 2.5" OVERLAY
   31  000000     .00               DO NOTHING

 PARAMETERS DETERMINING VARIABLE VALUES
 AS A FUNCTION OF NUMBER OF TESTS
 --------------------------------------

                           CONF.     PARAMETERS FOR        COST PER
              TYPE OF      LEVEL  FUNCTIONAL VARIATION       TEST
   ID  NAME    VARIATION   (PCT)    A     B     C     D    (DOLLARS)

   24 THK AC     STAT      -90     .00   .00   .00   .00     105.

 VALUES OF TESTED VARIABLES USED IN SIMULATIONS
 (CALCULATED FROM NUMBER OF TESTS)
 ----------------------------------------------

                NR OF  VALUE   NR OF  VALUE   NR OF  VALUE   NR OF  VALUE
```

```
  ID   NAME    TESTS  (C.V.)  TESTS  (C.V.)  TESTS  (C.V.)  TESTS  (C.V.)

  24  THK AC    12    4.4115   15    4.4219   18    4.4293   21    4.4349
                       .0510          .0509          .0508          .0507
1
   NUMBER OF TESTS ON                                 UNIF. ANN. UNIF. ANN.   DIFF.
   MATERIAL PROPERTY   AGE AT  DISTRESS SELECTED    COSTS     TESTING    BENEFIT/
  IDENTIFIED BY ID NO. FAILURE CAUSING   REHAB    1000-S OF    COST       COST
                        YEARS   FAILURE   OPTION    DOLLARS    DOLLARS     RATIO
     24

     15   0   0   0   0   10.29   RUT DEP     5       17.88      280.23     1.021
```