A Systems Analysis of the Highway Pavement Design Process

B. G. HUTCHINSON, Associate Professor of Civil Engineering, University of Waterloo, and
R. C. G. HAAS, Assistant Professor of Engineering, Carleton University, Ottawa

•INVESTMENTS in highway and street systems represent a considerable portion of our national productive effort. A state of imperfect technology coupled with the high expenditures involved has generated a continually increasing amount of research into various aspects of the road transport activity. A significant amount of this effort has been directed toward developing a fundamental understanding of the behavior of highway pavements and the use of this information in their design.

The pavement design problem has been recognized as a major area of research by the U.S. Bureau of Public Roads in formulating its National Program of Research and Development in Highway Transportation (1). This program sets forth three broad problem areas of the highest priority to highway transportation. It attempts to recognize the technological and administrative aspects of each problem area by stating that the basis for support of individual projects will include importance, possible benefits, probability of success, usefulness, and uniqueness.

The actual application of these criteria to such areas as highway pavement research has a very subjective basis. It appears to place a major emphasis on the technological aspects of the problem without attempting to evaluate the economic implications or the probable payoff from investments of research resources in the technological subproblems identified. In addition, the problem statements are oriented toward the existing philosophy of pavement design, which fails to recognize explicitly the progressive nature of pavement deterioration or the age at which failure occurs. This prevents the optimization of capital investments and maintenance costs with respect to pavement types and component material alternatives.

This paper attempts to recognize in an explicit manner both the technological and economic attributes of pavements that are pertinent to their design. It demonstrates that a true rationalization of the highway pavement design process is best achieved through a comprehensive application of systems engineering principles. The principal objectives of the paper are (a) to provide a systems analysis of the highway pavement design process and to define each of the elements of this process; (b) to suggest methods for organizing existing information on each of these elements, to explore the deficiencies of available information, and to suggest methods for the systematic collection of information, its storage, retrieval, and analysis; and (c) to provide some preliminary discussion relating to a sensitivity analysis of the pavement design process, which will provide an ordering of the probable payoff that is likely to accrue from information generated on the various subproblems.

The paper is essentially divided into two major sections. In the first section, existing design procedures are reviewed and the current philosophy of pavement design and the deficiencies of these methods are discussed. A comprehensive systems analysis of the highway pavement design process is described in the second section, along with some of the requirements pertinent to a sensitivity analysis of the process.

Paper sponsored by Committee on Theory of Pavement Design and presented at the 47th Annual Meeting.

EXISTING DESIGN PROCEDURES

The principal objective of a highway pavement is to provide for the safe and efficient passage of highway vehicles across natural land forms under all climatic conditions. This objective may be accomplished by a large number of different types of pavement. The principal task of the engineer charged with pavement design is to select the pavement strategy that is the most economical to construct and maintain throughout the specified design period and provides adequate levels of service.

The existing design procedures for highway pavements are all oriented toward a specific pavement technology. Separate design procedures exist for conventional flexible pavements, pavements incorporating stabilized base courses, rigid pavements, and so on. Their formal development is limited to an analysis of certain technological features of each principal pavement type. A common design framework does not exist that permits the systematic evaluation of a variety of design alternatives and that allows the designer to proceed to the selection of the most economical pavement strategy.

A Classification of Procedures

Figure 1 provides a concise summary of the evolution of design methods for flexible pavements and indicates in a general way the principal features and limitations of these methods. Figure 2 provides a similar summary of the evolution of design methods for rigid pavements and emphasizes some of the advancements in technology that have characterized all approaches.

The general approach to pavement design from the turn of the century to the Second World War consisted essentially of using standard pavement sections and evaluating their actual field performance in terms of "satisfactory" and "unsatisfactory." However, higher vehicle speeds, greater loads, and increased traffic volumes indicated to a number of highway agencies the need for some form of objective structural design method. This need was reinforced during the war when higher quality airfield pavements were required to accommodate the heavier wheel loads and traffic volumes generated by the war. In addition, greater emphasis was placed on the development of specifications for controlling the quality of paving materials.

In the 1950's the theoretical approaches to pavement structural design began to be consolidated and their relation to the in-service behavior of pavements explored. The late 1950's and early 1960's produced the first comprehensive efforts at evaluating the validity of pavement design procedures through the systematic observation of the performance of full-scale pavements.

The AASHO Road Test (2), which was completed in the early 1960's, was intended to have a significant impact on current design methods. Unfortunately, the accelerated nature of this experiment and the dominant influence of traffic masked the effects of the climatic environment on pavement performance.

The Special Committee on Pavement Design and Evaluation of the Canadian Good Roads Association initiated probably the most comprehensive and systematic field study of pavement behavior yet undertaken, about 10 years ago. The principal findings of this Committee are well described in the literature (3, 4, 5). The investigation has provided the first systematic information on failure age and its relation to pavement structural design, traffic loadings and climatic conditions.

Deficiencies of Current Procedures

The principal limitations of current pavement design techniques that prevent a complete rationalization of the design process include the following:

1. The primary mechanisms of pavement failure and the processes of secondary deterioration are imperfectly understood;
2. The implications of new and significantly different pavement materials can only be evaluated after several years of field performance data are available;
3. The transfer of pavement performance data from one geographic locality to another is at present a very subjective operation;

METHODS	FEATURES	LIMITATIONS
A METHODS BASED ON "JUDGEMENT" Examples: Most Can. & U.S. Urban Centers; Ont. Dept. of Hwys.	Attempt to prevent failure. Simple and quick in application. Negligible design costs.	(1)No provisions in method for economic comparisons of pavement type alternatives (A,B,C,D,E,F,G). (2)Weak, subjective link between design and performance evaluation (A,B,C,D,E,F). (3)Failure to recognize effect of layers (A,B,C). (4)Environmental effects accounted for in only a very subjective manner (A,B,C,D,E,F). (5)Failure to account for effect of repeated loads on pavement deterioration (A,B,C,D,F). (6)Variations in construction quality not adequately accounted for (A,B,C,D,E,F). (7)Failure to recognize progressive nature of pvt. deterioration by considering only failure or non-failure condition (A,B,C,D,E,F). (8)No distinction between static or moving nature of loads (A,B,C,D). (9)Inadequate recognition of seasona strength variation of subgrades (A,B,C,D,F). (10)Simulation of in-service material behaviour not adequately evaluated in laboratory testing (A,B,C,D,F).
B METHODS BASED ON SIMPLE STRENGTH TESTS Examples: CBR or Modified CBR Method; U.S. Corps of Eng., Wyoming	Attempt to prevent failure. Simple equip. & proced. for meas. subgrade and base properties. Empirical correl. with pavement thickness.	
C METHODS BASED ON SOIL FORMULA Examples: Group Index Methods; Can. Fed. D.P.W., U.S. F.A.A. Method.	Attempt to prevent failure. Simple soil classif. tests to assign mean expected strength values to subgrade. Empirical link with pavement thickness.	
D METHODS BASED ON TRIAXIAL TEST Examples: Kansas Method, Texas Method, Calif. Method.	Attempt to prevent failure. Test values can be used in stability analysis of pavement components and subgrade.	
E METHODS BASED ON PLATE BEARING TEST Examples: U.S. Navy Method, Can. D.O.T. Method.	Attempt to prevent failure by limiting deflec. Full-scale testing of subgrade and pvt. structure reaction to load.	
F METHODS BASED ON STRUCTURAL ANALYSIS OF LAYERED SYSTEMS Examples: Burmister's Method, Shell 3-Layer Method.	Attempt to control or avoid failure mechanisms. Objective analysis to predict stresses and strains at any point in pavement or subgrade.	
G METHODS BASED ON STATISTICAL EVALUATION OF PAVEMENT PERFORMANCE Examples: Design Eqn. From AASHO Test, CGRA Design Guide.	Attempt to measure performance v. age relations and to control failure age by limiting deflections. Full-scale testing and evaluation	

1900 1910 1920 1930 1940 1950 1960 1967

Figure 1. Classification of the approaches to flexible pavement design.

METHODS	Features	Limitations
METHODS BASED ON "JUDGMENT"	Group A methods are characterized by attempts to prevent failure and are simple in application. Group B methods attempt to control or avoid failure mechanisms and generally incorporate fatigue criteria. Group C methods attempt to measure performance-age relationships and to produce predictive models of these. Some of the most marked features of all groups have recently consisted of advances in design and construction technology that include the following: 1.Machines with automatic controls. 2.Central-mixing plants. 3.Slip form pavers. 4.Mechanical placing of reinforcement 5.Dowel placing machines. 6.New joint forming techniques. 7.New curing compounds.	(1)No provisions in method for economic comparisons of pavement type alternatives (A,B,C). (2)Weak, subjective link between design and performance eval. (A,B) (3)Variations in construction quality not adequately accounted for (A,B). (4)Failure to recognize progressive nature of pavement deterioration by considering only failure or non-failure condition (A,B). (5)Environmental effects accounted for in only a very subjective manner (A,B). (6)No provisions in method for economic comparisons of alternative joint designs (A,B,C).
METHODS BASED ON STRUCTURAL ANALYSIS OF STRESSES AND DEFLECTIONS		
METHODS BASED ON STATISTICAL EVALUATION OF PAVEMENT PERFORMANCE		

1900 1920 1940 1960 1967

Figure 2. Classification of the approaches to rigid pavement design.

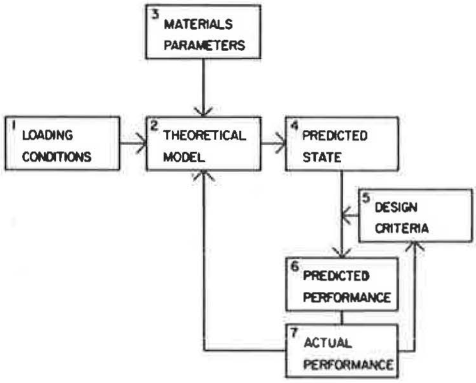


Figure 3. Structure of existing design procedures.

4. Pavement construction procedures and the natural heterogeneity of paving materials produce wide variations in the "quality" of the finished pavement, and current design procedures are unable to account for probable variations in this quality;
5. Laboratory methods of evaluating pavement material components in a manner that accurately simulates in-service time-temperature-age-stress-strain behavior are in a primitive state of development;
6. The optimization of initial capital and maintenance costs between alternative pavement types is impossible because of the lack of systematic information on performance;
7. The implications of changes in legal axle loads cannot be evaluated insofar as optimizing pavement investments in relation to the most efficient vehicle weights are concerned; and
8. Cost data for the various types of paving materials are not readily available for economic analyses of alternate pavement designs.

This listing indicates in a general manner a number of the factors retarding the development of a truly rational pavement design process. The literature contains many references to "rational" pavement design methods where the author implies that this involves accurate predictions of stresses and strains in various parts of the layered system through the use of structural analysis techniques. This paper uses the word "rational" in its broadest sense and implies that any rational method must consider not only the technological behavior of a pavement but also its economic characteristics.

Figures 1 and 2 summarize some of the principal limitations of current design procedures. While the models of pavement behavior underlying the various methods of design differ in detail, the basic philosophy underlying these methods is essentially the same and may be conveyed in the form shown in Figure 3. This diagram attempts to show that the constant interaction between the actual behavior of highway pavements and the models formulated to explain observed field behavior has stimulated the gradual evolution of design procedures.

Implicit in these current models of pavement behavior is the assumption that they are perfectly reliable predictors of actual pavement behavior, or at least some critical stress or strain condition within a pavement. The design criteria, which may be expressed either implictly or explictly as limiting deflections, stresses, and so on, are assumed to be absolutely indicative of failure conditions. In other words, the use of these design criteria implies either satisfactory or unsatisfactory pavement performance.

Pavement failure results from a progressive deterioration in pavement serviceability, which begins at the time a pavement is placed in service. The attributes of highway pavements of ultimate interest to the pavement design engineer are their probable failure ages and the cost streams necessary to achieve these service lives. With existing pavement design procedures, the relationship of the design criteria to probable service lives of pavements is based on subjective considerations rather than systematically collected evidence on field performance. In other words, in terms of Figure 3 the relationships between steps 4, 5, and 6 have not been formally established. The design criteria for highway pavements must not be viewed as ends in themselves but simply as a means to the prediction of failure age.

The current approaches based on the statistical analysis of the performance of actual pavements have measured failure ages directly and related these measurements to structural design, traffic loads, and climatic conditions. The major deficiency of these approaches is that it is difficult to generalize the results and use them for new pavement types for which little performance data are available. Their principal contribution arises from the information they give on the expected lives of pavement types that are currently

used. In this sense they do provide the pavement design engineer with the type of information required to optimize the capital and maintenance costs of pavements.

A HIGHWAY PAVEMENT DESIGN PROCESS

The need for a comprehensive formulation of a highway pavement design process that provides for the integration of both the technological and economic attributes of highway pavements has been discussed previously. An appropriate way of structuring any engineering design process is to organize it into six major phases: problem definition, solution generation, solution analysis, solution evaluation and optimization, implementation, and performance measurement.

The systems analysis of the highway pavement design process described in this section is subdivided into these six major phases.

Problem Definition

The problem definition phase can be further broken down into six major components, which are (a) objectives, (b) inputs, (c) outputs, (d) constraints, (e) cost function, and (f) decision criterion.

Objectives—The principal objectives to be fulfilled by a highway pavement are of an economic and social nature and may be expressed as follows:

1. To provide a pavement of adequate serviceability throughout its design life,
2. To provide pavements capable of permitting operating speeds and wheel loads of vehicles at levels that maximize the economic and social benefits to society of highway transportation, and
3. To minimize the total expenditures consumed by the provision of pavements.

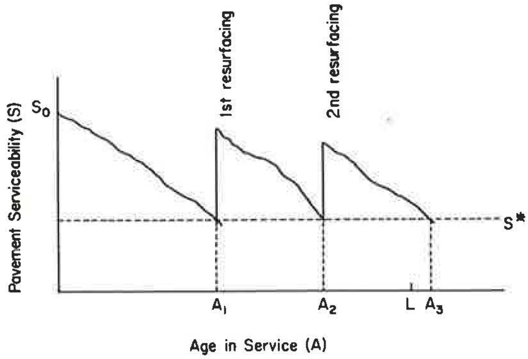
In general, higher overall pavement serviceability qualities can be provided throughout a highway system by the expenditure of larger sums of money on pavements. Higher wheel loads and higher operating speeds can be permitted only through the expenditure of such larger sums of money. These three objectives therefore tend to be contradictory and ideally a procedure is required which will permit improvements in objectives 1 and 2 to be "traded-off" against increased expenditures.

At present it is impossible to approach such a trade-off in any rational manner. Minimum acceptable standards must be established for pavement serviceability, wheel loads, and operating speeds. These standards are based on the highway authority's interpretation of what proportion of their resources the public is willing to allocate to the achieving of such attributes in a highway system, relative to the resources they are willing to devote to other objectives such as education, recreation facilities, and so on. The pavement designer must then attempt to minimize the expenditures consumed by the provision of pavements within the constraints established by these standards.

The pavement design process, however, must be structured in a manner that allows the implications of changes in these standards to be explored. For example, in the future the pavement design engineer will no doubt be called on to predict the cost implications of providing pavements with minimum pavement serviceability levels that are capable of handling operating speeds of 100 mph instead of the current 60-70 mph. He will also be required to predict the cost implications of increases in legal axle loads.

Pavement Performance—Unlike many other types of engineering systems, highway pavements undergo significant physical deterioration during relatively short life spans. The progressive nature of such deterioration and the age at which pavement failure occurs are of paramount importance to the pavement design engineer. The fundamental operating characteristic of a highway pavement is its pavement serviceability-age history. A hypothetical pavement serviceability-age history for a flexible pavement is shown in Figure 4.

This history is defined in terms of three basic variables: the pavement serviceability (S), the pavement serviceability level at which pavement failure occurs (S^*), and the ages (A) at which S^* occurs. The history shown implies that one or more resur-



S = pavement serviceability
S_0 = pavement serviceability at time of construction
S^* = failure level of pavement serviceability
A_1 = age at 1st resurfacing
A_2 = age at 2nd resurfacing
A_3 = age at failure of 2nd resurfacing
L = design life over which pavement strategies are compared

Figure 4. Generalized serviceability profile of highway pavements.

facings of the pavement occur during its life. The design life over which the economic characteristics of pavements will be compared is designated by the symbol L.

When a vehicle travels along a highway pavement, motions are generated in the body of the vehicle that are a function of the suspension characteristics of the vehicle, the speed of the vehicle, and the roughness of the highway pavement. The motion and vibration of the vehicle induce a response in the human occupants such as discomfort and fatigue and in some cases physiological damage.

Figure 5 (a) illustrates the components of this problem in terms of pavement roughness (r), vehicular characteristics (v), speed of the vehicle (p), vibration of the vehicle (m), and human response to this motion (h). Figure 5 (b) attempts to recognize the complexity of this problem and suggests by means of the matrix that the vehicular vibration generated by each combination of roughness r_i and vehicular class v_j will induce a set of human responses $\{h_{ij}\}$ for a fixed vehicular speed.

The problem facing the highway engineer is essentially one of averaging these human response measures to arrive at a single index that characterizes the extent to which a particular pavement section is serving the traveling public. This index, which must possess at least an interval scale status, has been called pavement serviceability and is shown in Figure 5 (b) as S_i. Terms used in Figures 4 and 5 are defined as follows in the sense in which they are used in this paper:

Pavement Roughness (r): the distortion of the pavement surface from the geometry of the designed pavement surface; this distortion may result from deficiencies in the original construction and permanent distortions induced by vehicular wheel loads and climatic conditions.

Pavement Serviceability (S): the average magnitude of human response to motion generated in highway vehicles by pavement roughness at a specified vehicular speed.

Failure Serviceability (S*): the level of pavement serviceability at which pavements are no longer considered to provide an adequate surface for the passage of vehicles at desired speeds.

Pavement Performance: the pavement serviceability-age history of a pavement.

The current procedure most commonly used for estimating pavement serviceability is that developed at the AASHO Road Test (2) in which a present serviceability rating is estimated subjectively. The validity of this procedure in estimating pavement serviceability depends on the subjective estimating abilities of the pavement raters and their facility to recognize each of the components classified in the matrix of Figure 5 (b).

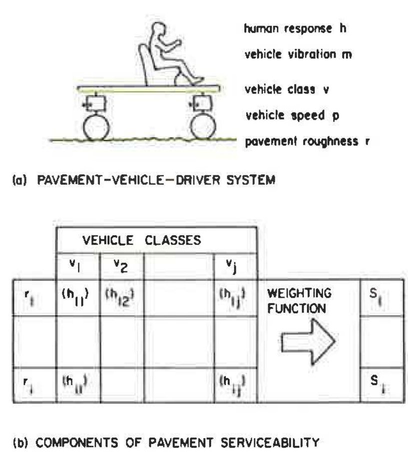


Figure 5. Components of pavement serviceability.

Hutchinson (6) has pointed out that if pavement serviceability measures are to be manipulated statistically, as they have been in the analysis of the AASHO Road Test data and in the CGRA studies (3), then they must achieve at least an interval scale status of measurement. In addition, if these measurements are to be used over longer periods of time and transmitted between various highway jurisdictions, then it would seem appropriate that the unit of measurement be stable and reliable.

It might be argued that a knowledge of the complete pavement serviceability-age history is not required and that only the failure ages need to be known. However, unless the total histories are known, it is impossible to evaluate such things as the cost implications of increasing the minimum acceptable level of pavement serviceability S*. Also, if a valid link is to be established between theoretical models of pavement behavior, cumulative damage theories, and pavement serviceability, then it is essential to have a precise knowledge of the pavement serviceability-age history. One further requirement of the pavement serviceability measure indicated by this discussion is that S* must be established independently of S.

The principles of subjective rating scale construction described by Hutchinson (6) indicate that the subjective units used by a pavement rater to express present serviceability ratings are highly dependent upon the spectrum of pavement serviceabilities to which the pavement rater has been exposed. In other words, the rating units actually used by a rater in a jurisdiction with a relatively narrow range of pavement serviceabilities will be quite different from the unit established by a rater in a jurisdiction with a wide range of actual pavement serviceabilities.

In addition, the fact that the level at which a pavement is no longer considered to serve the traveling public satisfactorily was observed to be equal to a present serviceability rating of 2.5 (7) cannot be considered a fundamental characteristic of highway pavements. This observation could have been predicted from a knowledge of the characteristics of subjective rating scales without conducting any field experiments. It is well known that raters tend to gauge their feelings by scaling up and scaling down from some mean condition represented by the verbal cue average.

It must be re-emphasized that present subjective rating procedures used to estimate pavement serviceability do not provide measurements in a form that can be validly used for statistical manipulation or to explore the implications of changes in the level of S at which S* is considered to occur. S* is not independently established with present procedures. If significant advances are to be made in the measurement of pavement serviceability then S must be estimated from objective measures of human response. Hutchinson (25) has reported a preliminary attempt to measure human response to vehicular motion by a tracking test. At the present time the level of S at which S* is considered to occur must be established arbitrarily just in the same way that other highway standards are established.

Input Factors—The specification of the inputs to a highway pavement involves the identification of all those factors external to pavements that contribute to decrements in pavement serviceability. While many factors such as wheel loads, climatic factors, subgrade characteristics, and so on are known to influence pavement behavior, it is difficult to specify these factors in any quantitative manner. This difficulty arises from the existing lack of knowledge on the fundamental mechanisms of pavement deterioration. The manner in which these input factors are specified must be conditioned by the way in which this information is to be used. There is no justification for attempting to predict the loading spectrum to which a highway pavement might be subjected unless it is possible to use this information.

A primary factor that contributes to the deterioration of pavements in Canada and the Northern United States is the distortion of the pavement surface induced by frost action. The CGRA pavement evaluation studies (4) have indicated that flexible pavements that are structurally adequate with respect to traffic loads and located on light clay subgrades will deteriorate to an unacceptable level of pavement serviceability in about 15 years simply from the influence of climatic factors.

Differential frost heaving of a subgrade soil is influenced by a large number of factors, among which are the rate and degree of soil freezing, groundwater conditions,

SUBGRADE CLASSES

1. Rock
2. Well graded granular
3. Poorly graded granular
4. Silty sands and gravels
5. Silts
6. Low-medium plastic clays
7. Highly plastic clays
8. Peat

DRAINAGE CLASSES

1. Good
2. Imperfect
3. Poor

TRAFFIC CLASSES

1. Less than 1000 A.D.T.
2. 1000 - 3000
3. Greater than 3000

RAINFALL CLASSES

1. 30" per year
2. 40"

FREEZING INDEX CLASSES

1. Less than 1000 degree days
2. 1000 - 1500
3. 1500 - 2000
4. 2000 - 2500
5. Greater than 2500

Figure 6. Environmental classification.

minor variations in soil texture, pavement thickness, and so on. The pertinent climatic factors at a particular location can only be estimated in a statistical sense, yet frost heaving is a function of, among other factors, the specific temperature regime rather than some annual average statistic.

Shields and Dacyszyn (8) have reported one of the few systematic studies of the seasonal variation in strength of flexible pavements. The study examined the seasonal strength characteristics of some 24 pavement sections in Alberta that were observed over a period of five years. They concluded that "seasonal strength variation in flexible pavements is a widely fluctuating value which cannot as yet be related directly to pavement strength characteristics or to generalized climatic statistics. It would appear that these variations and fluctuations are greatly influenced by micro-climatic features which would require intensive evaluation and detailed analysis for control purposes."

Similar comments could also be made about other factors, such as the specification of probable traffic loads. It is only realistic for the pavement design engineer to classify the environmental factors in a relatively coarse manner. It would be meaningless at this stage to attempt to predict precisely the probable distributions of axle loads, climatic conditions, the properties of component materials, and so on, since the pavement design engineer cannot use this information. A similar approach is followed in structural design procedures in which general zones of earthquake intensity, snow loadings, wind loadings, and so on are established. A more detailed discussion of the factors influencing pavement performance is given in a subsequent portion of this paper.

A number of environmental classes have been established for the analysis of some Ontario pavement performance data, which are described later in this paper. These classes were based on a consideration of the following environmental factors: subgrade soil classification, freezing index, precipitation, drainage, and traffic conditions. The particular subclasses identified within each of the factors are shown in Figure 6.

Pavement Output—The pertinent output characteristics of a highway pavement have already been conveyed in Figure 4. Ultimately, the pavement design engineer is concerned only with two variables—the ages A at which S* occurs. With this knowledge and information on the cost stream required to produce the predicted pavement serviceability-age history, the designer is in a position to compute the cost characteristics of each of the alternatives.

Different pavement designs commonly involve expenditures of resources at various points in time as well as having different failure ages. In order to provide a common basis for the comparison of the economic properties of designs, a standard time base, or design life L, must be selected.

Constraints—The design constraints may be defined as those factors that limit the extent of feasible pavement designs. One constraint on the behavior of pavements has already been established—the minimum acceptable level of pavement serviceability, S*.

A second constraint is the magnitude of the interest rate used for the calculation of the annual costs. While many public authorities do not presently execute formal economic analyses of highway investments, the importance of such aids to public enterprise decision-making has been recognized and they are becoming used more widely. A question of fundamental importance in their use is the magnitude of the interest rate to be used in the calculations.

Many analysts have argued that no interest should be used in the evaluation of investments financed from current revenues and that interest rates should only be used in the evaluation of investments financed from borrowed capital. However, it is now generally accepted that a representative market interest rate should be included in all economic evaluations whether current revenues or borrowed capital are involved.

The financial resources of public authorities are currently allocated by means of a budgetary constraint imposed by the body politic. The prevalent opinion seems to be that, because of the large role assumed by the so-called intangibles associated with public operations, this allocation can only be achieved subjectively.

There are a number of well-known deficiencies in this type of approach and Alder (9) argues that the overall choice of the quantity of resources to allocate to highway transportation can be made only as a reflection of the sum of numerous individual projects that are judged to be sound. Kuhn (10) further points out that, for these individual economic evaluations to be meaningful, an interest rate representative of the current market rate must be included whether the financing is supplied from current revenues or borrowed capital. He points out that the interest rate is the only mechanism that provides a basis for the allocation of resources between the public and private sectors of the economy.

The third constraint that should be imposed on the pavement design process is also an economic constraint and is a maximum limit on the expected annual cost of the optimal pavement strategy. This maximum limit must be established from a consideration of the economic characteristics of the overall highway project, of which the pavement structure is only one element.

Cost Function—The cost function is simply a device that relates the output characteristics of pavements (i.e., failure age and capital costs) to the primary design objective, which has been established as the minimization of costs. The following cost function has been suggested by Baldock (11):

$$AC = CRF_L \left[C + E_1 (PWF_A) + E_2 \left(PWF_{A_r} \right) - \left(1 - \frac{y}{x} \right) (E_1 \text{ or } E_2)\, PWF_{A_r} \right] + M \tag{1}$$

in which

- AC = annual cost of a 2-lane mile of pavement and shoulders,
- CRF_L = capital recovery factor for a design life of L years and a specified interest rate,
- C = initial capital cost of pavement and shoulders per mile,
- A = failure age of the initial pavement (years),
- A_r = failure age of first resurfacing measured from the original time of construction (years),
- PWF = present worth factor for A or A_r years and the specified interest rate,
- E_1 = first resurfacing cost per mile,
- E_2 = second resurfacing cost per mile,
- y = number of years from time of last resurfacing to the end of design life period, i.e., ($L - A$ or A_r),
- x = estimated life of last resurfacing (years), and
- M = average annual maintenance cost per mile.

In order to predict the expected annual cost for each of the pavement strategies under consideration the design engineer must establish (a) capital costs, (b) failure age of the initial pavement, (c) failure ages of the resurfacings, (d) costs of the resurfacings, (e) interest rate, and (f) maintenance costs.

Decision Criterion—Since the objectives and the cost function are one-dimensional, the decision criterion is straightforward and may be concisely stated: select that pavement strategy with the minimum expected annual cost in dollars.

Figure 7 summarizes the problem definition phase by illustrating the interrelationships between the six components described.

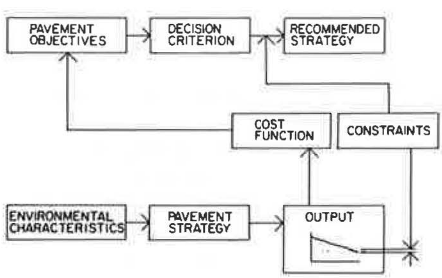


Figure 7. Components of the problem definition phase.

Solution Generation

There are a large number of potential solutions to a specific pavement design problem. These range from pavement strategies that have been used a large number of times and whose probable performance characteristics are well known, through to relatively new types of pavements for which very little performance information is available. The designs may consist of various types of portland cement concrete, asphaltic concrete surface courses supported by a variety of granular base courses and stabilized base courses, composite pavements, and so on.

Two general classes of potential solutions are established in this investigation, (a) standard pavement strategy, and (b) new pavement strategy. These two classes have been identified primarily as an aid to the analytical phase of the design process. Standard pavement strategy may be defined as a design type for specified environmental service conditions whose failure age distribution is known from accumulated relative frequency data on its performance. New pavement strategy may be defined as a pavement design type for which no prior experience or for which only limited evidence is available for specified environmental service conditions.

It is beyond the scope of this paper to list the possible pavement strategies that might be used as solutions to a pavement design problem. It is sufficient to state that at this stage of the pavement design process the pavement designer is faced with an array of possible solutions and he must select one of these strategies. The designer can assemble capital and maintenance costs fairly easily, but the problem is to predict the expected failure age in order to compute the expected annual cost of each strategy.

Solution Analysis

A method of approach for analyzing the two broad classes of highway pavements that are currently used is developed in this section. In addition, an approach to new pavement strategies is also described.

Flexible Pavements—It has been established previously that the principal technological problem is to predict the serviceability-age history for any pavement design alternative being considered. Typically, the conventional flexible pavement used by most authorities consists of a three-layer system with an asphaltic concrete surface course, a granular-type base course, and a subbase course of lower quality granular material. The principal objective of this phase of the design process is to generate sufficient information to allow the pavement designer to make a choice between overall pavement types. The selection of the most economical detailed design option within this overall pavement type is executed in the evaluation and optimization phase.

It has also been established that current flexible pavement design procedures do not permit serviceability-age histories to be predicted. However, the CGRA pavement evaluation studies do permit the serviceability-age histories to be predicted for standard pavement strategies. A number of regression models have been established for the Canada-wide data but difficulty has been experienced in arriving at a general model. Hutchinson (12) has examined the Ontario pavement performance data in an attempt to examine its usefulness for direct application to pavement design.

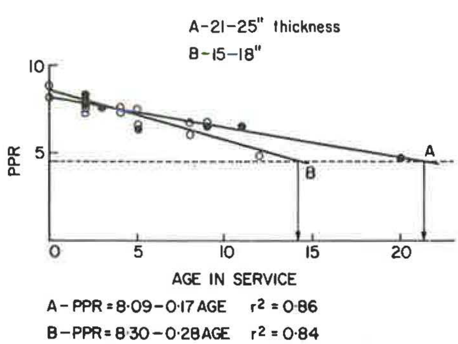


Figure 8. Pavement performance trends (pavements subjected to similar environmental conditions).

Available Ontario performance data have been sorted into common environmental classes of the type discussed previously and trends between present performance rating and the age in service has been plotted in the form shown in Figure 8. Pavement designs have been separated only in terms of total pavement thickness.

Lines were fitted to those serviceability-age histories for which sufficient data were

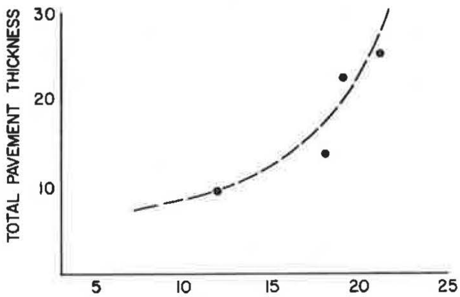


Figure 9. Thickness vs failure age for a particular environmental class.

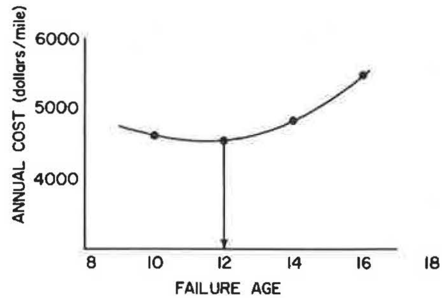


Figure 10. Annual cost curve for various pavement thicknesses.

available. In all other instances the serviceability-age trends were hand-fitted to the data subject to the constraint that the maximum value of the present performance rating at age 0 is equal to 8.5. This initial value is suggested by the field rating studies conducted by highway departments across Canada on many newly constructed pavement sections. The mean failure age in years has been scaled from the performance trend lines of this type at a present performance rating equal to 4.5 and used to prepare diagrams of the type shown in Figure 9. It must be emphasized that the thicknesses shown in

TABLE 1

ANNUAL COST COMPUTATIONS

TOTAL THICKNESS	FAILURE AGE	PWF_A	INITIAL[1] CAPITAL COST	RESURFACING COST	ANNUAL COST
9	10	0.5584	47,520	19,738	4,580
9.5	12	0.4970	49,456	20,534	4,560
11	14	0.4423	55,264	21,364	4,866
13.5	16	0.3937	65,944	22,228	5,492

1 - 2 x 12' lanes plus 2 x 10' shoulders

2 - thickness 1½" and price compounded @ 2% per annum to account for price increase plus 15% engineering and supervision costs

Assumptions

L = 25 years; i = 5%; X = 15 years

H_1 = 3", H_2 = 6" and H_3 = variable

Costs

asphaltic concrete surface course 3" thickness = $1.50/sq.yd.

granular base course 6" thickness = $0.95/sq.yd.

subbase course = $0.15/sq.yd./inch thickness

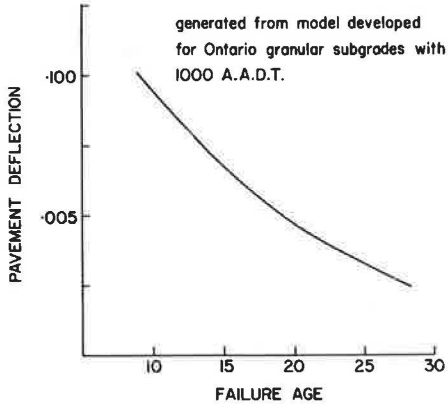


Figure 11. Deflection-age trend.

Figure 9 are total pavement thicknesses and consist of various combinations of surface course, base course, and subbase course thicknesses.

The information conveyed in Figure 9 can now be used to established a first estimate of the most appropriate total pavement thickness. Equation 1 can be used along with the type of information shown in Figure 9 to compute an annual cost curve as a function of failure age (or total pavement thickness). A typical set of computations is given in Table 1 and the information is summarized in Figure 10. This annual cost-failure age curve indicates that a total pavement thickness of about 10 inches would be the optimal design thickness for minimum annual cost and the expected life of the initial pavement would be 12 years. This optimality exists only for the cost information contained in Table 1 and the thickness-age relation of Figure 9. Different capital costs, resurfacing costs, thickness-age relation, etc., would of course change the optimal pavement thickness.

The preliminary analyses of the CGRA pavement evaluation data have shown that the surface deflections of flexible pavements are valid indicators of their relative strengths. Figure 11 shows a relationship that has been generated from the preliminary performance equations developed in this study. In addition, Meyerhof (13) has examined the relationship between the total pavement thickness and deflection for the CGRA data and the results of this study are shown in Figure 12.

Meyerhof suggests that, for normal flexible pavement thicknesses and from considerations of elastic theory, the theoretical relationship between the surface deflection and thickness may be expressed by

$$d \cdot D = C \tag{2}$$

in which

- d = surface deflection,
- D = total pavement thickness, and
- C = a constant for the standard CGRA Benkelman beam test,

and by

$$C = \frac{0.52\,W}{E_s^3\,n}$$

in which

- W = wheel load,
- E_s = subgrade modulus of elasticity, and
- n = the modular ratio of pavement to subgrade.

The deflection-thickness curves for various values of C are shown in Figure 12 and Meyerhof suggests the following average values:

Subgrade Type	C
Gravel	0.30
Sand	0.35
Silt	0.50
Clay	0.60
Peat	1.5-2.5

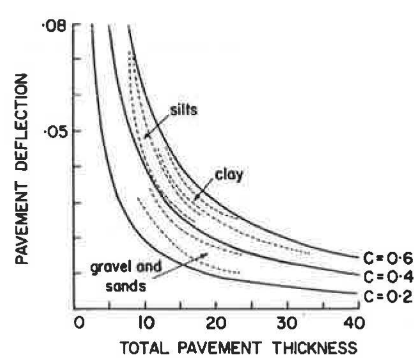


Figure 12. Deflection-thickness trends.

If relationships of the type shown in Figures 11 and 12 are available for a given environmental class, then they may be used along with cost data to arrive at an estimate of the optimal pavement thickness in the same manner as the information contained in Figure 9 was used.

The analytical framework described may be used to arrive at the optimal conventional flexible pavement strategy using the type of information obtained in the Canadian pavement evaluation studies.

The use of the surface deflection as an indicator of pavement strength is more sensitive than thickness since it also expresses some of the quality characteristics of the component materials. However, a large number of factors influence serviceability trends in flexible pavements.

Rigid Pavements—Very little systematic performance information is available for rigid pavements. The primary design variables that influence rigid pavement performance are slab thickness, the nature of the reinforcement, the joint designs, subbase properties, and subgrade properties.

Adequate performance data on rigid pavements with a variety of design variables are not currently available in Canada and an explicit procedure for arriving at the optimal rigid pavement design cannot be established. However, it would be a simple matter to calculate the annual costs associated with each rigid pavement design variation from capital cost estimates and failure-age predictions.

Factors Influencing Pavement Serviceability Changes—It has been established that the ultimate rationalization of the highway pavement design process is dependent upon a quantitative understanding of the rate of decrease in pavement serviceability with age in service. The prediction of this rate of change of serviceability must be based on an understanding of the factors causing the deterioration, their relative influence in a particular area or situation, and any interactions between these variables that influence the degree and rate of deterioration.

Figures 13 and 14 summarize the factors known to influence the performance of flexible and rigid pavements respectively. These flow charts do not attempt to indicate the relative importance of the variables but simply to classify them. The degree to which any of these factors, or combinations of factors, contribute to a loss in pavement serviceability is influenced by the climatic environment, quality of construction, and traffic at a particular location.

The diagrams show three main visible manifestations of pavement distress, which are further subdivided into a number of possible varieties. Since these classes of distress, in many cases, do not remain in their original or primary state, some of the possible consequences are shown. This secondary deterioration can often be much more detrimental to performance and in many cases may conceal the initial cause. It may also be responsible in certain cases for some confusion in field investigations of pavement failure mechanisms. Some of the factors identified in Figures 13 and 14 need to be further subdivided for a truly comprehensive picture of the pavement deterioration problem.

At the present time there is no generally accepted method for surveying pavement condition and classifying the various types of distress, and their relative importance in a particular area, as to the overall performance of a pavement. Research efforts have often tended to concentrate on factors that may be analytically complex but whose influence on pavement deterioration may be relatively minor.

The second step then, following the qualitative and comprehensive recognition of all the factors influencing performance, is broadly one of measurement and the development of techniques for the storage and retrieval of this information. The basic problem is to develop appropriate measurement techniques and to decide which are the most important factors in a particular jurisdiction. It is important that these techniques be developed not as ends within themselves but as useful means of providing information to predictive models of pavement performance. As previously pointed out, such models have been developed in Canada for rural highway conditions; however, they have a number of limitations, including applicability to most urban conditions. The format of the best of these models shows "age" as the most influential variable (14). This term en-

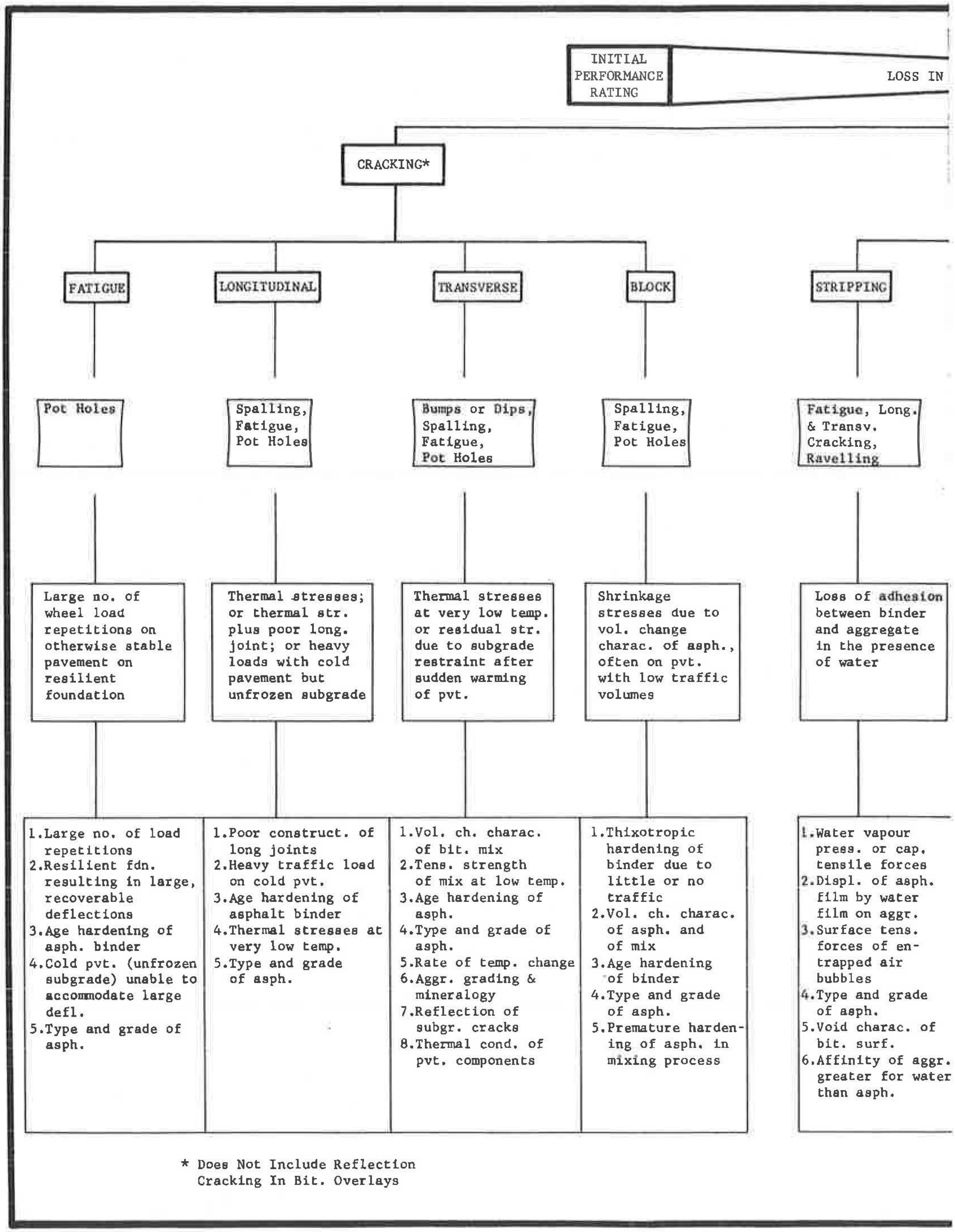
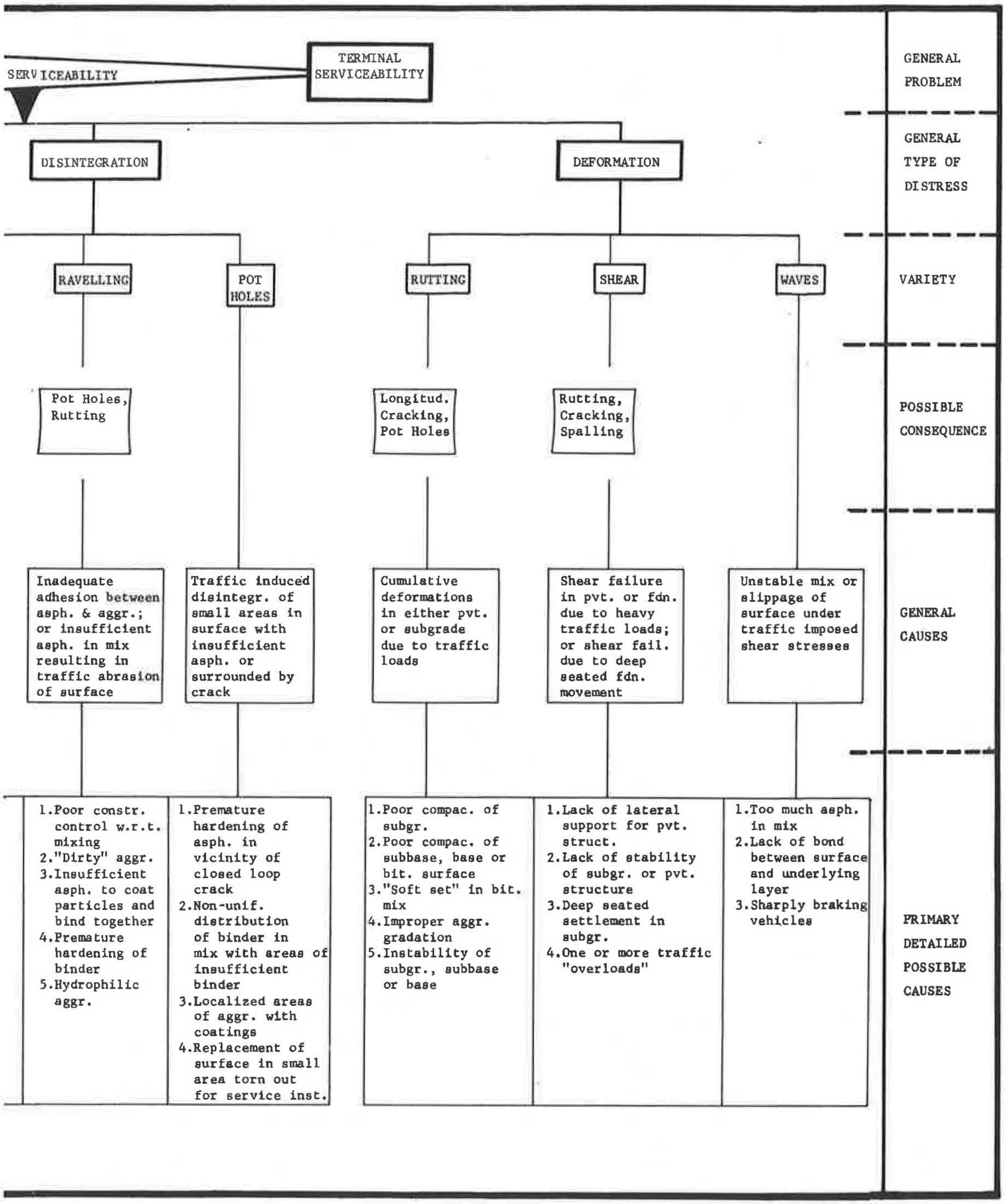


Figure 13. Qualitative representation of factors affecting flexible pavement performance.


SERVICEABILITY
TERMINAL SERVICEABILITY
DISINTEGRATION
DEFORMATION
RAVELLING
POT HOLES
RUTTING
SHEAR
WAVES
Pot Holes, Rutting
Longitud. Cracking, Pot Holes
Rutting, Cracking, Spalling
Inadequate adhesion between asph. & aggr.; or insufficient asph. in mix resulting in traffic abrasion of surface
Traffic induced disintegr. of small areas in surface with insufficient asph. or surrounded by crack
Cumulative deformations in either pvt. or subgrade due to traffic loads
Shear failure in pvt. or fdn. due to heavy traffic loads; or shear fail. due to deep seated fdn. movement
Unstable mix or slippage of surface under traffic imposed shear stresses
1.Poor constr. control w.r.t. mixing 2."Dirty" aggr. 3.Insufficient asph. to coat particles and bind together 4.Premature hardening of binder 5.Hydrophilic aggr.
1.Premature hardening of asph. in vicinity of closed loop crack 2.Non-unif. distribution of binder in mix with areas of insufficient binder 3.Localized areas of aggr. with coatings 4.Replacement of surface in small area torn out for service inst.
1.Poor compac. of subgr. 2.Poor compac. of subbase, base or bit. surface 3."Soft set" in bit. mix 4.Improper aggr. gradation 5.Instability of subgr., subbase or base
1.Lack of lateral support for pvt. struct. 2.Lack of stability of subgr. or pvt. structure 3.Deep seated settlement in subgr. 4.One or more traffic "overloads"
1.Too much asph. in mix 2.Lack of bond between surface and underlying layer 3.Sharply braking vehicles
GENERAL PROBLEM
GENERAL TYPE OF DISTRESS
VARIETY
POSSIBLE CONSEQUENCE
GENERAL CAUSES
PRIMARY DETAILED POSSIBLE CAUSES

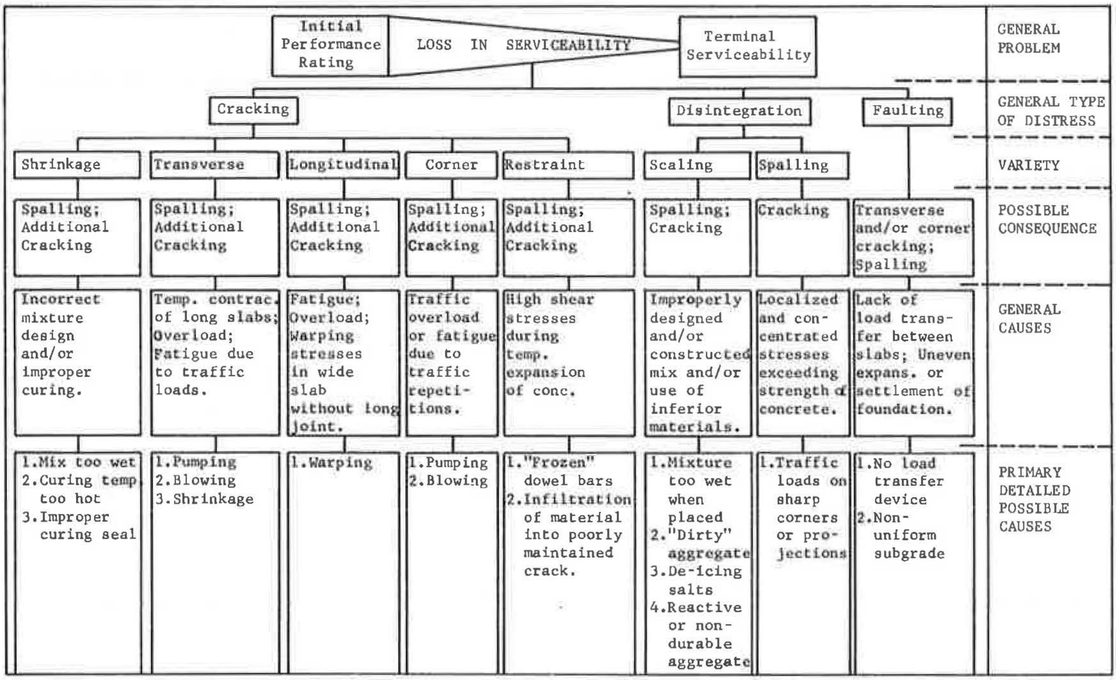


Figure 14. Qualitative representation of factors affecting rigid pavement performance.

compasses a number of the more detailed performance factors previously pointed out, which could ideally be incorporated into more precise predictive models if sufficient information were available.

The third broad step involved in progressing toward a comparative evaluation of all performance factors consists of investigating causal mechanisms of pavement distress. These investigations should be concerned with estimating the effects of various factors on the performance of the pavement structure, for a probable range of behavior. In addition, such investigations should be integrated with economic analyses of the potential payoff involved in being able to control any one factor. This type of approach can provide for optimum allocations of research and development funds. The current general situation of incomplete information makes such idealized comparisons impossible but in some cases allows the development of a sort of priority rating scheme based on subjective predictions of potential payoff. An example of this is the widespread incidence of transverse cracking of flexible pavements in Western Canada and the recent intensive research efforts in three prairie provinces (15, 16, 17, 18). Here, it was apparent that the secondary effects of transverse cracking were in many cases resulting in very rapid losses of serviceability for the pavements involved. It was further apparent that control of such deterioration could result in very substantial savings.

While the foregoing example is one in which large savings are possible without formal economic analysis of expected payoff, the probable payoffs on other performance factor evaluation and control are often not so apparent and require a greater degree of objectivity for rational decision-making. This includes the situation previously discussed where micro-climatic conditions control the performance of individual sections and data on certain factors in effect cannot be used by the designer.

New Pavement Strategies—The procedure previously described provides a basis for the analysis of those pavement strategies for which adequate performance information is available. The review of the information available in Ontario on the performance of

conventional flexible and rigid pavements indicated that this information was generally inadequate with the exception of a few environmental classes.

Two general classes of highway pavement have been identified in the Solution Generation phase. The basis for discrimination between these classes was stated to be the availability of performance data but a specified classification criterion was not established. Two additional procedures are required for the Solution Analysis phase. First, a rule must be developed that will permit a pavement to be classified as a standard pavement strategy or a new pavement strategy. Second, an overall framework is required that will permit new pavement strategies to be compared with standard pavement strategies in order to select the best course of action for a specific pavement design problem. A unified approach to both of these problems is developed in the following based on certain principles of Bayesian decision theory. The principles of Bayesian decision theory pertinent to this formulation have been reviewed by Hutchinson previously (19) and the following developments assume a knowledge of this information.

It has been pointed out that the failure age of the pavement strategy operating within a particular environmental class must be regarded as a random variable and this variable may be assumed to be normally distributed. In the procedure formulated for the selection of the optimum conventional flexible pavement design, it has been assumed that the expected or average value of the particular failure age distribution was adequate for analytical purposes. This is in fact an oversimplification, since the cost function is a nonlinear function of failure age.

The essential requirement involved in the analysis of new pavement strategies is to predict the failure age distribution, or the parameters of the distribution for the particular strategy. It is pertinent to consider in a general way how information on a new pavement strategy might be accumulated.

In the first instance preliminary laboratory tests and analysis may be performed to explore some of the implications of the new design but ultimately the probable failure age must be estimated from some very meager objective evidence or estimated subjectively. If the new design is judged to be superior when compared with the best standard design, then actual performance data can be accumulated with each successive implementation of the new design. Field performance meansurements involve the expenditure of significant amounts of resources and the problem is to establish the point at which the continued measurement of performance is no longer justified economically.

The essence of this problem when conveyed in terms of Bayesian decision principles can be conveyed in the form of a tree diagram as shown in Figure 15. The meanings of the symbols used are as follows:

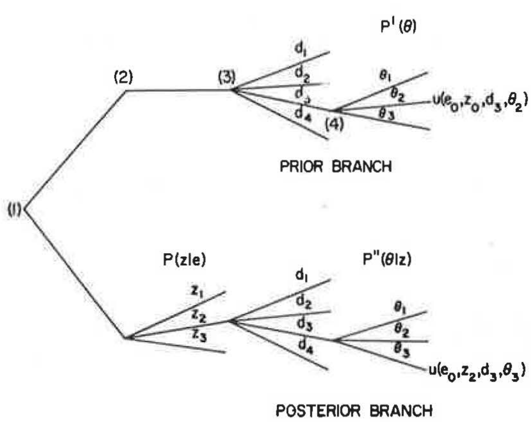


Figure 15. Simple decision tree.

d_0 = the decision to implement the new pavement strategy;

d_1 = the decision not to implement the new pavement strategy, which implies the use of the optimal pavement strategy;

θ = the state of nature that is a particular failure age;

e_0 = a dummy experiment, which conveys that no performance measurement is performed;

e_1 = performance measurement executed, which implies that the new pavement strategy should be implemented for trial;

z = the outcome of the new pavement strategy trial, which is its failure age;

u_t = the negative of the annual cost associated with the particular sequence of events expressed in the

brackets; e.g., $u_t(e_1, z_2, d_0, \theta_2)$ is the annual cost associated with the decision to measure first the performance, observe an outcome z_2 of this experiment, select a strategy d_0, and, finally, observe a failure age θ_2;

$P'(\theta)$ = the prior probability of occurrence of each possible failure age;

$P(z/e)$ = the probability of occurrence of each possible outcome of the experiment e;

$P''(\theta/z)$ = the posterior probability of occurrence of the failure age, given that the outcome of the experiment e is z; and

C_s = the negative of the annual cost of performance measurement.

The problem conveyed in Figure 15 can be described in general terms as follows. The designer is at node (1) and he must first decide whether to follow the prior branch and make an immediate choice between d_0 and d_1, or to postpone this choice by first implementing the new pavement strategy, measuring its performance, and on the basis of this new information making a choice between d_0 and d_1.

This type of problem can be approached by a method of analysis known as preposterior analysis, which is well described by Raiffa and Schlaifer (20). The essence of this method of analysis is that it provides a basis for evaluating the alternatives prior to actually implementing an experiment. The major features of this method of analysis are summarized in the following:

d' may be defined as the act that is optimal under the prior distribution of $\tilde{\theta}$:

$$E(\theta')\,[u_t(d', \theta)] \geq E(\theta')\,[u_t(d, \tilde{\theta})] \tag{3}$$

d_z may be defined as the act that is optimal under the posterior distribution of $\tilde{\theta}$, which has been determined by the outcome z of an experiment e:

$$E(\theta''|z)\,[u_t(d_z, \tilde{\theta})] = \max_d E(\theta''|z)\,[u_t(d, \tilde{\theta})] \tag{4}$$

If, instead of choosing the optimal prior act d' directly, the decision-maker performs an experiment e, observes an outcome z, and then chooses d_z he increases his terminal utility by

$$v_t(e, z) = E(\theta''|z)\,[u_t(d_z, \tilde{\theta})] - E(\theta''|z)\,[u_t(d', \tilde{\theta})] \tag{5}$$

$v_t(e, z)$ is termed the conditional value of the sample information z. Equation 5 can only be evaluated conditionally after a particular z has been observed. However, before z has been observed, the expected value of sample information can be computed from

$$v_t^*(e) = E(z|e)\,[v_t(e, \tilde{z})] \tag{6}$$

The economic significance of this quantity is that the expected terminal utility of a particular experiment is the expected utility of an immediate terminal action augmented by the expected value of sample information, which is

$$u_t^*(e) = u_t^*(e_0) + v_t^*(e) \tag{7}$$

The expected net gain of experimentation is defined as the expected value of sample information less the cost of obtaining it:

$$v^*(e) = v_t^*(e) - C_s \tag{8}$$

Analysis Process for New Pavement Strategies—These statistical decision principles can now be used to establish a systematic analysis process for new pavement strategies. This process is described as a sequence of steps:

1. List the expected annual cost of the optimal pavement strategy, AC_s.

2. List any observed failure ages for the new pavement strategy operating under the same environmental conditions and calculate the relative frequency of occurrence of each failure age. If prior evidence is not available, then these relative frequencies may be estimated subjectively.

3. Establish the cost function for the new pavement strategy in the form shown in Eq. 1. This is a straightforward procedure with the notable exception of the resurfacing costs expressed by the term E_1. This cost estimate must include not only the internal costs such as engineering and material costs but also the external costs to highway users that may result from the resurfacing operation. While the dollar value associated with these generally intangible costs is difficult to evaluate it is important that they be included in this manner in order to place the costs in their proper perspective. It is interesting to note certain comments by Moyer and Lampe (21) in this regard: ". . . in the selection of pavement type for urban freeways with traffic volumes ranging from 50,000 to 200,000 vehicles per day, portland cement concrete has generally been selected as the preferred pavement type in California because the traffic delays and accident hazards created by pavement repairs and resurfacing have been assumed to be much greater on asphalt concrete pavements than on portland cement concrete pavements. This study indicated that the magnitude and importance of the traffic delay and accident costs in the selection of pavement type for urban freeways has been greatly exaggerated. There is evident need for conducting factual studies to determine the true nature of these costs."

4. Calculate the expected value of sample information from

$$v_t^*(e) = E(z|e)\ \{E(\theta''|z)\ [u_t(d_z, \tilde{\theta})] - E(\theta''|z)\ [u_t(d', \tilde{\theta})]\} \tag{9}$$

5. If $v_t^*(e)$ is positive then the optimal prior act should be selected. (Remember that u_t is the negative of the annual cost.)

6. Calculate the annual cost of performance measurement and express it as C_s. If $v_t^*(e)$ is negative then execute performance if

$$|v_t^*(e)| \geq C_s \tag{10}$$

This implies that the new pavement strategy is selected for use even though it may not have been optimal with respect to immediate terminal action.

7. Calculate the expected utility of the new pavement strategy with respect to immediate terminal action:

$$u_t^*(e_0, d_0) = E(\theta''|z)\ [u_t(d_0, \theta)] \tag{12}$$

8. The new pavement strategy may be regarded as a standard pavement strategy if

$$u_t^*(e_0, d_0) \geq u_t^*(e, d_0) - C_s \tag{13}$$

Solution Evaluation and Optimization

At the completion of the solution analysis phase the pavement designer will have an estimate of the expected annual cost of each of the major types of pavement that he has considered. The objective of this phase is to explore the implications of the detailed design options that are possible within the most promising major design type.

This operation is particularly important for flexible pavements, in which equivalent strengths can be achieved by a large number of different combinations of layer thicknesses. The optimum combination is a function of the relative costs of the layer materials and their relative contributions to pavement strength.

For example, the layer equivalency equation developed at the AASHO Road Test (2) for flexible pavements,

$$D = 0.44D_1 + 0.14D_2 + 0.11D_3 \tag{14}$$

can be achieved by a large number of different combinations of layer thicknesses (subject to the constraints $D_1 \geq 2$ inches and $D_2 \geq 3$ inches). The optimum combination is a function of the relative cost of the layer materials and their relative contributions to pavement strength. If the cost data for each layer are given per inch of depth and per square yard of surface, and these might be, for example,

c_1 = \$0.50 per sq. yd. per inch of thickness,
c_2 = \$0.15 per sq. yd. per inch of thickness, and
c_3 = \$0.07 per sq. yd. per inch of thickness,

the total cost is given by

$$C = D_1 \cdot c_1 + D_2 \cdot c_2 + D_3 \cdot c_3$$

and the problem is to minimize C by selecting values for D_1, D_2, D_3 that will result in a specified thickness index D. This is a simple problem and may be solved by calculating the cost/contribution ratio for each layer:

layer 1: $\frac{0.50}{0.44} = 1.138$

layer 2: $\frac{0.15}{0.14} = 1.071$

layer 3: $\frac{0.07}{0.11} = 0.636$

Equation 14 demands that minimum thicknesses of 2 inches and 3 inches be used for the surface and base courses respectively. For the above conditions the remainder of the pavement should consist of layer 3 material since it possesses the minimum cost/contribution ratio.

More complex optimization techniques such as linear programming may be involved for other pavement types, such as rigid pavements, where various detailed design options may possess differential contributions to strength and relative costs.

Information Systems—The solution analysis phase of the systems process discussed in this paper is basically dependent on a certain amount of the appropriate evaluation data. Unfortunately, the required information systems are generally quite inadequate for the degree of sophistication we may desire for comparative analyses and in fact are in a very premature state of development, even for urban planning purposes. The first of these systems directly associated with the transportation field and using computer technology have come from the need to produce data for urban transportation planning models. However, as pointed out by Horwood (22), these have been generally ad hoc in nature and have been produced to satisfy their predominant purpose of traffic forecasting. Consequently, such approaches have produced very little "spin-off" in utilizing the information gathered for other purposes, largely because of the varied methods of organizing data and the attendant difficulties in processing. This type of situation applies to the field of highway pavements to an even greater degree but it appears that, because of the strong interest recently shown in development of urban data banks and the corresponding experience gained, plus the marked increases in computer operational capabilities, the development of highly flexible and sophisticated information systems for such purposes can soon become a distinct reality. It further appears that the professional groups charged with the attendant responsibilities must also be well versed in the statistical methodology of experimental design and analysis of variance and will provide a highly significant coordinating function within any one agency, such as a state or provincial highway department.

Before considering the basic requirements of an information system, it may be useful to list the major phases involved in considering the overall capability of such a system. In summary form these are

1. Proposed use of data,
2. Collecting the data,
3. Organizing the data,

4. Storing the data,
5. Retrieving the data, and
6. Analyzing the data.

When a decision has been made that some sort of automated storage and retrieval system is necessary for a highway agency to handle its planning, design, evaluation, cost, and maintenance data, then it immediately faces a series of basic questions which include the following:

1. What computer hardware equipment is required? This problem involves a variety of sub-problems and may in itself require a fairly detailed systems approach. It depends on such factors as the applicability and availability of the agency's current data-processing equipment, the quantity of information to be stored, the wide variety of available systems on the market, future requirements for data storage, software problems, available funds, availability of technical manpower, etc.
2. What purposes is the information to be used for? This is perhaps one of the most fundamental questions because it determines what data are to go into the system and what the analyses will be. If it is not adequately answered, the entire system can become most inefficient. In other words, as pointed out by Barraclough (23), a careful examination of the proposed use of each item of information must be made before a decision is reached to collect it.
3. What type of geocoding system is required? In the field of highway pavements, there can be little argument with the basic premise that some sort of locational identification of data is required. A number of systems are in current use or have been proposed for transportation planning, urban planning, and other purposes and have been discussed by Vance (24). His recommendation of the existing Universal Transverse Mercator Grid for use by transportation planners seems to be compatible with the highway pavement situation and the system could be used in a similar manner.
4. What type of query system is required? Querying refers to the techniques used to gain access to data in a variety of combinations, with efficiency. It is important that the system be developed for wide applicability and flexibility; otherwise each analysis will require its own specific retrieval technique. Horwood (22) has discussed the requirements of a good query system with respect to transportation planning and has stated, "A data handling procedure designed for ease of use is the single most important element of an information system." His comments are also significant to the data-programming requirements associated with the topic of this paper.
5. What type of output devices are required? Automatic graphic display of information is perhaps much more important to transportation and urban planning functions than to the highway pavement information system. However, a wide variety of relatively sophisticated graphic display subsystems are being developed and the possible applicability of these to producing plotted results of the stored data analyses warrants careful consideration.
6. What are the operational needs of the system? These requirements refer to day-to-day processing operations, production of output data at specific time intervals, generation of reports, and other functions.

The question of intended use of any item of stored data has been pointed out as fundamental to the problem of what data are to be stored. Barraclough (23) discusses some of the implications of either not getting required or sufficient data, or of getting unusable data, and goes on to present a long list of the sorts of items of information that might be desirable for land-use models. A similar listing for flexible pavement performance prediction models, with a sample in-depth listing of the transverse cracking factor (assuming that the appropriate objective measurement techniques have been developed) is presented, with the aid of Figure 13, for any particular evaluation section as follows:

1. Fatigue cracking
2. Longitudinal cracking
3. Transverse cracking (see detail)
4. Block cracking

5. Stripping disintegration
6. Raveling disintegration
7. Pot-hole disintegration
8. Rutting deformation
9. Shear deformation
10. Wave deformation
11. Gross pavement performance data
12. Traffic data
13. Environmental data
14. Construction data by variations in properties of as-placed specification items

    3a. Continuous temperature profile of pavement layer
    3b. Depth of frost penetration
    3c. Continuous precipitation record
    3d. Continuous recording strip to measure time of cracking
    3e. Continuously recorded stress and strain data
    3f. Void and density characteristics of the bituminous surface
    3g. Geotechnical characteristics of the subgrade
    3h. Volume, density, and moisture characteristics of the subgrade
    3i. Mineralogical characteristics of the pavement aggregates
    3j. Rheological characteristics of the binder at various age intervals
    3k. Rheological and tensile strength characteristics of the bituminous surfacing mixture at various age intervals
    3l. Rheological profile through the depth of the bituminous surface at various age intervals
    3m. Thermal conductivity and expansion-contraction characteristics of the bituminous surface
    3n. Amount of binder in the bituminous mixture
    3o. Gradation characteristics of the pavement aggregates
    3p. Source of binder for the bituminous surface mixture.

This in-depth listing could in some cases be further broken down into a number of sub-factors; in any case, it serves to illustrate the somewhat staggering array of information that might be collected. It further implies that an indiscriminate collection of such data would result in an information system of considerable complexity and great cost, in addition to the overwhelming efforts and costs associated with actually obtaining the required field and laboratory measurements. What is needed, then, is some sort of ordering system that establishes, say, first-order information, second-order information, and so on. The decision as to how specific items of data fit into the ordering system must be based on their relative influence on pavement performance. Such analyses of sensitivity, as previously discussed, depend on both technical and economic payoff considerations. Technical evaluations can often be very efficiently accomplished through carefully designed and controlled field experiments in which the pavement is a part of the regular highway system. An excellent example of this is the recent Saskatchewan field experiment on transverse cracking of flexible pavements in which it was concluded that asphalt source could significantly affect the degree of such cracking (17). Unfortunately, this type of planned experimentation has seen very limited use among highway agencies, although there are many situations where it could be employed to considerable advantage with very little additional expenditure during planning, design, construction, or operation.

Decisions as to what depth in the ordering system is to be used for data acquisition and storage depend on such factors as costs of obtaining the data, sensitivity of the model to the data, payoff involved in increased model sensitivity, and capability of the information system itself.

Implementation

A fundamental problem in the implementation phase of the highway pavement design process is to produce materials of a quality and homogeneity that are essentially in

agreement with the assumptions underlying the structural design of the pavement. The future performance of a pavement and its associated maintenance costs are directly related to the success in achieving these desired levels of quality.

Present quality control methods for highway paving materials are largely intuitive procedures conditioned by the construction engineers' experiences and the results of casual materials tests. In addition, the rationale underlying present highway materials specifications is largely arbitrary and frequently bears little relation to the actual capabilities of the various construction processes. Formal quality control procedures are required that are an integral part of the total highway pavement design process.

Very little systematic evidence has been obtained to illustrate the influence of the quality of construction on pavement performance. Wilkins (26) has shown for the Canadian pavement evaluation studies that minor areas of surface distress strongly influence the serviceability rating assigned to a pavement section. He has noted that if failure occurs in only 5 percent of a section the pavement is considered unacceptable as to serviceability and must be repaired or rehabilitated in spite of the fact that large areas of the pavement may have relatively high ratings. Economic implications of nonuniformity of construction indicate that the development of formal quality control procedures for construction probably has the greatest potential payoff of any area of the highway pavement design process.

SUMMARY AND CONCLUSIONS

The development of a rational highway pavement design process requires the ability to predict the pavement serviceability-age history of a potential highway pavement design under the expected traffic loadings, the climatic conditions, and the cost streams necessary to produce this serviceability profile. With the development of this capability the pavement designer is in a position to make a rational decision involving the selection of that design alternative which provides an adequate level of pavement serviceability throughout the design life and which is the most economic to construct and maintain.

Current approaches to pavement design do not formally recognize that a significant amount of physical deterioration can be tolerated in highway pavements and that this physical deterioration only has meaning with respect to the vehicles using a highway and their human occupants. In effect, they are oriented toward the concept of only satisfactory or unsatisfactory pavement performance.

Systematic field performance studies in Canada have indicated that pavements that are adequately proportioned to carry traffic loadings will deteriorate due to nonload associated factors. A quantitative understanding of the factors that induce this progressive deterioration in pavement serviceability is largely hindered by a lack of knowledge of the mechanics of pavement behavior.

A systems analysis of the highway pavement design process has been developed in this paper that attempts to recognize in a formal way both the technological and economic characteristics of highway pavements. The total process is broken down into its principal phases, which are problem definition, solution generation, solution analysis, evaluation and optimization, implementation, and performance assessment.

The current state of knowledge within each of these principal phases is reviewed and the relative importance of the deficiencies in knowledge discussed. The need for a properly designed data and retrieval system for field-performances studies is discussed and recommendations regarding such a system are set forth.

The primary deficiencies in current knowledge regarding pavement structures are considered to lie in the areas of field performance evaluation and quality control. In addition, the development of a comprehensive understanding of the nonload-associated causes of pavement deterioration and their relative effects on performance is essential to rationalizing the design process.

ACKNOWLEDGMENT

The studies on which this paper is based were supported by the National Research Council of Canada, the Ontario Department of Highways and the British American Research and Development Co.

REFERENCES

1. National Program of Research and Development in Highway Transportation. U.S. Bureau of Public Roads, Jan. 1967.
2. The AASHO Road Test: Report 5—Pavement Research. HRB Spec. Rept. 61E, 1962.
3. A Guide to the Structural Design of Flexible and Rigid Pavements in Canada. Canadian Good Roads Association, Sept. 1965.
4. Pavement Evaluation Studies in Canada. Proc. Internat. Conf. on Structural Design of Asphalt Pavements, Univ. of Michigan, 1962.
5. Field Performance Studies of Flexible Pavements in Canada. Proc. Internat. Conf. on Structural Design of Asphalt Pavements, Univ. of Michigan, 1967.
6. Hutchinson, B. G. Principles of Subjective Rating Scale Construction. Highway Research Record 46, p. 60-70, 1964.
7. Rogers, C. F., Cashell, H. D., and Irick, P. E. Nationwide Survey of Pavement Terminal Serviceability. Highway Research Record 42, p. 26-40, 1963.
8. Shields, B. P., and Dacyszyn, J. M. Seasonal Variations in Flexible Pavement Strength. Proc. Canadian Good Roads Association, 1965.
9. Alder, H. A. Economic Evaluation of Transport Projects. In Transport Investment and Economic Development (edited by G. Fromm). Brookings Institution, 1965.
10. Kuhn, T. E. Public Enterprise Economics and Transport Problems. Univ. of California Press, 1962.
11. Baldock, R. H. The Annual Cost of Highways. Highway Research Record 12, p. 91-111, 1963.
12. Hutchinson, B. G. The Use of Canadian Pavement Evaluation Data for Design. Proc. Canadian Good Roads Association, 1966.
13. Meyerhof, G. G. Preliminary Analysis of Benkelman Beam Deflections and Flexible Pavement Design. Proc. Canadian Good Roads Association, 1962.
14. Wilkins, E. B. Investigations of Pavement Design and Evaluation in Canada. Canadian Congress of Professional Engineers, Montreal, June 1967.
15. Shields, B. P., and Anderson, K. P. Some Aspects of Transverse Cracking in Asphalt Pavements. Proc. Canadian Tech. Asphalt Assoc., Vol. 9, 1964.
16. Anderson, K. O., Shields, B. P., and Dacyszyn, J. M. Cracking of Asphalt Pavements Due to Thermal Effects. Proc. AAPT, 1966.
17. Culley, R. W. Transverse Cracking of Flexible Pavements in Saskatchewan. Tech. Rept. 3, Sask. Dept. Highways, June 1966.
18. Highway Engineers Are Sorting Out the Variables in Asphalt Paving. Heavy Construction News, June 26, 1967.
19. Hutchinson, B. G. The Rationalization of Pavement Evaluation Decisions. Proc. Australian Road Research Board, 1966.
20. Raiffa, H., and Schlaifer, R. Applied Statistical Decision Theory. Harvard University Graduate School of Business Administration, 1961.
21. Moyer, R. A., and Lampe, J. E. A Study of Annual Costs of Flexible and Rigid Pavements for State Highways in California. Highway Research Record 77, p. 133-172, 1965.
22. Horwood, E. M. Urban Information Systems and Transportation Planning. Highway Research Record 194, p. 86-95, 1967.
23. Barraclough, R. E. Information for Land-Use Models. Highway Research Record 194, p. 1-14, 1967.
24. Vance, J. A. Geographical Data Coding Grid. Proc. Canadian Good Roads Association, 1966.
25. Hutchinson, B. G. The Measurement of Highway Pavement Performance. Proc. Internat. Conf. on Structural Design of Asphalt Pavements, Univ. of Michigan, 1967.
26. Wilkins, E. B. Effect of Strength Variations on Pavement Design. Proc. Canadian Good Roads Association, 1966.