GENERAL CONCEPTS OF SYSTEMS ANALYSIS AS APPLIED TO PAVEMENTS

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A pavement management system can incorporate a large number of activities in planning, design, construction, maintenance, evaluation, and research. Its principal purpose is to achieve the best possible use of available funds, consistent with providing safe and smooth pavements. Systems analysis methods can provide a means for the comprehensive and efficient handling of the various activities and for achieving the desired end result. This paper demonstrates that such systems methodology can be used to provide a framework for the pavement management activities as well as provide the techniques for developing actual working management systems. It describes the general nature and applicability of the systems methodology, and it defines the basic structure of a pavement management system. The various levels of management are indicated. Design, one of the major subsystems, is selected as an example of the more in-depth use that might be made of systems analysis methods. Particular consideration is given to the input information needs of the designer, the generation of alternative design strategies, the nature of the outputs, and the economic evaluation of the outputs for selecting an optimal strategy.

THE AMOUNT of new information and techniques available to the pavement field have ncreased most markedly during the past decade. Because of the difficulties associated vith properly assimilating, coordinating, and using all this new knowledge, attempts vere initiated about 8 years ago to apply the principles of systems engineering. These vere based on the premise that it was possible to develop a more efficient, unified, and omprehensive approach to the overall pavement management system and to its comonent subsystems.

A pavement management system includes the entire set of activities that go into the lanning, design, construction, maintenance, evaluation, and research of pavements. Vithin this general definition, any public agency has some such system, involving everal levels of management. However, these systems are often loosely coordinated nd inflexible, even though they may be relatively sophisticated in certain component ctivities. Moreover, they are often weak in areas such as economic evaluation.

The efforts at applying systems engineering to pavement management have been wofold: (a) developing a general framework or structure for all the activities involved in pavement management (1, 2, 3, 4, 5, 6) and (b) developing and implementing eal working systems within various public agencies (7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 7).

Some confusion and misunderstanding have arisen though in the application of these ystems principles, largely with respect to the jargon that has been used. The jargon as been somewhat detrimental to the real purpose of applying systems principles, that s, to make more efficient use of current knowledge and techniques and of new information as it becomes available. Systems engineering should facilitate the development f efficient, comprehensive, and economical practices; it should not impose any artiicial or restrictive conditions.

The general intent of this paper is to present the basic systems concepts that are ppropriate to the field of pavement management. More specifically, the objectives are

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ublication of this paper sponsored by Committee on Theory of Pavement Design.

1. To consider the general nature and applicability of systems engineering principles;
2. To define the basic structure of a pavement management system and, for illustrative purposes, of design, one of the principal subsystems; and
3. To discuss some of the key components of the design subsystem, particularly those relating to the generation of alternative design strategies and their economic evaluation.

GENERAL NATURE AND APPLICABILITY OF SYSTEMS METHODOLOGY

Nature of the Systems Method

Systems methodology comprises a body of knowledge that has been developed for the efficient planning, design, and implementation of new systems and for the structuring of the state of knowledge about an existing system or modeling of its operation. It is a comprehensive problem-solving process, and the framework that characterizes it has been formally developed in the postwar decade from observations of a large numbe of efficiently and systematically conducted projects (18).

There are 2 main identifiable aspects to the use of systems methodology (19):

1. The framing or structuring of a problem or body of knowledge and
2. The use of analytical tools for modeling and solving the problem.

These aspects are complementary and interrelated; one is insufficient without the othe The framing of a problem is usually too generalized by itself for achieving a useful operational solution, while the application of analytical techniques to an inadequately structured problem may result in an inappropriate solution (20).

Structure of the Systems Method

The structure or framework of any problem-solving process should provide for a systematic incorporation of all the technical, economic, social, and political factors of interest. Moreover, it should be a logical simulation of the progression of activities involved in efficiently solving a problem.

Figure 1 shows the major phases and components of such a process. In this general form, the process is applicable to a wide variety of problems. The recognition of a problem comes from some inadequacy or need in the environment. The definition of the problem involves an in-depth understanding that provides the basis for proposing alternative solutions. The alternatives are analyzed to predict their probable outputs or consequences, which are then evaluated so that an optimal solution can be chosen. The solution is implemented and operated, and checks are made on how well the system fulfills its function so that necessary improvements can be made. The process is continuous, iterative, and applicable to both overall problems and their components.

Some Basic Terminology

The systems terminology most often confused is that associated with the problem-definition phase. Inputs can be thought of as those factors that place some demand on the system (i.e., loads and stresses). They, together with the constraints, usually represent information that must be acquired. Objectives also represent necessary information, but usually must be developed or specified. Similarly, outputs and their values, functions used to combine them, and the decision rule used to choose the best solu tion must be developed, and these have been discussed in more detail, particularly wit respect to the highway and pavement field, in a number of sources (4, 5, 19, 21, 22, 23)

The system under consideration must be clearly recognized and identified; otherwise, there can be confusion in determining the inputs and in specifying the applicable objectives and constraints. For example, consider the frequently used term "pavement system." It is sometimes unclear whether the actual physical structure, the design method, the construction or maintenance policies, or some combination of the foregoing are being considered.

BASIC COMPONENTS OF A PAVEMENT MANAGEMENT SYSTEM

Definition and Structure of the System

The definition of a pavement management system as consisting of a comprehensive, coordinated set of activities used in the planning, design, construction, maintenance, evaluation, and research of pavements is shown conceptually in Figure 2. It shows the logical sequence of activities that would be used by an agency in providing pavements. This is a broad, encompassing framework that allows for considerable variation of models and details within each major phase or subsystem. The activities shown incorporate a number of levels of management. For example, planning activities might be primarily concerned with investment decisions and programming on a network basis, while design or construction activities might be primarily concerned with management at the project level.

Major Subsystems

The 6 major subsystems—planning, design, construction, maintenance, pavement evaluation, and research—are directly related to each other, and any one can be of major importance in a given situation. Each subsystem incorporates a variety of major and minor problems that are amenable to being structured and solved within the framework shown in Figure 1.

Planning involves assessment of deficiencies or improvement needs on a network basis, establishment of priorities for eliminating or minimizing these deficiencies, and development of a scheduled program and budget for carrying out the needed work.

Design involves acquisition or specification of a variety of input information, generation of alternative design strategies, analysis of these alternatives, and evaluation and optimization to select the best strategy. Both the usual operational extent of the design subsystem and its relation to all other subsystems of the pavement management system are shown in Figure 2.

Construction translates a design recommendation into a physical reality. Its major activities include detailing of specifications and contract documents, scheduling, construction operations, quality control, and acquisition and processing of data for transmittal to the data bank.

Maintenance includes establishment of a program and schedule of repair or rehabilitation work, implementation of the program, and acquisition and processing of data for transmittal to the data bank.

Pavement evaluation includes establishment of control or evaluation sections; periodic measurement of pavement characteristics such as structural capacity, roughness, distress, and skid resistance; and transmittal of data to the data bank. The acquired data can be used for (a) checking the adequacy with which the pavement is fulfilling its intended function, (b) planning and programming future rehabilitation needs, and (c) improving the technology of design, construction, and maintenance (24).

Research depends on the resources and requirements of the particular agency involved. Research activities can be initiated from problems arising in the planning, design, construction, or maintenance phases, and they usually make extensive use of the information acquired in the evaluation phase. In fact, evaluation itself can be considered as research.

The data bank is separately shown to emphasize its role in centrally coordinating data from all the pavement activities and in serving as an information base for analyses of the effectiveness of these activities. Data banks can range from simple manual record files to sophisticated, computerized systems (25).

Major Pavement Outputs

The major outputs of a pavement must be defined so that what the various pavement management activities are trying to achieve as an end product is clearly recognized. A major task in the design phase is to predict these outputs (i.e., the analysis of the alternative design strategies, as shown in Fig. 2). They are then actually measured in the evaluation phase, after the pavement has been constructed and is serving traffic.

Figure 1. Phases and components of systems method.

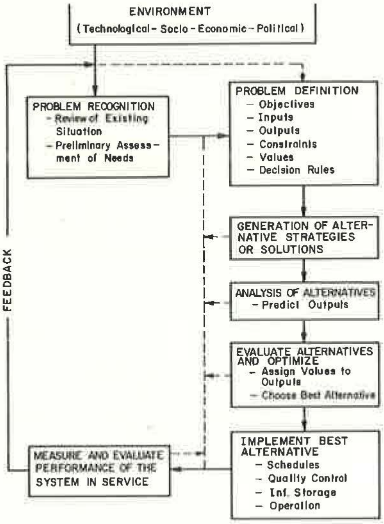


Figure 2. Classes of activities in pavement management system.

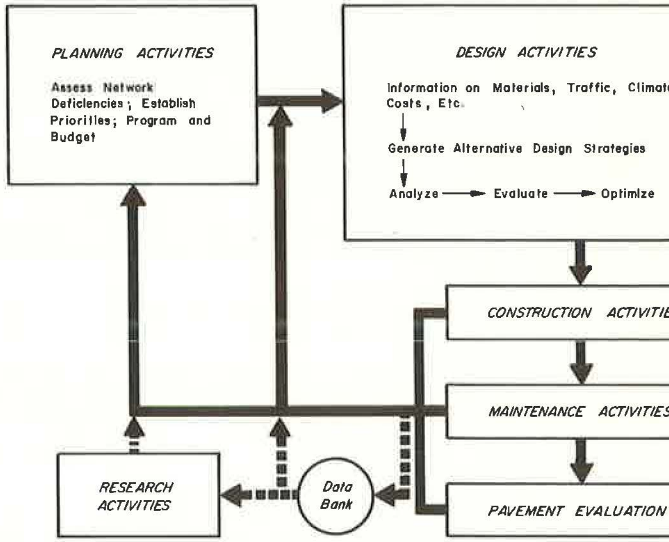
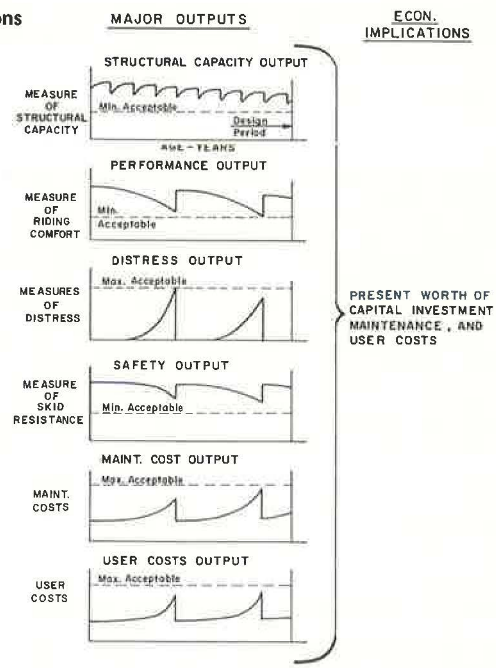


Figure 3. Outputs and associated value implications of typical pavement during design period.



The major outputs of a pavement, any of which can reach a limit of acceptability during the design period, are shown in Figure 3. The economic implications of these outputs can be in terms of the present worth of capital investment, maintenance, and user costs.

DESIGN SUBSYSTEMS

Pavement Design Framework

Many methods are available for designing pavements. Any particular methodology will differ to some degree from any other but still have some features in common. In other words, there is an identifiable framework that characterizes all pavement design methods. Figure 4 shows such a framework that classifies the major design activities or components according to the levels of (a) information needs such as inputs, (b) alternative strategies or solutions, and (c) analysis, economic evaluation, and optimization.

Information Needs of the Designer

The top row in Figure 4 shows the information and tools required in design to generate alternative design strategies. Data on available materials, expected traffic, and climatic factors are often the first information items acquired. Any design method that includes materials characterization uses these data as a basis for establishing a range of loads and environment for testing purposes and might also use the data in both proposals and analyses of alternative design strategies.

The selection of a design period is only implicitly included in some methods. Other design methods might explicitly select a design period, say, 25 years, during which alternatives are compared. Without a consistent analysis period, the economic comparison of alternatives cannot be properly done.

The structural model available for design might be simple in concept, such as a limiting strength value or an empirical index value. Or the model might be comparatively complex and use layer theory.

Economic models also vary by method in complexity. A straightforward estimate of initial capital costs of construction or a net present value model that incorporates present and future costs and benefits may be used.

Few design methods use available construction variance data and maintenance variance data in other than a subjective manner. The designs proposed or the design charts that are used might inherently include the effects of expected variances in construction through conservative or overdesigned pavement thicknesses. A better approach is one that explicitly uses construction and maintenance variance data in a probabilistic manner to establish measures of reliability for the various design alternatives. Such stochastic applications to the pavement field are expected to have more widespread use in the future.

The objectives that are set for design should be related to performance, distress, safety, and economy requirements. Many design methods only include objectives on an implicit basis.

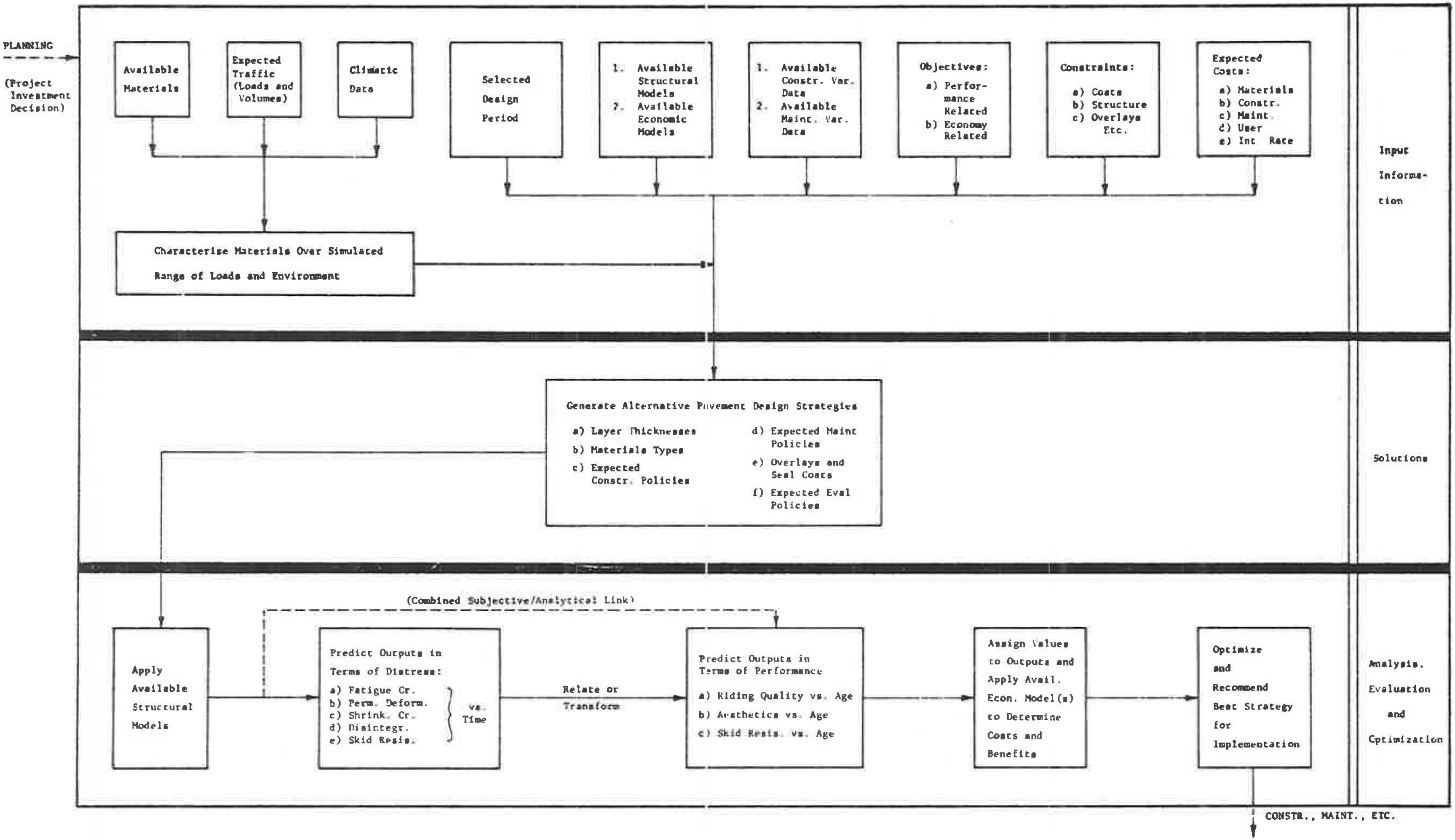
Constraints either on a design method per se or on the designs produced by that method are usually more explicitly stated. For example, there may be a limit on costs, a minimum time to the first overlay, a minimum thickness of pavement, and so on.

Expected costs are vital design information. Among the cost categories, both present and future, are materials, construction, maintenance, user, and interest rate.

Generating Alternative Pavement Design Strategies

The generation of alternative pavement design strategies is shown along the middle row in Figure 4. The word strategies is used to emphasize that a design alternative should consist of not just pavement layer thicknesses but also material types and the specification (or at least the assumption) of expected construction, maintenance, overlay (or other types of rehabilitation), and performance evaluation policies. The need for a design alternative to specify material types and layer thicknesses is apparent.

Figure 4. Pavement design activities.



However, unless construction and maintenance policies are included, the outputs subsequently predicted for that pavement structure may have appreciable error.

Overlays, seal coats, or other rehabilitation also becomes a part of any design strategy if one or more of the pavement outputs (as shown in Fig. 3) drops to the minimum acceptable level before the end of the design period. The exception is a maintenance policy that keeps the pavement at or about the minimum acceptable level of serviceability to the end of the design period. Alternatively, if financial constraints prevail, maintenance at this level might continue only until funds were available for rehabilitation.

In the formulation of rehabilitation alternatives, there are 2 major, interrelated aspects that the designer should consider:

1. Structural aspects, with respect to providing measures that deal with excessive distress, lack of adequate serviceability, lack of adequate safety, and so on; and
2. Policy aspects, with respect to traffic handling and time of day and season of the rehabilitation measure.

The method of handling traffic is a most important consideration because it can markedly affect user delay costs and, therefore, the rehabilitation alternative that is eventually chosen after the analysis and evaluation have been completed.

As a part of a design strategy, the specification of a policy for performance evaluation of a pavement throughout the design period might be considered unusual in conventional pavement design methodology. However, because the feedback information provided in pavement evaluation is primarily directed toward planning and design needs, the designer should have a key interest in pavement evaluation policies. For example, suppose that a highway agency conducts roughness measurements every 3 years on its secondary road network. The data, along with other periodic evaluation data, are stored in a data bank. Thus, the designer knows or is in a position to expect that he or she will have certain periodic information on the behavior and performance of any particular project and can use this to monitor design predictions.

These expected evaluation policies should be communicated to those responsible for actually conducting the evaluation throughout the analysis period. In this way, any changes in policies can be communicated to the designer.

The foregoing components of a design strategy demonstrate that a number of potential alternatives are available for any particular design problem. To analyze and evaluate all these alternatives and to generate all of them in the first place require a computerized process that combines solution generation with analysis and evaluation. This is the approach used in some of the new working design systems, such as that used in Texas (7, 8, 9, 10). Figure 5 shows the components of an alternative pavement design strategy and the large number of possible alternatives that might be considered.

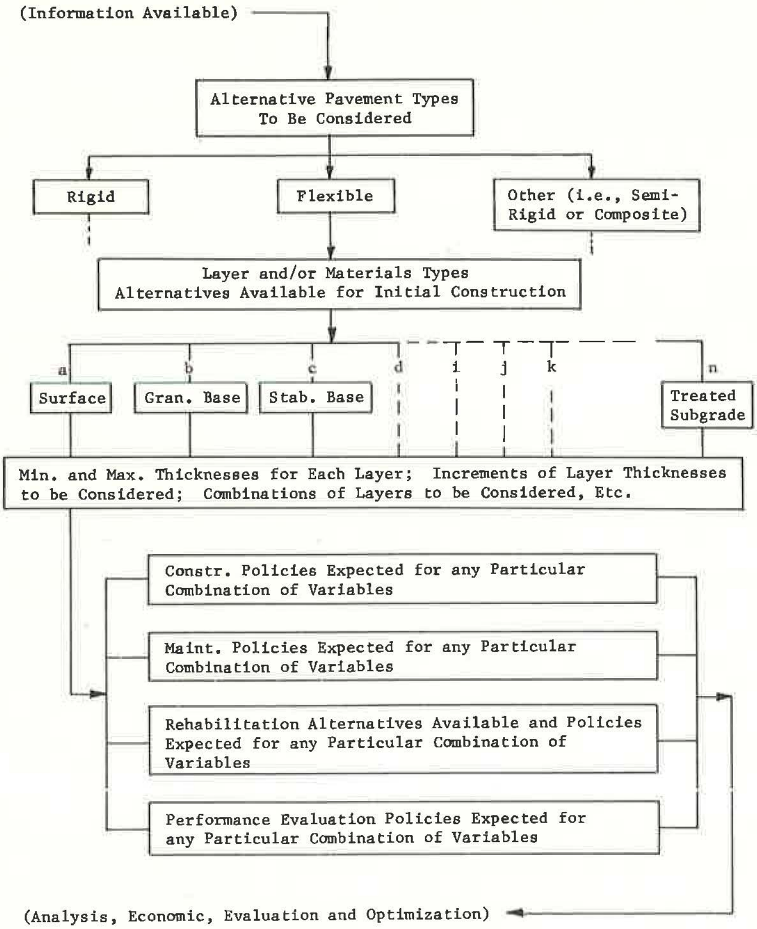
Analysis, Economic Evaluation, and Optimization

The bottom row of Figure 4 shows the main component activities that would ideally be involved in the analysis, evaluation, and optimization of the various alternative design strategies. Most design methods do not include all of these activities; however, design methodology in general appears to be moving toward this more idealized form.

The first major step in the analysis of any pavement design alternative is the application of the available structural models. If they are sufficiently comprehensive, they would be used first to predict the outputs of that alternative in physical terms, i.e., the distress that is expected to occur during the design period. The major distress modes are shown as fatigue cracking, permanent deformation, shrinkage cracking, disintegration, and loss of skid resistance.

The current state of technology cannot adquately predict both the type and the degree of all these forms of distress as a function of time or traffic. Consequently, several structural models used today attempt to make a direct prediction of outputs in terms of serviceability versus age. This approach is shown by the dashed line in Figure 4 noted as a combined subjective/analytical link. The terms are used to indicate that some methods might make only a subjective estimate of the serviceability-age relation or just an estimate of service life based on experience.

Figure 5. Components of generating alternative pavement design strategies.



The complete transformation of the predicted distress outputs to performance-related outputs (i.e., serviceability versus age) is not possible with current technology. Development of the necessary transformations has been defined as a first priority research need by a group of pavement experts (26).

The economic evaluation of an alternative pavement design strategy, as shown in Figure 4, should first involve the assignment of costs and benefits to the predicted outputs. These are then incorporated in some economic model to determine total costs and benefits, or "value." The assignment of benefits is included as an idealization because this is a relatively undeveloped aspect of pavement design technology, except for some recent work by McFarland (27).

When all the alternative strategies have been analyzed and evaluated, an optimization is conducted to select the best strategy. This is a task in most methods that simply involves the choice of that alternative with the least total cost. The recommendation of the optimal strategy for implementation completes the design task.

Some Further Comments on Economic Evaluation

Existing practice in the pavement field is restricted to a consideration of only capital, maintenance, and engineering costs. The implied assumption is that user costs do not vary with level of serviceability, condition, extent and time of rehabilitation, extent and timing of maintenance, and so on. However, as demonstrated by McFarland (27), user costs can vary significantly with these factors. Cost reductions can be considered as savings or benefits (28), and thus the economic evaluation of pavements should consider both benefits and costs.

The major initial and recurring cost factors that should be considered during the analysis period include materials, supply, and processing; construction costs; maintenance costs; cost of investment in materials, construction, maintenance—i.e., the interest (28); engineering and administrative costs; vehicle operating costs; user travel time costs; accident costs; and discomfort costs. The first 5 factors relate to the public agency that provides the pavement, and the last 4 relate to the user.

The economic models that can be used to incorporate costs, or costs and benefits, include equivalent uniform annual cost method; present worth method for costs or benefits or net worth of benefits minus costs (i.e., the net present worth method); rate-of-return method; benefit-cost ratio method; and cost-effectiveness method. These methods have the common feature of being able to consider future streams of costs, or of costs and benefits (i.e., present worth, rate-of-return, and benefit-cost methods), so that alternative investments may be compared. Differences in the worth of money over time, as reflected in the compound interest equations used, provide the means for such comparisons.

The present worth method is widely used in the transport field and is the method most applicable to the pavement sector. For costs alone, the following equation can be used:

$$TPWC_{x_1,n} = (ICC)_{x_1} + \sum_{t=0}^{t=n} pwf_{i,t} \left[(CC)_{x_1,t} + (MO)_{x_1,t} + (VC)_{x_1,t}\right] - (SV)_{x_1,n}\, pwf_{i,n} \qquad (1)$$

where

$TPWC_{x_1,n}$ = total present worth of costs for alternative x_1 for an analysis period of n years;
$(ICC)_{x_1}$ = initial capital costs of x_1;
$(CC)_{x_1,t}$ = capital costs of x_1 in year t;
$pwf_{i,t}$ = present worth factor for discount rate i for t years = $1/(1 + i)^t$;
$(MO)_{x_1,t}$ = maintenance plus operation costs for x_1 in year t;
$(VC)_{x_1,t}$ = user costs (including vehicle operation plus travel time, accidents, and discomfort if designated) for x_1 in year t; and

$(SV)_{x_1, n}$ = salvage value, if any and if included, for x_1 at the end of the analysis period, n years.

The present worth of benefits can be calculated in the same manner as the present worth of costs by the following equation:

$$TPWB_{x_1, n} = \sum_{t=0}^{n} pwf_{i,t} \left[(DUB)_{x_1, t} + (IUB)_{x_1, t} + (NUB)_{x_1, t} \right] \qquad (2)$$

where

$TPWB_{x_1, n}$ = total present worth of benefits for alternative x_1 for an analysis period of n years;
$(DUB)_{x_1, t}$ = direct user benefits accruing from x_1 in year t;
$(IUB)_{x_1, t}$ = indirect user benefits accruing from x_1 in year t; and
$(NUB)_{x_1, t}$ = nonuser benefits accruing from x_1 in year t.

The indirect and nonuser benefits are difficult to measure for pavements. Consequently, it is reasonable to consider only direct user benefits within the current state of technology.

The net present value can simply be calculated as the difference between Eqs. 2 and 1. Obviously, benefits must exceed costs if a project is to be justified on economic grounds. For an alternative pavement design, x_1, the net present value calculation is not applicable to x_1 itself but rather to the difference between it and some other suitable alternative, say, x_0. Direct user benefits are calculated as the user savings (due to lower vehicle operating costs, lower travel time costs, lower accident costs, and lower discomfort costs) realized by x_1 over x_0.

Thus, the net present value method is applied to pavements on the basis of project comparison, where the alternatives are mutually exclusive. When an alternative is evaluated, it needs to be compared not only with some standard or base alternative but also with all the other alternatives. The equation form of the net present value method for pavements may then be expressed as follows:

$$NPV_{x_1} = TPWC_{x_0, n} - TPWC_{x_1, n} \qquad (3)$$

where

NPV_{x_1} = net present value of alternative x_1 for an analysis period of n years;
$TPWC_{x_0, n}$ = total present worth of costs for alternative x_0 (where x_0 can be the standard or base alternative, or any other feasible mutually exclusive alternative) for an analysis period of n years; and
$TPWC_{x_1, n}$ = definition given for Eq. 1.

CONCLUSIONS

1. A pavement management system includes activities related to the planning, design, construction, maintenance, performance evaluation, and research of pavements.
2. Systems engineering methodology can be used to provide the framework for a pavement management system and to develop real working systems.
3. The design subsystem of pavement management can be represented for all particular methods used by various agencies in terms of (a) information needs and available techniques of the designer; (b) generation of alternative design strategies; and (c) analysis, economic evaluation, and optimization of these strategies.

ACKNOWLEDGMENTS

This paper is based on various research funded primarily by Gulf Oil Canada, Ltd., the National Research Council of Canada, and the Ontario Ministry of Transportation and Communications. Various activities of the Pavement Management Committee of the Roads and Transportation Association of Canada also provide a basis for this paper.

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DISCUSSION

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The application of systems analysis concepts to the general problem of pavement design provides increased efficiency and thoroughness not previously available to the pavement designer. An excellent review of recent efforts in this area is given by Haas Noticeably lacking from attempts to define pavement design systems and their necessa inputs and outputs however is a consideration of nonuser costs. The extent to which nonuser costs will affect pavement design strategies is difficult to estimate because of the scarcity of relevant data.

A qualitative understanding of the potential impact of nonuser costs on the systems analysis of pavement design may be obtained by considering the problem of skidding ac cident reduction. To reduce the frequency of skidding accidents, certain pavement site are selected for resurfacing, grooving, alternative traffic control, and application of other skidding accident countermeasures to selectively reduce frictional demand or increase frictional availability or do both (29). Such measures may entail nonuser effects such as pollution, resource availability, and distribution of costs among users and nonusers.

The effect of pollution may be visualized if one imagines that the speed limit of a section of highway with a high skidding accident potential is lowered to reduce friction demand. If the lowering results in a new mean traffic speed that increases localized concentrations of hydrocarbons or nitrous oxides, then nonusers near such concentrations (pedestrians or possibly homeowners) experience a disbenefit, and a nonuser cost must be assigned. A similar situation arises when traffic control techniques are employed to alter vehicle driving patterns. The changed acceleration patterns are likely to be associated with increased vehicle exhaust emissions (30). Probably of much greater significance than the air pollution consideration is that of noise pollution by grooved and highly textured sections of highway (31). Clearly this noise pollution is a disbenefit, and a complete accounting demands that it be assigned a nonuser cost.

The second category of effects, resource availability, refers to the potential for increased or altered fuel and construction material consumption patterns, which may affect local availability of resources. Added traffic controls to reduce friction demand, for instance, may increase fuel consumption per vehicle to the extent that such increases, when summed over a calendar year (or longer), represent very sizable quantities. These quantities must be considered in light of what will very likely be a multiplicity of sites with increased traffic controls throughout the nation. (The Federa Highway Administration is likely to formulate the research results of its Skid Accident Reduction Program into guidelines for state highway departments.) Similarly, resurfacing to increase friction availability may unnecessarily strain supplies of constructio materials needed either in other highway projects or in nonhighway projects.

The third category, distribution of costs, is concerned with the observed imbalance in nonuser and user cost burdens for highway facilities in certain locations and under certain conditions (32). Major emphasis projects to reduce skidding accidents may accentuate existing cost imbalances or create new ones.

Thus the equation proposed by Haas for the total present worth function may be altered to read

$$TPWC_{x_1,n} = (ICC)_{x_1} + \sum_{t=0}^{t=m} pwf_{1,t} \left[(CC)_{x_1,t} + (MO)_{x_1,t} + (VC)_{x_1,t} + (NUC)_{x_1,t} \right] - (SV)_{x_1,n}\, pwf_{1,n} \quad (4)$$

where

$TPWC_{x_1, n}$ = total present worth of costs for alternative x_1 for an analysis period of n years;
$(ICC)_{x_1}$ = initial capital costs of x_1;
$(CC)_{x_1, t}$ = capital costs of x_1 in year t;
$pwf_{i, t}$ = present worth factor for a discount rate i for t years = $1/(1 + i)^t$;
$(MO)_{x_1, t}$ = maintenance plus operation costs for x_1 in year t;
$(VC)_{x_1, t}$ = user costs for x_1 in year t;
$(NUC)_{x_1, t}$ = nonuser costs for x_1 in year t; and
$(SV)_{x_1, n}$ = salvage value for x_1 at end of n years.

At first glance the example given above and pavement design in general seem to be naturally separated from the larger problem of highway right-of-way selection. That the 2 processes, pavement design and right-of-way selection, are related and must be conducted together is well illustrated by the problem of traffic-induced vibrations. Such vibrations are dependent on traffic mix, mean traffic speed, roadway surface texture, and the undulatory character of the roadway surface. The surface dependencies allow us to continue our consideration of skidding accident reduction effects since many of the various strategies for increasing friction availability entail surface texture changes. (The comments that follow, however, are independent of friction availability and demand issues.) The impact of vibrations on nonusers depends on the properties of the soil through which the vibrations are propagated and on the type of structures receiving vibrations (and their frequency of occurrence and distribution). Consideration must therefore be given to the type of pavement used as a function of soil type and structure type, i.e., as a function of right-of-way. Conversely, the right-of-way selection process must give consideration to the effect of pavement designs on vibration attenuation and propagation.

It is evident that the problem of pavement design is a multiobjective problem. Consideration of nonuser costs implies that there is an objective beyond maximum pavement longevity, maximum safety, or the like. That implied objective is in its broadest sense the maximizing of social welfare. The important point to be made is that even in the design of systems that are in reality microcosms of larger public investments nonuser costs require consideration to avoid localized inequities.

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