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FOREWORD

All but one of the papers included in this RECORD were prepared for a Symposium on Pavement Design and Management Systems. The symposium was designed to present actual cases of the application of pavement design and management systems by highway agencies. The purpose was to demonstrate that systems concepts can be applied to pavement design. Both expected advantages and difficulties encountered in implementing systems concepts are covered by the authors. A short summary of the symposium and a review of the papers are included.

The last paper, by Creech and Runkle, was not presented at the symposium, but is pertinent to the subject and should be of interest to readers.

—James F. Shook

SUMMARY OF SYMPOSIUM ON PAVEMENT DESIGN AND MANAGEMENT SYSTEMS

W. R. Hudson, University of Texas at Austin

During the 1974 meeting of the Transportation Research Board, a Symposium on Pavement Design and Management Systems was held. The symposium was sponsored by the Committee on Theory of Pavement Design and was chaired by William Gartner, Jr., who asked in his opening remarks, "Do you have the data needed to use the pavement management system?" It seems to me that the question should be, What factors really affect the performance of pavements? If a variable affects pavement performance, then it is essential that we obtain the necessary data to consider its effect in he design, construction, and maintenance of pavements. Even if we have to estimate he factor, we can still consider its effect on pavement performance and costs in some way.

A great deal of money is expended each year in pavement construction, maintenance, and research. The problems considered are not simple; neither are the answers.

Since the symposium, many new questions have been raised concerning pavement design and maintenance.

1. What effect will reduction in speed limits have on pavement maintenance? Can we accept a lower level of serviceability than we needed at a higher speed limit?
2. What effect on pavements will an increase in vehicle load have? (This has been proposed to increase fuel efficiency.)
3. What effect will increased asphalt costs have on pavement design, selection of materials, and overall pavement economy? (Costs have doubled or tripled within a 3-month period.)
4. In a staged-construction project for which there is no more money because of nflation, what will happen if the next surface increment is delayed by 1 year?

These questions cannot be answered by pavement design methods that involve only strength, thickness, and load. However, they can be treated by the pavement management systems outlined by speakers at the symposium. The 6 papers presented appear n this report and are briefly summarized in the following paragraphs.

Haas presents some terminology and general descriptions of systems analysis and pavement systems methodology. He points out that the pavement management system s a consistent methodology for considering design, planning, economics, construction, maintenance, rehabilitation, and salvage of a pavement.

Lewis reports on an operational pavement management system used by the Texas Highway Department. A flexible pavement management system is in use in 10 of the 25 Texas districts. Each district is semiautonomous and makes its own decisions on ype of pavement methodology to be used. Lewis points out the importance of involving he user of the pavement management system in the development and implementation of he method. The use of the design method or management system in Texas grows each month.

Peterson reports on a pavement evaluation method that the Utah State Department of Highways uses for planning, programming, budgeting, and redesign of pavement systems. He outlines a broad measurements program that is used to evaluate pavements and to predict their remaining life. He also outlines the pavement management informa-

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

tion system that is being developed to handle data and analysis. These data include serviceability, skid resistance, surface condition, and deflection or structural conditi

Phang discusses the complexity of providing good pavements in Ontario. The numb of steps, decisions, and people involved is large. He points out the need for a paveme data system and explains that their pavement design methodologies are being codified into a pavement management system.

That data are important is illustrated by the fact that many states already invest a great deal of energy and effort in data collection. For example, no highway departme works without traffic and load information. They also have road inventory and life fil cost files, and maintenance information. Data available from the weather bureau are also used. All that is necessary is to coordinate these data coherently into a pavemen feedback or pavement management data system.

McMahon describes the improved structural analysis subsystem being developed by the Federal Highway Administration. He discusses some of the damage problems tha are currently affecting pavements and describes the FHWA design check procedure. This procedure examines viscoelastic material parameters, if they are necessary.

Lytton reports on the implementation of the Systems Analysis Method for Pavemen (SAMP) developed under the National Cooperative Highway Research Program. He di cusses specifically the implementation of SAMP-6 and points out that it can be improv and upgraded. SAMP-5 was upgraded to SAMP-6, and subsequent improvements will perhaps result in SAMP-7, and so on.

Pavements are complex physical systems, but they are essential to transportation. This symposium showed that a rational methodology of systems analysis exists and ca help to solve the pavement design and management problems.

The management system requires experience, knowledge, data, and most importa educated people. People have to develop it, provide the data for it, and finally use it. During the symposium, no one said that the computer designed the pavement. Far from it, the computer is a tool that only codifies and analyzes data. The pavemen designer or the administrator makes the final decision. The pavement management system merely collects and codifies the information to provide the designer and the administrator with the most objective information possible for their use.

GENERAL CONCEPTS OF SYSTEMS ANALYSIS AS APPLIED TO PAVEMENTS

Ralph Haas, University of Waterloo, Ontario

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 increased most markedly during the past decade. Because of the difficulties associated with properly assimilating, coordinating, and using all this new knowledge, attempts were initiated about 8 years ago to apply the principles of systems engineering. These were based on the premise that it was possible to develop a more efficient, unified, and comprehensive approach to the overall pavement management system and to its component subsystems.

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

The efforts at applying systems engineering to pavement management have been twofold: (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 real working systems within various public agencies (7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17).

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

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

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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.

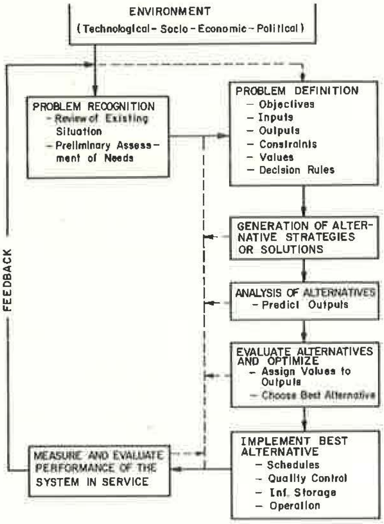


Figure 2. Classes of activities in pavement management system.

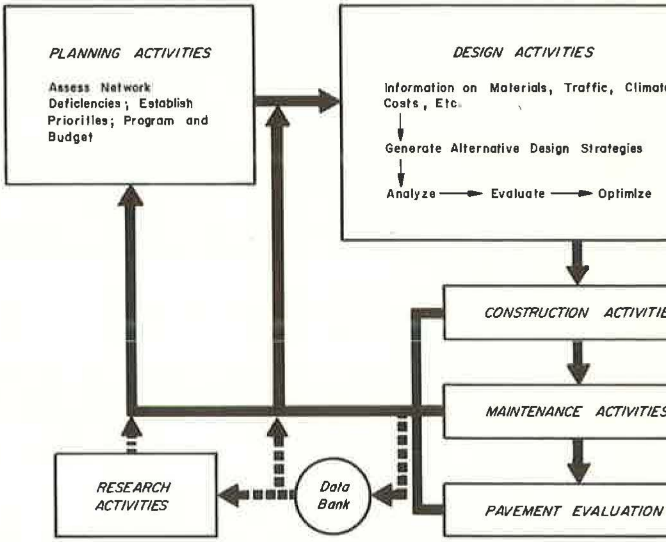
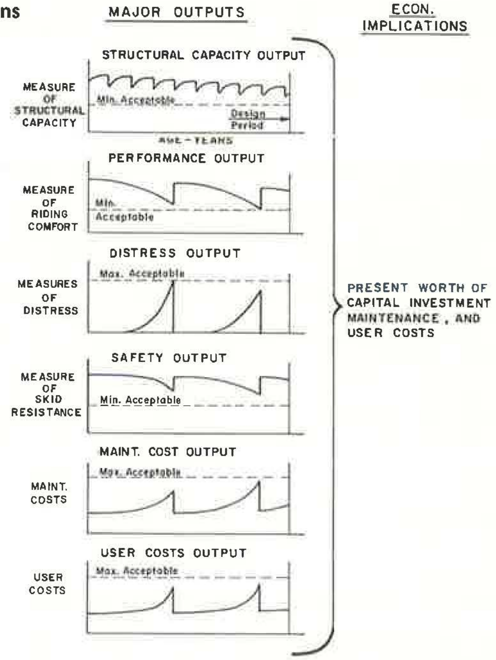


Figure 3. Outputs and associated value implications of typical pavement during design period.



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.

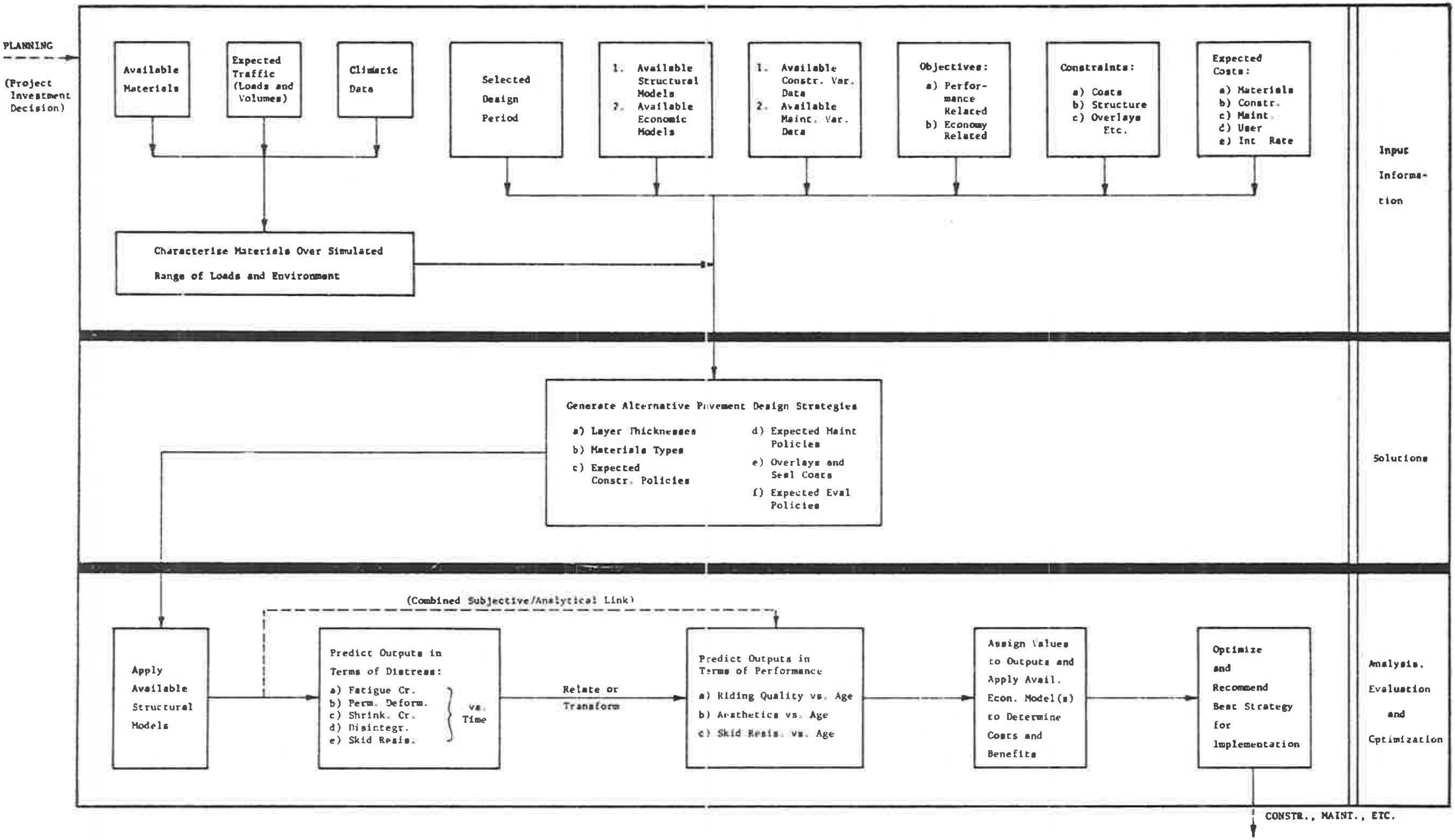
Constraints either on a design method per se or on the designs produced by that method are usually more explicitly stated. For example, there may be a limit on costs, a minimum time to the first overlay, a minimum thickness of pavement, and so on.

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.

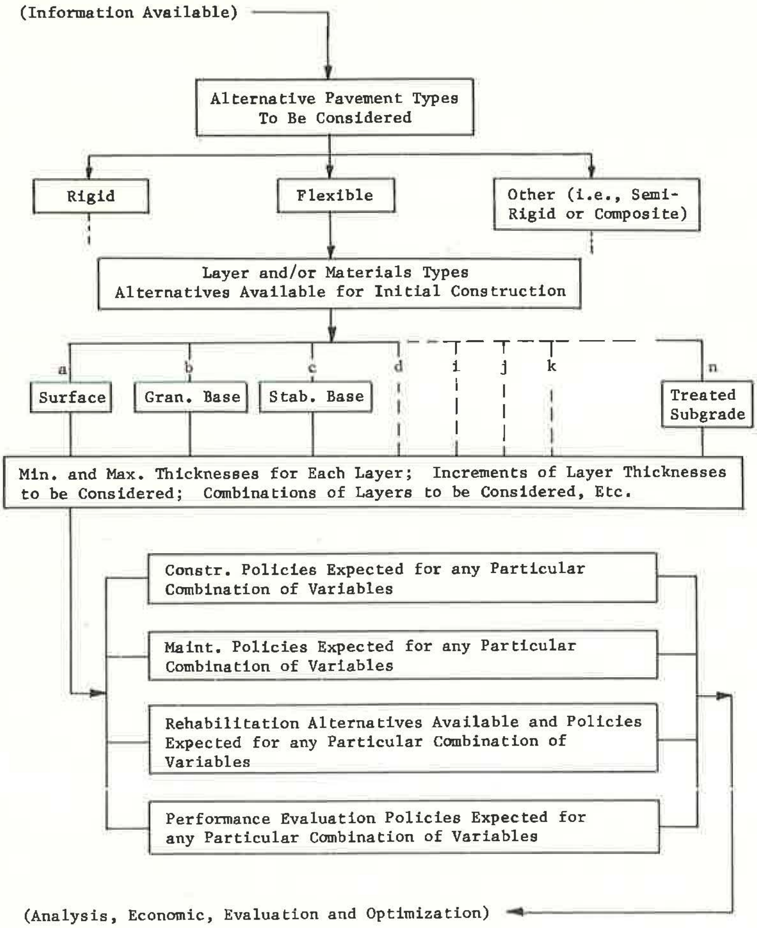
Analysis, Economic Evaluation, and Optimization

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 adqatuely 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:

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

where

$\mathrm{TPWC}_{x_1,n}$ = total present worth of costs for alternative x_1 for an analysis period of n years;
$(\mathrm{ICC})_{x_1}$ = initial capital costs of x_1;
$(\mathrm{CC})_{x_1,t}$ = capital costs of x_1 in year t;
$\mathrm{pwf}_{i,t}$ = present worth factor for discount rate i for t years = $1/(1 + i)^t$;
$(\mathrm{MO})_{x_1,t}$ = maintenance plus operation costs for x_1 in year t;
$(\mathrm{VC})_{x_1,t}$ = 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:

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

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 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 suitabl 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 lowe 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 metho for pavements may then be expressed as follows:

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

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 availabl techniques of the designer; (b) generation of alternative design strategies; and (c) analysis, economic evaluation, and optimization of these strategies.

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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 accident 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

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

where

$\mathrm{TPWC}_{x_1, n}$ = total present worth of costs for alternative x_1 for an analysis period of n years;
$(\mathrm{ICC})_{x_1}$ = initial capital costs of x_1;
$(\mathrm{CC})_{x_1, t}$ = capital costs of x_1 in year t;
$\mathrm{pwf}_{i, t}$ = present worth factor for a discount rate i for t years = $1/(1 + i)^t$;
$(\mathrm{MO})_{x_1, t}$ = maintenance plus operation costs for x_1 in year t;
$(\mathrm{VC})_{x_1, t}$ = user costs for x_1 in year t;
$(\mathrm{NUC})_{x_1, t}$ = nonuser costs for x_1 in year t; and
$(\mathrm{SV})_{x_1, n}$ = 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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TEXAS HIGHWAY DEPARTMENT PAVEMENT MANAGEMENT SYSTEM

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This paper describes a conceptual version of a pavement management system to assist in making pavement decisions that will result in users getting better services for their expenditures. These decisions are made about programming, designing, constructing, and maintaining pavements. A description is given of the conceptual system and the present working system.

•THE TEXAS Highway Department is developing and implementing a pavement management system. Initial attempts to use the AASHO Road Test results to develop a better pavement design method (1) led to a working pavement design system (2), which led to this pavement management system concept.

The primary decision stages in the pavement management process are programming (preliminary design), design (plans, estimates, specifications), construction, operatio (traffic, environment, maintenance), and retirement (abandon, salvage, rebuild). The purpose of the pavement management system is to provide information to decision-makers during these 5 stages so that decisions result in either satisfactory service at a lesser cost or the best service with available resources (3). The systems methodology includes identifying the decisions that must be made and the information that is required for them, supplying these data to the decision-makers in a timely and useful form, and monitoring the process to measure success and improve shortcomings.

In Texas, we started with the intention of improving our design procedure, and that effort evolved into developing a pavement management system. Basically, we ran into the following situations: Design decisions were frequently controlled by programming or budgeting constraints; and pavement performance (which we were trying to predict in design) is often affected by construction, environmental, or maintenance inputs to the pavement. We found that a pavement design methodology must consider budget constraints and the construction, maintenance, and natural environment the pavement will encounter. Failure to do so results in the pavement not being built as designed or not performing as predicted (4).

CONCEPTUAL PAVEMENT MANAGEMENT SYSTEM

Conceptually, our system contains the following key elements: design analysis package, pavement feedback data system, and personnel and equipment.

Design Analysis Package

Ultimately, our system should contain a group of pavement design computer programs consisting of a pavement design system, a pavement rehabilitation system, and special analysis routines. The pavement design system will compare all alternate pavement types—thin-surfaced flexible pavements, deep-strength asphaltic pavements, plain concrete pavements, continuously reinforced concrete pavements, and even some of the newer reinforcement systems such as prestressed pavements. The system will assist the decision-maker to select the proper pavement type for a given project and then to design that pavement.

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The pavement rehabilitation system may be a special case of the pavement design system, adding input about the existing pavement and its performance (5). I see a need to receive and analyze the opinions or judgments of local maintenance and engineering personnel about future performance (6).

The special analysis routines are computer programs such as stress analysis routines or fatigue analysis systems or other costly programs that will be used to investigate special conditions. Outputs from these analyses probably will be used to place constraints on the general pavement design system usage or to develop statewide standards. Generally, use of these routines on a project-to-project basis is prohibitive because of computer costs, materials characterizations, and personnel training.

Pavement Feedback Data System

The correct jargon may be pavement management information system instead of pavement feedback data system, which we adopted (7, 8). Whatever the name, important considerations include the data, the storage and retrieval software, and the data analysis and reports software. Also, the management of the system including data editing, methods of purging the files of redundant data, and general maintenance of the files should be considered. The data must answer the following questions:

1. What is the pavement? That is, what is the typical section?
2. Where is it located on the highway network?
3. When was it built?
4. What traffic is traversing it?
5. How is it performing?
6. What maintenance is being applied to it?

We have spent considerable energy studying storage and retrieval software and know that, before it can be designed, we will have to answer certain questions such as the following:

1. What are the data?
2. How will they be used?
3. How frequently will they be accessed?
4. When and how will they be acquired?
5. What are the available hardware and software that can be used?

We have concluded that the Texas Highway Department has ample computer facilities to process (store and retrieve) efficiently the pavement data that we can afford to acquire.

Our pavement management system must supply data to decision-makers in a timely and useful manner. Our feedback data system must contain analysis routines to reduce the raw data to useful statistics, and timely reports must be generated from the processed data. The data system will have to anticipate what reports will be needed so that a minimum of programming will be required to generate them. In other words, the data system will have to contain analysis routines and a report generator.

Managing the information system so that it continues to meet the needs of the users is perhaps the most difficult part of the data system. Recognition that management is an essential element and planning for it in the early stages will help to overcome this difficulty.

Personnel and Equipment

A most difficult problem in establishing our pavement management system lies in the personnel area. This problem becomes clearly evident if one examines our existing organization for pavement design. We have 26 rather autonomous districts, responsible for design, construction, and maintenance of the highways within their areas. Each district generally has 7 or 8 permanent resident engineer's offices that prepare plans and supervise construction for their areas. The following process generally describes the procedures used to make pavement management decisions.

Preliminary design decisions, including selection of pavement type, are usually made at the district headquarters by either the district engineer, assistant district engineer, or district design engineer. Detailed pavement design decisions including location of material sources, final thickness design, and plan preparation are most frequently made by the resident engineer with input from the district laboratory regarding available materials. Construction is then usually supervised by that same resident engineer's office, but may be assigned to another office. Routine and minor maintenance is handled by maintenance crews under the supervision of maintenance foremen; there are 7 or 8 maintenance sections per district. Major maintenance decisions involving overlays or reconstruction are usually made by the resident enginee

The expertise used in making decisions is engineering judgment gained from experience with the materials, traffic, and environment (9). Our difficult task, then, lies in identifying the personnel making the decisions and supplementing that experience (or expertise) with additional information. This additional information might be the results of theoretical analyses or the results of empirical measurements. Whatever, we will have to train the people to use the data, which will basically be new to them.

The operators of the system, that is, the people who collect and process the data, also have to be considered: equipment operators, researchers to use the data in improving models, and a manager to ensure that the system is responsive to the users' needs.

The equipment includes skid- and texture-measuring devices, deflection-measuring devices, roughness-measuring equipment, the computer (including terminals located in district offices), and whatever special laboratory equipment is required for materia characterization. Special equipment for pavement distress surveys will also be required on high-capacity, high-speed freeways such as those in Houston, Dallas, Fort Worth, and San Antonio. We have given a cursory examination to aerial photography and photologging as possibilities for this equipment. We are certain that selecting the equipment and preparing manuals for its calibration, operation, and control are majo tasks.

PRESENT STATUS OF DEVELOPMENT AND IMPLEMENTATION

Design Analysis Package

We have operational and in some usage a flexible pavement design system (10). Its objective is to minimize the present value of total cost for a satisfactory pavement ser vice. The designer specifies a minimum serviceability level, a desired reliability, a analysis period, a minimum time to the first overlay, and a minimum time between future overlays. Costs considered include initial construction cost and the constructio cost of future overlays. One important additional feature is the consideration of the serviceability loss due to the presence of swelling clays.

Some personnel from 10 districts have been trained in using this system (11). Thei usage represents roughly 50 percent of the flexible pavement designed in those 10 districts. Fifty percent of 40 percent of the districts is 20 percent coverage of the state.

Implementation of our rigid pavement design system (RPS) is presenting some elusi problems (12). The designers who have used it generally feel that they have no design problems except for perhaps 1 or 2 factors. They may be uncertain about, for exampl thickness of pavement or subbase type or joint spacing. The RPS developers believe that pavement designers have many problems including the selection of the type and thickness of rigid pavement, type and thickness of subbase, and proper amounts and spacing for reinforcement.

I am not completely convinced that our RPS offers a good solution to either recognized or unrecognized problems of designers, nor am I convinced that the designers recognize or admit to nearly all of the problems they have. I am convinced that the solution lies in having the developers work closely with the users so that the needs and problems of each are recognized.

We have operational an asphaltic concrete overlay mode only (13, 14). It utilizes Dynaflect deflection measurements on the existing road, and we could add, without too much difficulty, the traffic the existing road has carried and its present serviceability as inputs.

Pavement Feedback Data System

Our pavement management information system is still just an idea with the exception of skid information. In several districts we are collecting on a periodic basis skid measurements and surface construction materials information. These data are stored and retrieved in a data system (15). Those engineers who have studied the pavement management system being considered in Texas feel that the biggest payoff will come from implementation of the feedback data system; yet, it will require the largest effort.

Personnel and Equipment

The organization of personnel and the assignment of responsibilities have not proceeded much beyond the conceptual stage mentioned earlier. We have attempted to identify those existing tasks that can be considered part of our pavement management system, and in addition we have identified some completely new ones. These include primarily measuring pavement performance and putting all of the operations together in the system, i.e., managing the system. We have many ongoing tasks ranging from pavement design to data collection in our road life studies by existing personnel. These tasks and people must be identified and included in the system.

Our largest equipment problem involves getting a workable, repeatable fleet of roughness-measuring devices to handle a 70,000-mile network inventory.

SUMMARY AND CONCLUSIONS

1. A pavement management system is not merely a pavement design system. In fact, a typical structural design analysis will frequently be overridden by the realism of financial constraints.
2. Decisions about pavements are based primarily on experience. This experience must be recognized and supplemented, not replaced.
3. Throughout all phases, from development to implementation, the user of the system must be involved. Otherwise, the system will probably not respond to the needs of the user, or possibly the user cannot recognize the responses and apply them to his or her needs.
4. In many respects the pavement management system must be custom-designed for an organization.

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UTAH'S PAVEMENT DESIGN AND EVALUATION SYSTEM

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The system developed for evaluating existing pavement condition and determining future needs considers structural adequacy, serviceability, slipperiness, and surface defects of each pavement section. The data are processed through the computer, and output tables show existing condition and predicted life, thickness requirements for a specified life period, surface defects or distress, and a priority rating. Statewide data have been gathered and analyzed each year since 1970. The pavement design procedures have been computerized so that data can be entered at a remote terminal and the pavement design can be determined through the computer and printed out by the terminal. Under development is a pavement management system that considers all highway department operations that could possibly affect pavement performance.

THE UTAH State Department of Highways adopted the AASHO interim pavement design guide in the fall of 1962 for the design of all pavements. In 1964 a study (5, 12) was initiated by the department to evaluate the pavements that had been designed with the AASHO guide. The present serviceability index (PSI) was determined yearly for each project. During its first few years, the research study was concerned with evaluating each pavement and determining its performance characteristics. Performance curves were plotted for each project, and several new projects were added to the study each year as they were completed. Performance varied considerably from project to project and from year to year. Not all projects exhibited level trends (same PSI each year) or descending trends (decreasing PSI), but some showed fluctuations up or down or an increase in PSI (Fig. 1). This condition had also been observed in other states. Because of the variations, evaluating the pavement design procedures in a limited number of years was difficult if not impossible. Rather, a continuing effort was required to evaluate each project until failure or the end of its design life. Many projects were built in staged construction, and when resurfaced the performance trends were altered. As a result of these factors, we felt the full potential was not being obtained from the research study.

Beginning in 1969 the study was modified by a statistical experimental design that considers factors of age, soil support values, traffic design 18-k (80-kN) loads, and terminal serviceability index (TSI). This type of experimental design permitted the use of statistical procedures in the data analysis. The projects being studied were placed in appropriate cells within the experimental design. Individual projects are strongly influenced by various factors such as pavement age, accumulated traffic loads, construction quality, maintenance quality, climatic conditions, and pavement design. The cell design helps to temper the extremes from these factors for projects within a cell. A typical performance curve for one of the cells is shown in Figure 2.

Two research projects were started in 1968 (7, 9) in which the Dynaflect was used for deflection measurements. One study was concerned with the application of deflection measurements to pavement overlay design and analysis, and the other was concerned with predicting performance from deflection measurements. The study for predicting performance used the same experimental design and pavements as the serviceability study. The AASHO Road Test (1) equations that related deflections to performance of a pavement under a number of axle load applications of various sizes were

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Figure 1. Variations in performance curves.

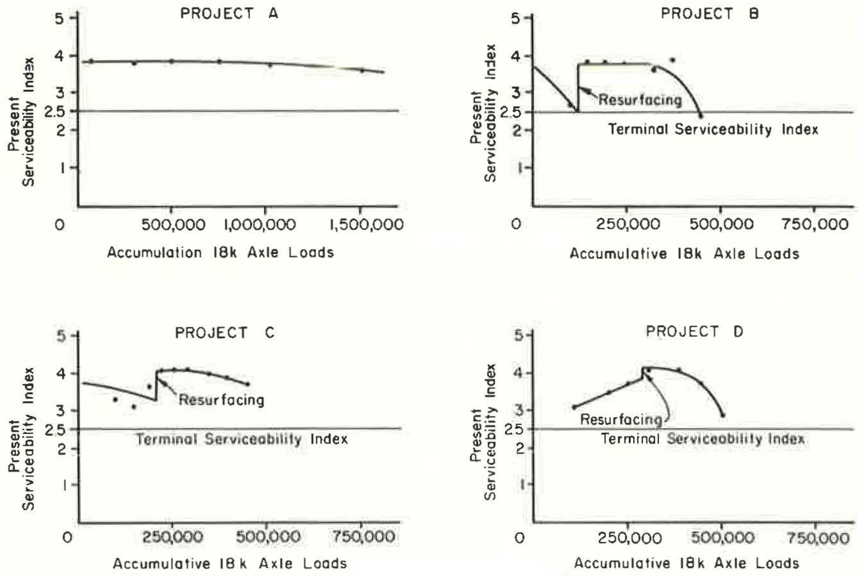


Figure 2. Performance curve for 1 cell from the experimental design.

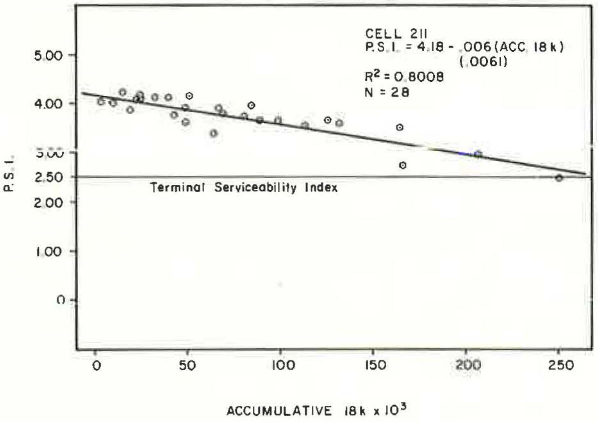


Figure 3. Typical pavement deflection characteristics for a 1-year cycle.

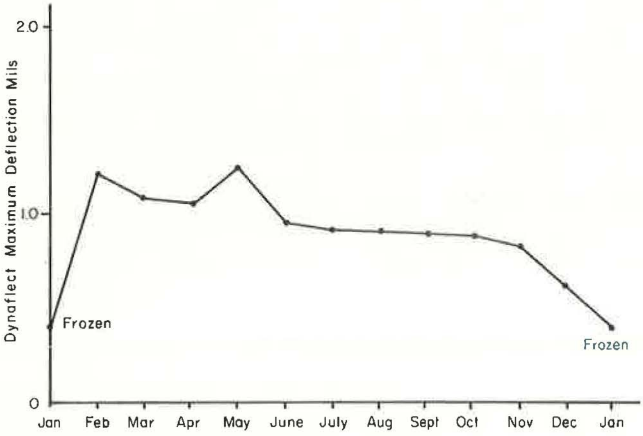
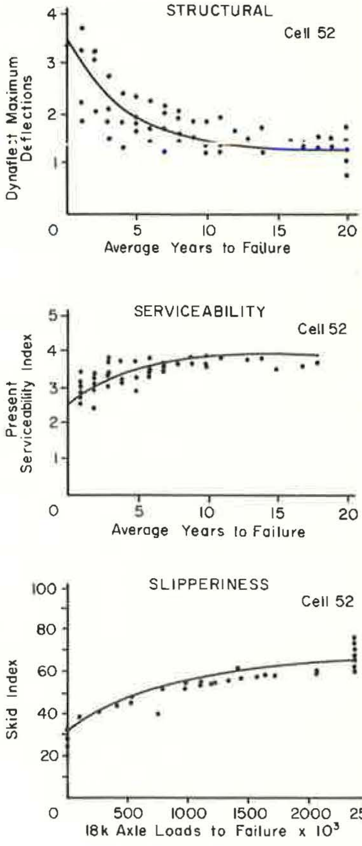


Figure 4. Typical prediction curves.



modified for use with the Dynaflect in Utah. We soon discovered that deflection measurements taken in the spring were unreliable because of the rapid changes in temperature and moisture that occurred at that time of the year. To measure the deflections on a pavement at the precise time when they were the highest in the spring period was difficult and sometimes impossible. The high deflection might last only a few days, and we could not tell whether the measurement taken was actually the maximum spring deflection. The changes occurring in deflections during a year are shown in Figure 3. Because of the impracticality of monitoring deflections every few days on every project in the state during the spring period to find the maximum or average deflection, we use fall deflections for pavement evaluation. The relatively arid climate in Utah permits deflections to be taken from June to November.

In 1969 we acquired a Mu-meter, which proved to be a reliable tool for evaluating skid resistance on pavement surfaces (11, 13). In the fall of 1969, we combined the results from the various research projects (1, 3, 4, 5, 6, 7, 10, 16) into a system that could be used as an aid for managing all pavements throughout the state (8). The system included structural adequacy determined from deflections, PSI, and slipperiness from the skid resistance measurements. These factors were based on concepts developed from the previous research. Typical prediction curves are shown in Figure 4. We anticipated that the system would provide answers to the following major questions:

1. When will pavement improvements be required?
2. What type of improvement is required?
3. How much of a correction is required?
4. What are the priority ratings for improvements?

A fourth factor of sufficiency, based on tolerable levels from design standards, provides the basic criteria for determining reconstruction of the roadway. Sufficiency determinations are made by the Transportation Planning Section (14, 15). Knowing the remaining life from the structural adequacy, serviceability, and slipperiness factors, we can determine the additional needs and correct for all the factors. We found that the various factors could not be related to produce one number that would indicate overall pavement condition. A pavement could fail in one area but be in good condition in another. The resulting number could indicate that the pavement was in fair to good condition when in fact it was not. A failure in any area is critical and, therefore, all must be looked at individually as well as collectively when recommendations are made for improvements or rehabilitation.

The effect of all the factors is sometimes overlooked because it is extremely difficult to determine the exact deficiencies of a pavement by visual observation. A pavement can have a weak base, yet the surface will appear to be good, or the surface can be deteriorated when the base has adequate strength. If the structural strength of the in-place pavement is ignored when it is weak, the correction will be short-lived, resulting in early failure. A design requiring additional structural strength should include an overlay that would correct the 3 major factors.

Data for the system were first gathered on a statewide inventory basis in 1970. The data were analyzed by the computer, and output tables covered average condition and predicted life, thickness requirements for a 10-year life, and priority listing. The priority listing included a condition statement based on the shape of the deflection basin. The 1970 system output was used by the Highway Systems Planning Division to help develop the required information for the 1990 functional plan and needs estimate for Congress.

The output was also used to evaluate the recommendations from the districts for roadway improvements. The recommendations from the system did not agree with those from the districts in some cases. In some of those cases the districts modified their recommendations, but in others they indicated they could not. The pavements in question were shown to be in good condition in all areas by the system data, yet the districts claimed they were highly distressed. A further evaluation showed that those sections did have a high PSI, based primarily on a relatively smooth riding surface, but had extentive cracking. Therefore, the basic conflict was the difference in the user's viewpoint of performance as evidenced by a high PSI and the maintenance engineer's concern for distress as shown by extensive cracking. Performance and distress are comparable on many pavements but not all. As a result of this experience, additional field data were gathered on pavement surface defects or distress for the system in 1971, 1972, and 1973, and another output table was produced showing the surface defects

The system was designed so that information developed on all pavements in the state could be used as feedback data to improve the system. Additional experience by the users of the system output allows them to make recommendations for further improvements and refinements. The system was initially designed for the benefit of planning and programming, maintenance, materials and tests, research, and pavement design.

PAVEMENT DESIGN

The pavement design process has been computerized, and the input information consists of

1. Traffic data for the design year including a breakdown for heavy trucks, light trucks, and passenger cars;
2. Load distribution factors;
3. Percentage of traffic in heaviest lane;
4. Dynamic CBR values;
5. Unit costs for various materials;
6. Terminal serviceability index;
7. Regional factor; and
8. Structural coefficients.

The data are processed by the computer, and the output consists of structural number required, design 18-k (80-kN) axle loads, and a series of acceptable pavement designs, including costs, from which the best or most economical design is selected. Computer terminals are being placed in the district offices so that the pavement designs can be directly obtained.

PAVEMENT EVALUATION SYSTEM

All pavements in the state are evaluated according to a set schedule. New pavements are evaluated only every second or third year, and old pavements are evaluated each year because they deteriorate rapidly. Each pavement is evaluated according to deflection, serviceability, skid resistance, and surface defects. The measurements are made during the relatively stable climatic period between June and November; nonetheless, climatic conditions differ from year to year and cause some variation in results.

The field data gathered by the Dynaflect crew include for each mile (1.6 km) of pavement tested the deflection readings from the 5 sensors and the pavement and ambient temperatures. A Cox roadmeter is used to gather continuous roughness data (12) for the pavements tested. The Mu-meter is used to measure skid resistance of the pavement surface. The pavement surface is wet, and ¼ mile (0.4 km) out of each mile is tested. A crew evaluates a 500-ft (150-m) section out of each mile to obtain data on the type and extent of cracking, patching, and rutting and rates the surface condition for uniformity, aggregate pop-out, surface wear, weathering, and crack condition. Data on present traffic and projected increases are obtained for all test sections.

All test sections are assigned to cells according to an experimental design that permits the use of the proper prediction equations. The data are then processed by the computer, and the following information is produced for each project. The deflection information includes

1. The deflection readings of 5 sensors at each test site,
2. Average Dynaflect maximum deflection (DMD),
3. Surface curvature index (SCI) (the numerical difference between sensors 1 and 2, which provides an indication of the strength of the surface layers),
4. Base curvature index (BCI) (the numerical difference between sensors 4 and 5, which provides an indication of the strength of the subgrade),

5. Predicted remaining structural life in 18-k (80-kN) axle loads and years,
6. Bituminous overlay thickness required for the pavement to achieve 10 years of structural life from the time the measurements are taken, and
7. Condition statement based on DMD, SCI, and BCI, which indicates the relative strength of the pavement system, e.g., pavement weak, subgrade strong.

The serviceability information includes

1. Summation of the roughness count per mile,
2. Cracking,
3. Patching,
4. Rutting,
5. PSI, and
6. Predicted remaining serviceability life in 18-k (80-kN) axle loads and years until the pavement reaches the terminal serviceability index.

The skid-resistance information includes

1. Skid index values from the Mu-meter, and
2. Predicted remaining safe skid-resistance life in traffic loads and years.

The surface defect information includes

1. Transverse cracking (1 ft/1,000 ft^2, 1 m/93 m^2);
2. Longitudinal cracking (1 ft/1,000 ft^2, 1 m/93 m^2);
3. Load-associated cracking, map or alligator (1 ft^2/1,000 ft^2, 1 m^2/93 m^2);
4. Patching (1 ft^2/1,000 ft^2, 1 m^2/93 m^2);
5. Average condition of the transverse and longitudinal cracks, including opening, multiplicity, and abrasion on a scale from 1 to 5, where higher values indicate a better condition;
6. Average surface wear on a scale from 1 to 5;
7. Average weathering on a scale from 1 to 5;
8. Average pop-outs per square foot on a scale from 1 to 5;
9. Average uniformity on a scale from 1 to 5; and
10. Average rut depths.

The results from the field evaluation and data analysis are then combined; a typical table for one of the projects tested is shown in Figure 5. This table gives a summary of all data, the average condition and expected remaining life in terms of deflection, serviceability, skid resistance, and surface defects.

A computer program provides a priority need listing for all projects. This program gives first priority to structural needs and then to serviceability and slipperiness needs because structural rehabilitation is generally more costly. If structural rehabilitation is required, a detailed project evaluation is made to determine the exact needs.

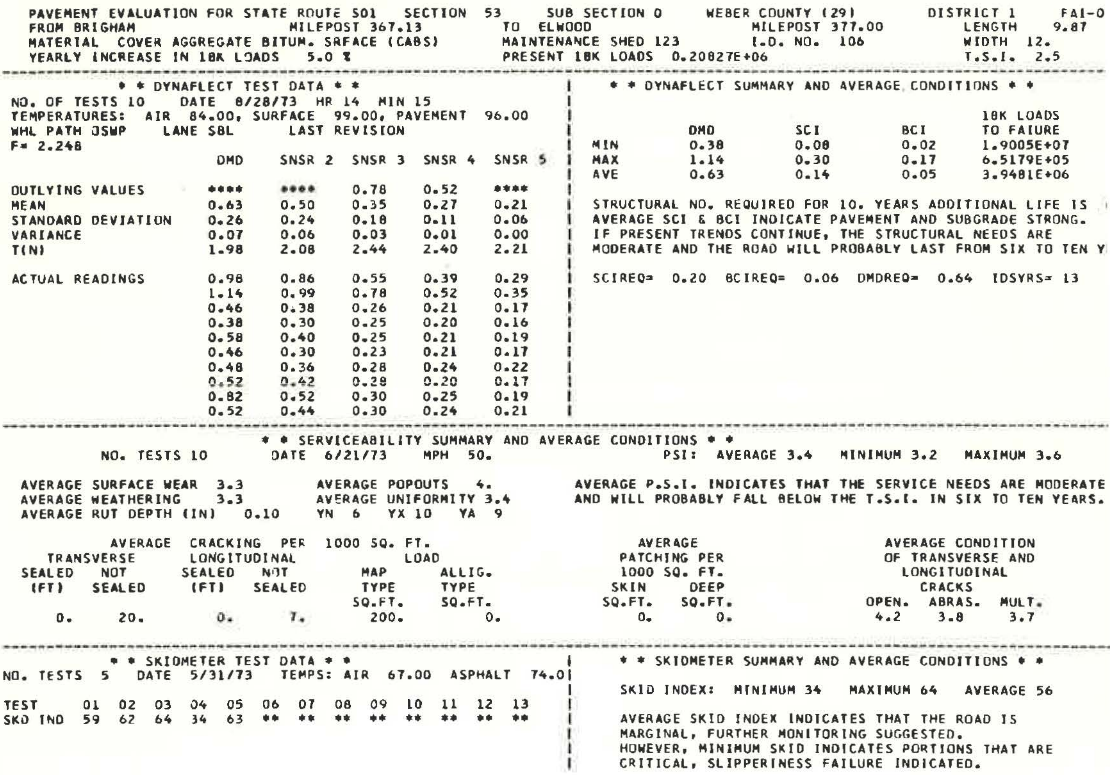
PAVEMENT MANAGEMENT SYSTEM

A research study was started in July 1972 to develop a pavement management system. This has evolved into more than a simple pavement management system because of the necessity to coordinate a number of existing systems in the department. The pavement information storage and analysis program (PISAP) will function with a data bank, in which data are primarily stored according to a road section. The types of data proposed for the data bank are geometrics, pavement design, construction control, environmental conditions, maintenance activities, pavement rehabilitation, traffic data, and pavement evaluation.

Subprograms of PISAP will analyze the data and provide information to appropriate offices on the condition of each pavement section. As the road section deteriorates, it will move up in the priority list provided by PISAP. Each year the road sections with the highest priorities will be slated for reconstruction or rehabilitation based on available funds.

The PISAP data bank will contain 3 major files: historical, management, and operational. With the information PISAP provides, management will be able to make more

Figure 5. Typical output from pavement evaluation system for a road section.



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   PAVEMENT EVALUATION FOR STATE ROUTE 501   SECTION  53     SUB SECTION 0     WEBER COUNTY (29)        DISTRICT 1     FAI-0
   FROM BRIGHAM                     MILEPOST 367.13           TO  ELWOOD                MILEPOST 377.00           LENGTH     9.87
   MATERIAL  COVER AGGREGATE BITUM. SRFACE (CABS)             MAINTENANCE SHED 123      I.D. NO.  106             WIDTH  12.
   YEARLY INCREASE IN 18K LOADS    5.0 %                      PRESENT 18K LOADS  0.20827E+06                      T.S.I.  2.5
--------------------------------------------------------------------------------------------------------------------------------
              * * DYNAFLECT TEST DATA * *                         |     * * DYNAFLECT SUMMARY AND AVERAGE CONDITIONS * *
NO. OF TESTS 10    DATE  8/28/73  HR 14  MIN 15                   |
TEMPERATURES:  AIR  84.00, SURFACE  99.00, PAVEMENT  96.00        |                                                 18K LOADS
WHL PATH OSWP    LANE SBL      LAST REVISION                      |              DMD         SCI          BCI       TO FAIURE
F= 2.248                                                          |   MIN        0.38        0.08         0.02      1.9005E+07
                          DMD    SNSR 2  SNSR 3   SNSR 4  SNSR 5  |   MAX        1.14        0.30         0.17      6.5179E+05
                                                                  |   AVE        0.63        0.14         0.05      3.9481E+06
OUTLYING VALUES         ****     ****    0.78     0.52    ****    |
MEAN                    0.63     0.50    0.35     0.27    0.21    |   STRUCTURAL NO. REQUIRED FOR 10. YEARS ADDITIONAL LIFE IS
STANDARD DEVIATION      0.26     0.24    0.18     0.11    0.06    |   AVERAGE SCI & BCI INDICATE PAVEMENT AND SUBGRADE STRONG.
VARIANCE                0.07     0.06    0.03     0.01    0.00    |   IF PRESENT TRENDS CONTINUE, THE STRUCTURAL NEEDS ARE
T(N)                    1.98     2.08    2.44     2.40    2.21    |   MODERATE AND THE ROAD WILL PROBABLY LAST FROM SIX TO TEN Y
                                                                  |
ACTUAL READINGS         0.98     0.86    0.55     0.39    0.29    |   SCIREQ=  0.20  BCIREQ=  0.06  DMDREQ=  0.64  IDSYRS= 13
                        1.14     0.99    0.78     0.52    0.35    |
                        0.46     0.38    0.26     0.21    0.17    |
                        0.38     0.30    0.25     0.20    0.16    |
                        0.58     0.40    0.25     0.21    0.19    |
                        0.46     0.30    0.23     0.21    0.17    |
                        0.48     0.36    0.28     0.24    0.22    |
                        0.52     0.42    0.28     0.20    0.17    |
                        0.82     0.52    0.30     0.25    0.19    |
                        0.52     0.44    0.30     0.24    0.21    |
--------------------------------------------------------------------------------------------------------------------------------
                               * * SERVICEABILITY SUMMARY AND AVERAGE CONDITIONS * *
            NO. TESTS 10        DATE  6/21/73  MPH  50.                       PSI:  AVERAGE 3.4    MINIMUM 3.2   MAXIMUM 3.6

  AVERAGE SURFACE WEAR   3.3         AVERAGE POPOUTS    4.         AVERAGE P.S.I. INDICATES THAT THE SERVICE NEEDS ARE MODERATE
  AVERAGE WEATHERING     3.3         AVERAGE UNIFORMITY 3.4        AND WILL PROBABLY FALL BELOW THE T.S.I. IN SIX TO TEN YEARS.
  AVERAGE RUT DEPTH (IN)    0.10     YN  6   YX 10   YA  9

             AVERAGE  CRACKING  PER  1000 SQ. FT.                          AVERAGE                      AVERAGE CONDITION
     TRANSVERSE       LONGITUDINAL             LOAD                  PATCHING PER                    OF TRANSVERSE AND
  SEALED    NOT       SEALED    NOT        MAP       ALLIG.              1000 SQ. FT.                     LONGITUDINAL
   (FT)    SEALED      (FT)    SEALED      TYPE      TYPE                SKIN     DEEP                       CRACKS
                                         SQ.FT.     SQ.FT.            SQ.FT.    SQ.FT.                OPEN.  ABRAS.   MULT.
      0.      20.        0.      7.        200.          0.                0.       0.                 4.2    3.8      3.7

--------------------------------------------------------------------------------------------------------------------------------
             * * SKIDOMETER TEST DATA * *                         |      * * SKIDOMETER SUMMARY AND AVERAGE CONDITIONS * *
NO. TESTS  5   DATE  5/31/73    TEMPS: AIR   67.00  ASPHALT   74.0|
                                                                  |      SKID INDEX:  MINIMUM 34   MAXIMUM 64   AVERAGE 56
TEST     01  02  03  04  05  06  07  08  09  10  11  12  13       |
SKD IND  59  62  64  34  63  **  **  **  **  **  **  **  **       |      AVERAGE SKID INDEX INDICATES THAT THE ROAD IS
                                                                  |      MARGINAL, FURTHER MONITORING SUGGESTED.
                                                                  |      HOWEVER, MINIMUM SKID INDICATES PORTIONS THAT ARE
                                                                  |      CRITICAL, SLIPPERINESS FAILURE INDICATED.
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informed decisions, causes of premature failure can be readily determined, and proper corrective action can be taken more quickly.

SUMMARY

A pavement evaluation system to determine existing condition and future needs has been the outgrowth of research conducted in Utah beginning in 1964. Improvements will be made in the system as additional information becomes available. Certain assumptions that were made during the development of the system will be modified or verified as additional data are gathered and analyzed.

In field inventories, sampling and testing must be carefully planned and executed. Data of poor quality can destroy the effectiveness of a pavement evaluation system. A good experimental design is necessary for classifying the projects tested and for ensuring reliable results.

Utah's pavement information storage and analysis program has the potential for becoming a valuable tool for personnel concerned with the design and management of pavements. Further research is needed to relate the performance of a pavement to distress. A pavement distressed because of cracking may have a high performance level because of a smooth riding surface. The distress of the pavement surface may cause a rapid deterioration in performance. Performance is the primary item of concern to the user, and distress is of concern to the maintenance engineer.

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FLEXIBLE PAVEMENT DESIGN IN ONTARIO

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The present design methodology for flexible pavements is based on the accumulated experience of pavement performance. More definitive design procedures are needed to assess alternative designs, stage construction, and maintenance strategies. A deflection-based flexible pavement design methodology linked with economic analysis should complement the experience approach. An alternative design subsystem that considers the properties of materials is discussed, and how this subsystem and suitable criteria can be substituted in the deflection method of design in a modular fashion is indicated. A tightening money supply for highways requires more sensitive economic management tools in the pavement design area.

•A HIGHWAY agency is charged with providing and maintaining a system of roads that adequately serve the present and future highway transportation needs of the community within the scope of allotted funds. The paved highway surface is the visible manifestation of the product and reflects the quality of service that the agency provides. Therefore, pavements must be designed, constructed, and maintained to provide acceptable standards of safety and riding comfort for several years, at an acceptable cost.

Two principal design decision areas must be considered when a pavement is defined: the pavement surface geometry area and the pavement structure area. Figure 1 shows how the various design areas in both geometry and structure contribute to the attainment of the objectives of safety, comfort, and economy. In geometric design, the design elements of alignment, speed, and capacity contribute to safety; in pavement design, adequate skid resistance of the pavement surface contributes to safety. In geometric design, the vertical and horizontal alignment and the highway aesthetics contribute toward riding comfort, whereas pavement structural design is intimately connected with smoothness and riding quality. The economics of pavements depend not onl on the pavement structure but on the alignment and cross-section design as well. Inclusion of vehicle user costs as these are affected by pavement surface conditions will increase management sensitivity to public acceptability of serviceability to be provided

This paper describes the pavement structure design activities within the Ontario Ministry of Transportation and Communications. Those activities are directed toward the attainment of the pavement surface goals.

PAVEMENT DESIGN MANAGEMENT PROCEDURES

The pavement design function is divided among a number of different areas of responsibility such as traffic, materials, and estimating. The final design is based on data contributed by each area. The management procedures and communication flow that are necessary to produce a design are described below.

The need for a new highway or for a reconstruction improvement to an existing highway is established from planning studies and from district and regional surveys. After approval and priority examination, the work is placed on the ministry's program.

Preliminary pavement design work on the new project is initiated by regional staff. This involves gathering detailed design data on traffic, subgrade soils, and availability of borrow and suitable aggregates and reviewing past performance of pavements in the

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area. A series of alternative pavement structure designs are then proposed, and rough estimates of quantities are made. Generally the alternative designs considered might consist of one or more of the following pavement types: conventional flexible structure, deep-strength asphalt, full-depth asphalt, composite (asphalt surfacing and concrete base), and concrete. The thickness combinations that are proposed conform to current policies, specifications, past experiences, and practical considerations. The preliminary pavement design data and alternative designs are next considered by the secretary of the Pavement Selection Committee, which is composed of senior management personnel, as shown in Figure 2.

The preliminary quantities for each alternative design are required so that their influence on unit prices can be taken into account when alternative designs are priced. The Estimating Office keeps a current file of unit prices and prepares construction cost estimates for 1 mile of pavement structure for each alternative design. These unit prices are also used to prepare cost estimates of resurfacing work. The estimates for life of original surface and life of subsequent overlays are prepared by the secretary of the Pavement Selection Committee and tabulated with the cost estimates for each alternative design. The present value of total costs for each alternative design and maintenance strategy for a range of life values is calculated and plotted by a computer program. Sometimes other alternative designs may supplement the list at this stage or later, after referral to the Pavement Selection Committee.

The Pavement Selection Committee examines the economic evaluations of alternative designs and maintenance strategies and considers a number of local and other factors before selecting the design that will be used. The factors considered are tailored after the AASHO project procedures (1). Once the selection of an appropriate alternative design is made and approved by the assistant deputy minister of engineering and operations, work on detailed design by regional staff commences. The applicability of the design to each length of road is then examined and, where necessary because of changed local subgrade conditions, the approved pavement structure might be modified or the thickness of subbase or base increased or decreased. Changes may also be necessary because of scarcity or unsuitability of available aggregates.

If, when detailed investigation is completed, conditions are then found to be different from those considered in the preliminary design, new design alternatives have to be given to the Pavement Selection Committee.

When the detailed design is completed, the pavement design is discussed as part of the overall design by the Regional Review Committee, as shown in Figure 3. The regionally approved design is next scrutinized by the Systems Design Branch for conformity to standards before it is submitted to the Head Office Review Committee for final approval. The project is finally passed on to Contract Control for the preparation of tender and contract award. Construction control of the contract is undertaken by district and regional staff. The constructed pavement then becomes the responsibility of maintenance personnel.

The need for resurfacing an existing pavement is generated by district and regional staff road condition reports. Overlay thicknesses are normally the minimum needed to restore distorted cross section and reduce bumps and dips to acceptable amounts. Design procedures follow the flow shown in Figure 3.

The management structure that is involved in the pavement design process is shown in Figure 4.

DATA BANK IN THE MANAGEMENT PROCESS

New pavements must be designed, constructed, and maintained. Each phase in the process requires management attention and decisions. The management structure must be organized so that goals and objectives can be achieved with the greatest efficiency. Each part of the structure must be aware of the role it plays in attaining goals and must, therefore, measure performance and evaluate effectiveness in contributing toward achievement of goals. To do this, records of projects and contracts must be consulted and status and condition reports examined. A great deal of repetitive work of this type can be eliminated and the process speeded up by a data bank that incorporates the in-

Figure 1. Design areas in pavement geometry and structure.

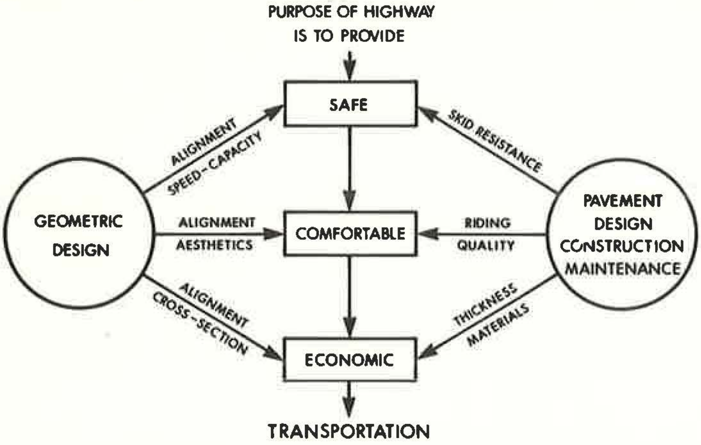


Figure 2. Flow of communication for preliminary thickness design.

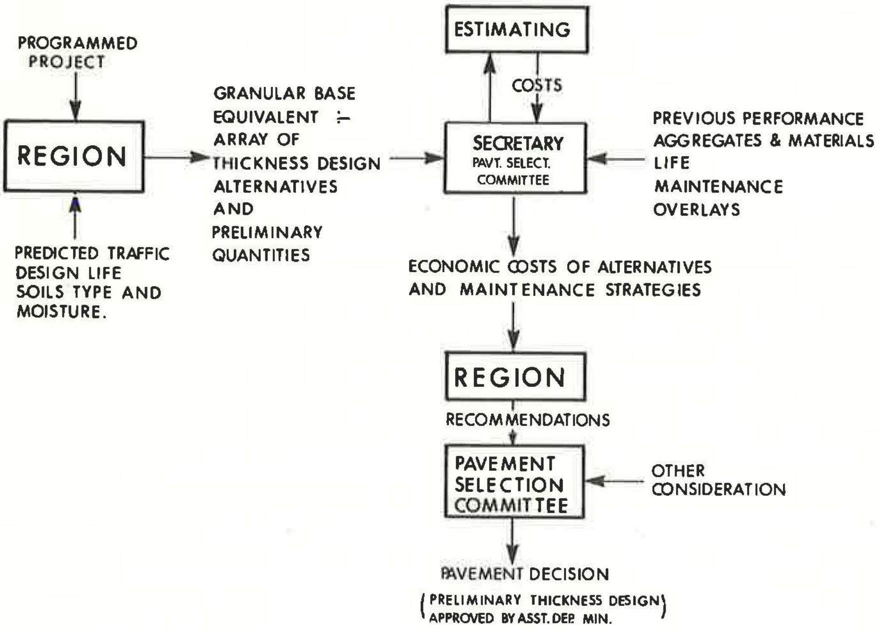


Figure 3. Flow of communication for final design.

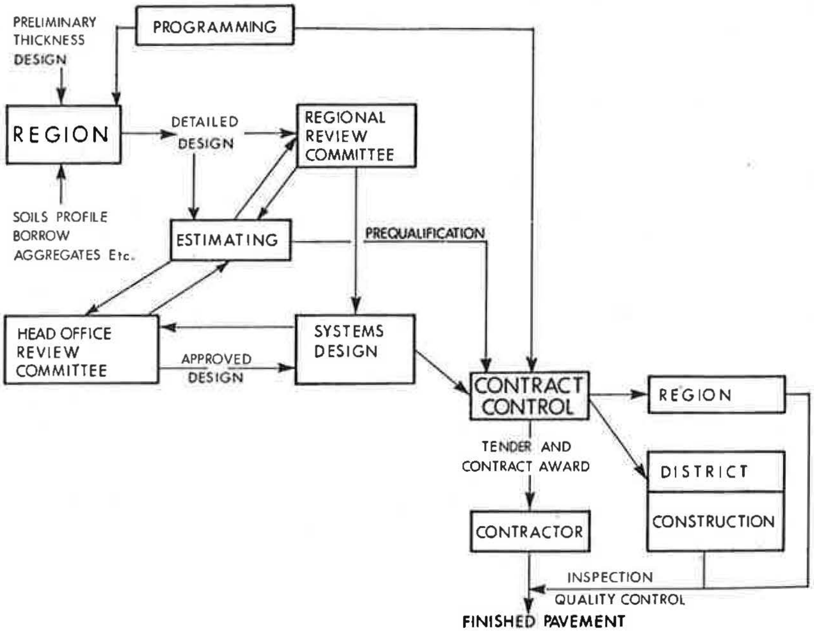
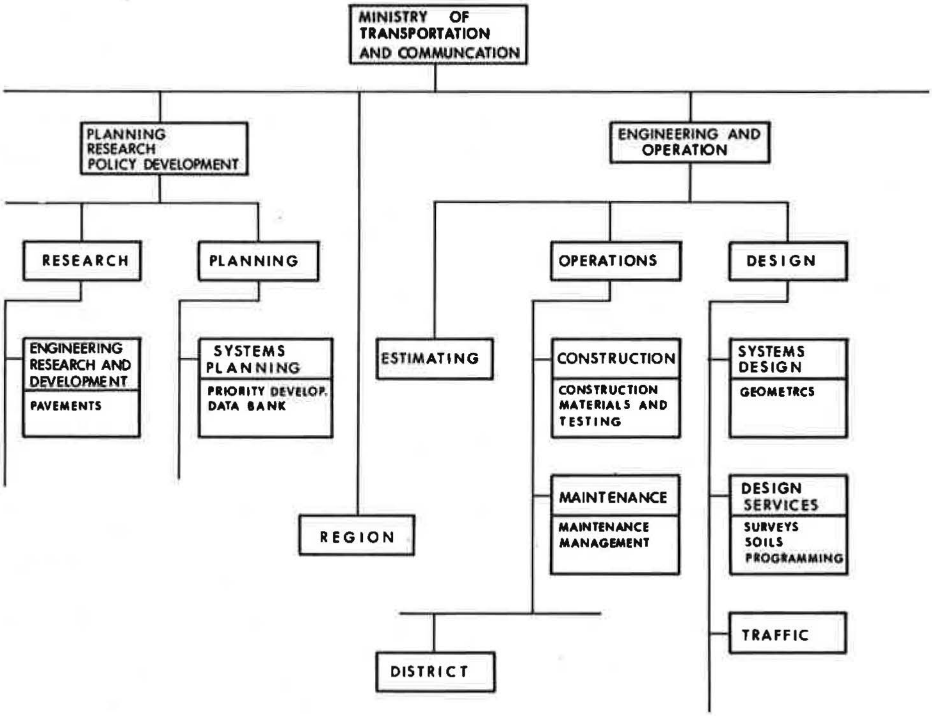


Figure 4. Units involved in pavement design process.



formation relative to pavements and that is accessible to any part of the management structure. Such an arrangement is shown in Figure 5. A pavement management and feedback information system (PMFIS) is now being developed for eventual incorporation in the ministry's data bank.

PAVEMENT DESIGN SUBSYSTEM

The pavement design management procedures described above set the framework in which the actual mechanics of pavement design is conducted. Pavements can be designed by many different methods (3, 4). The method used in Ontario is based on experiences; but, if more sensitive analyses are required or unfamiliar materials are proposed for use, a deflection-based design method (with alternative submodels) is available.

The design methods described below permit the designer to select those alternative designs that will satisfy the traffic needs and the subgrade conditions during a given period of years. To permit the adoption of the most suitable design from these alternatives, a number of additional factors must be considered. The procedures to develop the design alternatives and the related design information constitute the pavement design subsystem.

The procedure starts by obtaining from the design method a requirement for a thickness of the pavement structure in terms of granular base equivalent. The granular base equivalent requirement is converted to layer thicknesses to develop alternative designs according to the following equivalency values:

1 in. (25.4 mm) of hot-mixed asphalt concrete = 2 in. of granular A base (in conventional, deep strength and full-depth asphalt construction).
1 in. of granular subbase = $^2/_3$ in. of granular A base.
1 in. of treated base (either bituminous or portland cement) = 2 in. of granular A base.

The conventional design has thicknesses of asphalt concrete surfacing ranging from $1\frac{1}{2}$ to $5\frac{1}{2}$ in. (38.1 to 139.7 mm) depending on the classification of the highway and on th daily traffic. The well-graded granular A base course is generally 6 in. (152.4 mm) thick and may be of crushed gravel or crushed stone. The remainder of the pavement structural thickness is in the subbase, which is constructed with granular C, a material with wide gradation limits.

In deep-strength design, the asphalt thickness is usually kept between 8 to 10 in. (203.2 to 254 mm). The rest of the equivalent granular thickness needed is usually made up with granular A base material with a minimum of 6 in. (152.4 mm). Subbases are only used where needed. Full-depth asphalt designs are based on 1 in. (25.4 mm) of hot mix = 2 in. of granular base material, although there is evidence that the equivalency can be as high as 3.4 in. (4, 5). Rigid pavement thicknesses are determined from the current design thickness guideline table (6). Composite pavement thickness designs are limited to those previously used successfully, i.e., 3 in. (76.2 mm) of asphalt surfacing and 7 or 8 in. (180 to 200 mm) of plain concrete base on 4 to 6 in. (100 to 150 mm) o treated or untreated subbase.

Preliminary estimates of quantities of materials needed per linear mile of highway for all parts of the pavement and shoulders above the subgrade are obtained from tables prepared for this purpose. The quantities in the tables were calculated on the basis of standard cross sections, side slopes, and average spread densities.

The list of alternative designs is reviewed by the secretary of the Pavement Selection Committee, who may add other alternatives to the list. The Estimating Office examines these alternatives and, after considering contract price data, quantities needed, the area, and other factors, provides cost estimates for constructing 1 mile of each of the various designs.

Figure 5. Data bank.

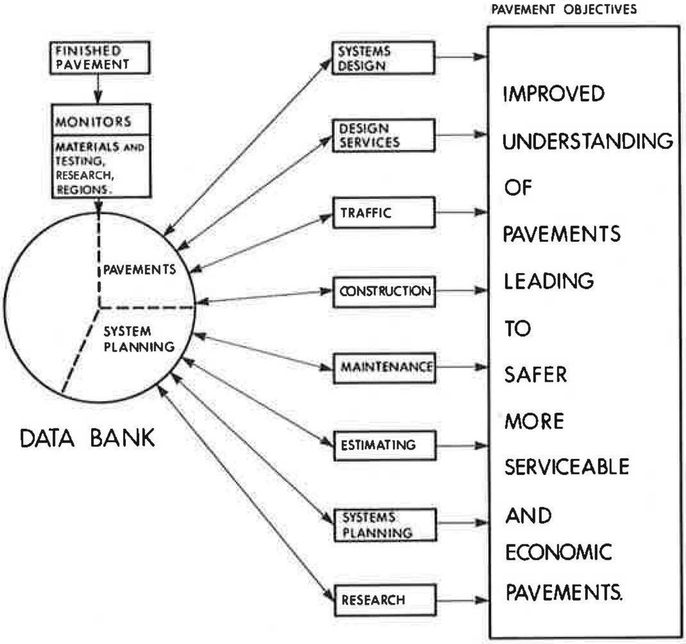


Figure 6. Structural design guidelines for flexible pavements.

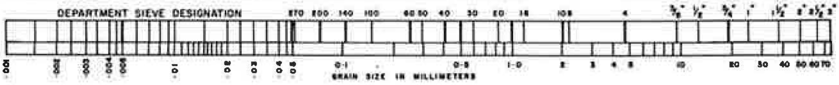
SUBGRADE MATERIAL / CLASS OF ROAD			GRAN. TYPE MATERIALS SUITABLE AS GRAN. BORROW	SANDY SILT AND CLAY-LOAM TILL			LACUSTRINE CLAYS	VARVED AND LEDA CLAYS
				SILT <40 V.F. Sa and Si. <45	SILT 40 - 50 V.F. Sa. and* Si. 45 - 60	SILT >50 V.F. Sa. and Si. >60		
			①	②	③	④	⑤	⑥
KINGS HIGHWAYS	MULTI-LANE	HM	5½"	5½"	5½"	5½"	5½"	5½"
		B	6" - 9"	6"	6"	6"	6"	6"
		SB	–	12" - 18"	18" - 24"	24" - 30"	18"	18" - 42"
		GBE	(17" - 20")	(25" - 29")	(29" - 33")	(33" - 37")	(29")	(29" - 46")
	2 LANES >2000 AADT	HM	4½"	4½"	4½"	4½"	4½"	4½"
		B	6" - 9"	6"	6"	6"	6"	6"
		SB	–	12" - 18"	18" - 24"	24" - 30"	18"	18" - 42"
		GBE	(15" - 18")	(23" - 27")	(27" - 31")	(31" - 35")	(27")	(27" - 43")
	2 LANES < 2000 AADT	HM	3½"	3½"	3½"	3½"	3½"	3½"
		B	6"	6"	6"	6"	6"	6"
		SB	–	12"	12" - 18"	18" - 24"	12" - 18"	18" - 30"
		GBE	(13")	(21")	(21" - 25")	(25" - 29")	(21" - 25")	(25" - 33")
SECONDARY ROADS	PAVED >1000 AADT	HM	1½"	1½"	1½"	1½"	1½"	1½"
		B	6"	6"	6"	6"	6"	6"
		SB	–	6" - 12"	12"	18" - 24"	12" - 18"	18" - 30"
		GBE	(9")	(13" - 17")	(17")	(21" - 27")	(17" - 21")	(21" - 29")
	UNPAVED <1000 AADT	HM	–	–	–	–	–	–
		B	6"	6"	6"	6"	6"	6"
		SB	–	6"	6" - 12"	18"	12"	18"
		GBE	(6")	(10")	(10" - 14")	(18")	(14")	(18")
TOWNSHIP ROADS	PAVED >200 AADT	HM	1½"	1½"	1½"	1½"	1½"	1½"
		B	4" - 6"	6"	6"	6"	6"	6"
		SB	–	6"	6"	6" - 12"	6" - 12"	12" - 18"
		GBE	(7" - 9")	(13")	(13")	(13" - 17")	(13" - 17")	(17" - 21")
	UNPAVED <200 AADT	HM	–	–	–	–	–	–
		B	4" - 6"	6"	6"	6"	6"	6"
		SB	–	6"	6" - 12"	12" - 18"	12"	12" - 18"
		GBE	(4" - 6")	(10")	(10" - 14")	(14" - 18")	(14")	(14" - 18")
MINING & ACCESS	------	HM	–	–	–	–	–	–
		B	4" - 6"	6"	6"	6"	6"	6"
		SB	–	6"	6"	6" - 12"	6" - 12"	12" - 18"
		GBE	(4" - 6")	(10")	(10")	(10" - 14")	(10" - 14")	(14" - 18")

HM - HOT-MIX ASPHALT THICKNESS
B - BASE THICKNESS
SB - SUB-BASE THICKNESS

GBE - GRANULAR BASE EQUIVALENCY THICKNESS
(1"HM ≈ 1" TREATED B. ≈ 2" GRAN. B. ≈ 3" SB)
**U.S. BUREAU OF SOILS CLASSIFICATION*

NOTE: THE RANGE IN TOTAL THICKNESS SHOWN IN THE ABOVE TABLE ARE DEPENDENT UPON THE MOISTURE CONTENT OF THE SUBGRADE.

U. S. BUREAU OF SOILS CLASSIFICATION							
Clay	Silt	Very Fine Sand	Fine Sand	Medium Sand	Coarse Sand	Fine Gravel	Gravel



The secretary of the Pavement Selection Committee evaluates the probable life spans of each alternative design on the basis of past pavement performance or by the deflection design method or does both (7). The maintenance strategy in terms of overlay thickness, probable life span, overlay costs, and annual maintenance costs is also determined on the basis of past experience or by the deflection design method (7) or both. More than one maintenance strategy can be evaluated for each alternative; however, this is not the practice.

The estimated construction costs and probable life spans of the initial pavement, the overlay costs and its probable life spans, and an analysis period and a rate of return are used to calculate the present value of total costs for each design alternative with its related maintenance strategy. The output of these calculations (an example of which is shown in Fig. 12) is a computer plot of total costs versus initial surfacing age. Various lines on the plot define the costs for different lives of the overlays. The most economic alternative can be readily determined from the plots.

On the basis of the economic evaluations and local experience, the regional staff recommends a design to the Pavement Selection Committee. Approval from this committee for the preliminary thickness design is required before work on detailed design can be initiated.

This method of selecting thickness designs evolved for the purpose of allowing input from several groups who are experienced not only in pavement design but also in geometric design analysis and local construction problems. Consideration of all aspects of the project is thus allowed to influence the design decisions.

No optimization techniques have been introduced into the design procedure at this time. However, this might occur later if a study of the constraints and trials of the technique indicate potential savings.

PAVEMENT THICKNESS DESIGN GUIDELINES

Provinces normally provide a 50 percent subsidy for roads in cities, towns, villages, most townships, counties, and regions. Under certain circumstances the subsidy can be as much as 80 percent; for connecting road links to very small communities, the subsidy can be 100 percent.

The pavement thickness design is the concern of the particular municipal authority. Thus, thickness design guideline tables for flexible and rigid pavements have been prepared by the ministry to be used in the preliminary design procedure leading to the selection of a pavement design (6). The flexible pavement design guideline table is in Figure 6.

DEFLECTION DESIGN METHOD FOR FLEXIBLE PAVEMENTS

The thickness guidelines shown in Figure 6 are used as the first level of design. If designers require this design to be confirmed or encounter conditions that are outside o the experience embodied in the guideline tables, an alternative deflection design method is available (3).

The concepts expressed in this method are that the pavement deflection under a standard wheel load represents the strength of the pavement structure and that pavement strength is related to the performance of the pavement under traffic. Implied in these concepts is the realization that the function of pavement structure is to spread the load over the subgrade in such a way as to prevent short-term failure in the subgrade and to minimize the rate at which long-term deformation accumulates in the subgrade under repeated traffic loading.

Pavement Response

Subgrades in Ontario are separated into 4 main classification groups: granular materials, sandy silt and clay loam tills, lacustrine clays, and varved and leda clays. A pavement structure can be represented as a homogeneous layer by applying equivalency values to the different types of surfacings, bases, and subbases. The deflection of the structure over a given subgrade can be represented by an equation (4):

$$D_{18}(H_e + a) = K \tag{1}$$

where

D_{18} = deflection of the pavement surface under an 18-k (80 kN) axle load, in in.;
H_e = equivalent granular base thickness, in in.; and
a and K = constants that depend on the subgrade soil conditions.

The deflection and equivalent thickness curves for Ontario were defined for the 4 principal subgrade types by assigning deflection values to different designs known to be satisfactory for a series of different traffic conditions (7). The curves are shown in Figure 7 and the equations are given in Table 1. By assigning different deflection values to the designs shown in Figure 6, one can arrive at somewhat different values for a and K in the equations. However, the equations as they stand appear to generate designs that are acceptable, and they are now used in this design method.

In an effort to further rationalize this aspect of the design procedure, a parallel procedure was developed to include material characterizations (8). This parallel procedure forms part of a design subsystem that can be substituted for the deflection method of design in a modular fashion. The derivation of the equations and the resulting design curves are described below.

According to N. Odemark (11), the pavement layers above the subgrade can be replaced by a layer of subgrade material with the thickness Z so that the same deflections should occur in this transformed uniform half space as in the layered system. The thickness A is the sum of the equivalent thicknesses of each pavement layer (Fig. 8).

$$Z = \sum_{i=1}^{m-1} 0.9h_1 \sqrt[3]{\frac{Em}{Ei}} \tag{2}$$

The deflection on top of the subgrade can then be calculated by using the formula for the elastic half space.

$$w_s = \frac{Kpa}{Em} \sin \alpha \tag{3}$$

where K is a value between 1.5 and 1.6 (12), depending on Poisson's ratio and on α.

For $K = 1.57\ (\pi/2)$, and $\sin \alpha = (a/Z)/\sqrt{1 + (a/Z)^2}$, and $P = P/\pi a^2$, Eq. 3 becomes

$$W_s = \frac{P}{2E_m Z} \times \frac{1}{\sqrt{1 + \left(\frac{a}{Z}\right)^2}} \tag{4}$$

We then solve for Z.

$$Z = \sqrt{\frac{P}{2E_m} - a^2} \tag{5}$$

The equivalent subgrade thickness Z can be transformed into an equivalent granular A thickness H_e, with the modulus E_{2g}. If all layers consisted of granular A material of thickness H_e, then, according to Eq. 2,

$$Z = 0.9H_e \sqrt[3]{\frac{E_m}{E_{2g}}} \tag{6}$$

Equations 5 and 6 lead to

Figure 7. Equivalent thickness and design deflection curves.

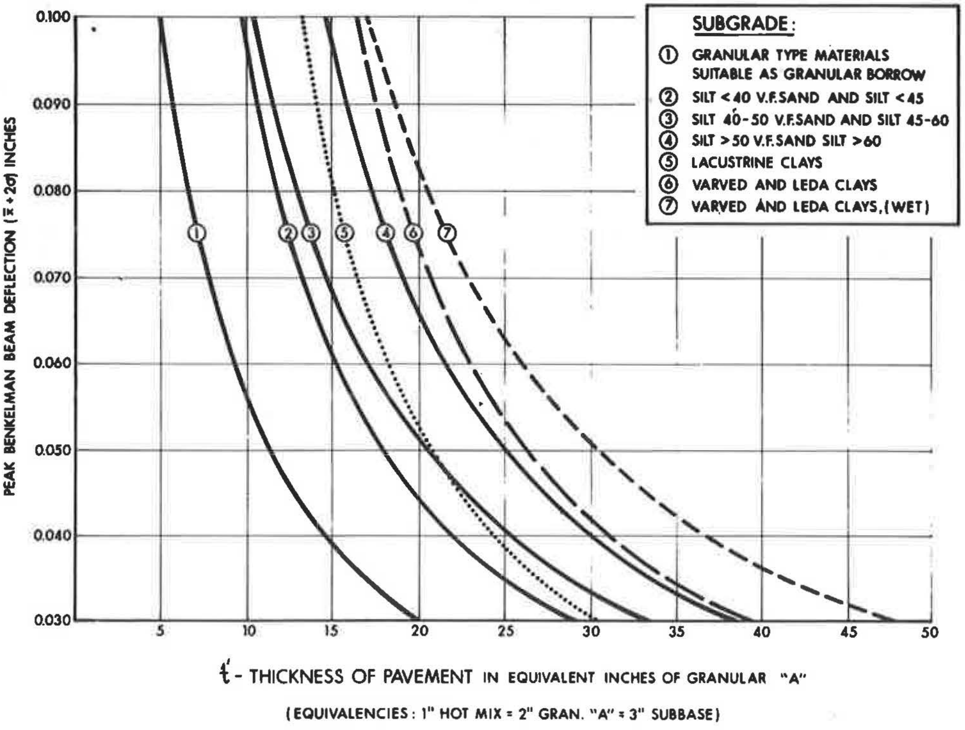
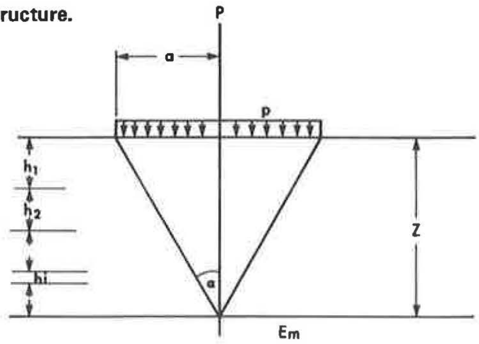


Table 1. Deflection and thickness relations derived from design thickness guidelines.

Subgrade Materials		Regression Equation[a]	Correlation
Number	Type	$\bar{\delta}(t' + a) = K$	Coefficient
1	Granular suitable as granular borrow	$\bar{\delta}(t' + 1.4) = 0.6363$	0.9780
2	Silt <40; very fine sand and silt <45	$\bar{\delta}(t' - 1.6) = 0.8113$	0.9853
3	Silt 40 to 50; very fine sand and silt 45 to 60	$\bar{\delta}(t' - 0.5) = 0.9871$	0.9631
4	Silt >50; very fine sand and silt >60	$\bar{\delta}(t' - 4.4) = 1.0190$	0.9530
5	Lacustrine clays	$\bar{\delta}(t' - 5.9) = 0.7314$	0.9814
6	Varved and leda clays, dry	$\bar{\delta}(t' - 6.5) = 0.9797$	0.9800
7	Varved and leda clays, wet	$\bar{\delta}(t' - 3.8) = 1.3249$	0.9780

[a] t′= thickness in equivalent inches of granular base.

Figure 8. Layered structure.



$$H_e = \frac{1}{0.9} \times \sqrt{\left(\frac{P}{2E_m W_s}\right)^2 - a^2} \times \sqrt[3]{\frac{E_m}{E_{2g}}} \tag{7}$$

Equation 7 is the first of 2 design equations.

The equivalent granular A thickness H_e is composed of various layers. Equations 2 and 6 lead to

$$H_e = \sum_{i=1}^{m-1} h_i \times \sqrt[3]{\frac{E_{2g}}{E_i}} \tag{8}$$

where

P = wheel load, in lb;
a = diameter of the loaded area, in in.;
W_s = calculated deflection of the subgrade surface;
E_m = modulus of elasticity of the subgrade; and
E_{2g} = modulus of elasticity of the granular base material.

The terms $\sqrt[3]{E_{2g}/E_i}$ are to be interpreted as layer equivalency factors based on granular A material, and they must be assumed to be in accordance with data on the basis of experience. The equivalencies used for the Ontario designs lead to

$$H_e = 2h_1 + h_2 + \frac{2}{3} h_3 \tag{9}$$

which is the second design equation.

The flexible pavement design chart based on these equations is shown in Figure 9. The Benkleman beam rebound deflection scale shown was tentatively set after study of various deflection criteria, the Brampton Test Road data, and the AASHO Test Road data (8). This alternative design procedure is still tentative.

Deflection Criteria

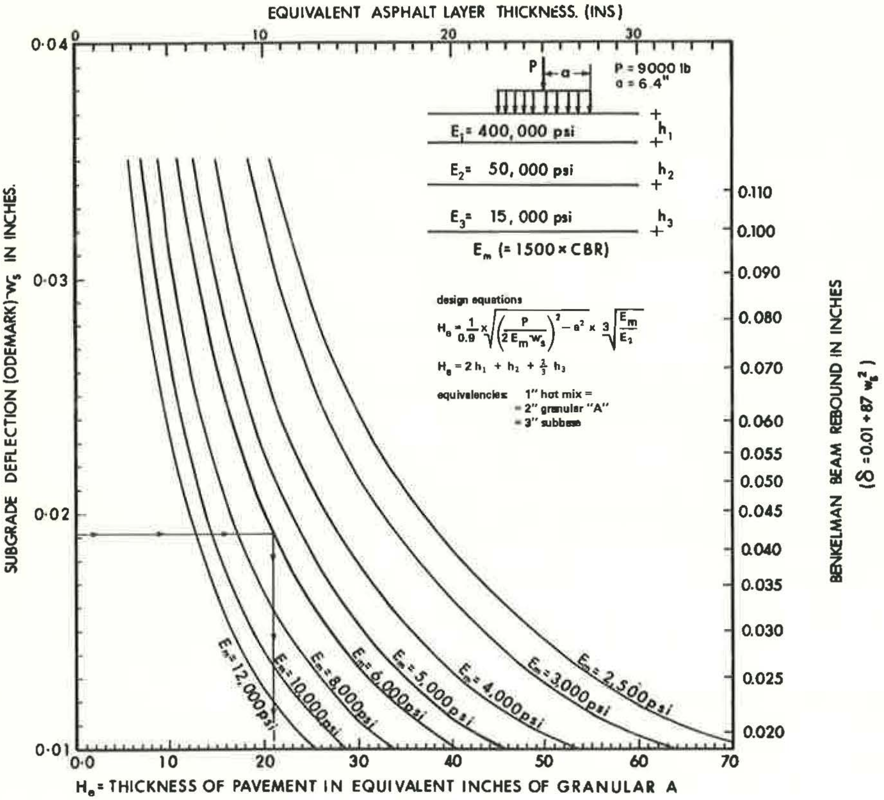
The Brampton Test Road demonstrated that the subsequent performance of a pavement can be predicted from a knowledge of its initial peak Benkelman beam rebound value. On the basis of this finding, a set of deflection criteria was proposed that provided for a higher terminal serviceability rating for strong pavements and a lower terminal serviceability rating for weak pavements (7). The proposed criteria are shown in Figure 10. More recently, further examination of the Brampton Test Road data by nonlinear elastic layer analysis procedures led to the proposal by Kamel (9) of an alternative set of deflection criteria. Also, examination of the AASHO Road Test data by elastic layer analysis procedures using a set of assumed elastic moduli values led to the proposal by Jung and Phang (8) of a third set of deflection criteria. This latter set of proposed criteria corresponds closely with that shown in Figure 10 and is slightly less conservative than the deflection criteria recommended by the Asphalt Institute (10). Further work is being carried out to arrive at firm criteria.

Pavement Life

At the present time, estimates of predicted pavement life for purposes of economic analysis are arrived at by reviewing the performance and ages of similar pavements in the locality. This method, although it may not be suitable for getting the precise values needed in calculation, nevertheless provides a value or range of values in which one can place a fair amount of confidence.

To arrive at the more precise values that are needed if the economic evaluations of alternative designs are to be meaningful, we must at this time apply the deflection and load repetition criteria chart (Fig. 10) and the deflection and equivalent thickness design curves (Fig. 7). By these charts and curves, we can either estimate the life of a given pavement thickness or arrive at a thickness for a proposed life. The solutions,

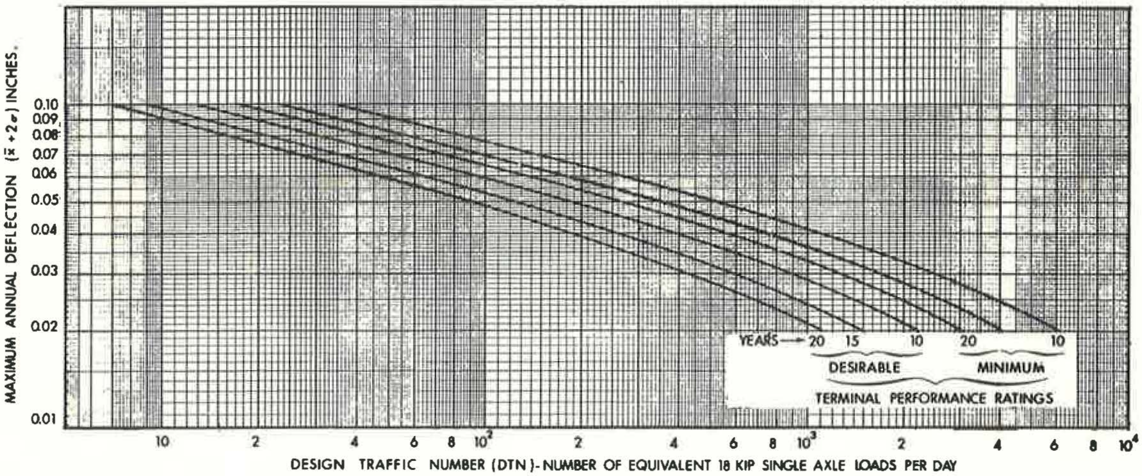
Figure 9. Design chart for flexible pavements in Ontario.



[illegible]

GRAN. TYPE MATERIALS SUITABLE AS GRAN. BORROW	SANDY SILT AND CLAY LOAM TILL			LACUSTRINE CLAYS	VARVED AND LEDA CLAYS
	SILT < 40 V.F. Sa and Si. < 45	SILT 40 - 50 V.F. Sa. and Si. 45.60	SILT > 50 V.F. Sa. and Si. > 60		
psi	psi	psi	psi	psi	psi
11,000	5,000 TO 7,000	4,000 TO 6,000	3,000 TO 5,000	3,500 TO 6,000	2,000 TO 4,500

Figure 10. Deflection criteria.



of course, can be obtained from computerized procedures. When the tentative alternative layer analysis procedures are used, pavement life in terms of equivalent 18-k (80 kN) load repetitions up to any desired terminal serviceability can be determined from the curves shown in Figure 11. This is used in conjunction with thickness design curves of Eq. 7.

OVERLAY DESIGN

Present practice in overlay design is to specify the thickness of padding lift, which is required to correct the longitudinal and transverse profiles, and then to specify the subsequent lift or lifts needed to further correct the transverse slope or the grade or to increase the final smoothness of the surface or to add the thickness required for strength. Overlay thickness is in many instances governed more by the need to correct heaves, dips, bumps, and cross section than by the requirement for added strength. This is the result of having to design built-in compensations for strength losses in the spring. In other words, the pavement is overdesigned for most of the year.

If the pavement to be overlaid needs to be strengthened, this is revealed by either the pavement condition report or by Benkelman beam deflection measurements. If Benkelman beam deflections are measured, the overlay thickness requirement can be be arrived at by use of the deflection method described by Phang and Slocum (7). Briefly, the deflection of the initial pavement is assumed to increase with the number of load repetitions because of fatigue and change in state of the materials. A deflection value of the time of overlay can be estimated from the curves shown in Figure 12. For a given overlay thickness, the deflection of the overlaid pavement can be estimated from waves shown in Figure 13. The deflection curves shown in Figure 12 are tentative.

The life of the overlay, for purposes of calculating economic costs in arriving at possible maintenance strategies, is now estimated after an examination of previous overlay performance and ages in the locality. The records available for this purpose are quite scanty; however, this method of estimation is preferred.

If the overlay is designed by a deflection method, an estimate of the overlay life can be obtained by consulting the curves shown in Figure 12.

ECONOMIC ANALYSIS OF NEW HIGHWAYS

The foregoing are brief descriptions of the various elements of the deflection design method with the tentative alternate layer analysis procedures. They are used by the secretary of the Pavement Selection Committee in examining the alternative designs and in setting up the maintenance strategies, which are an integral part of the economic analysis.

The economic evaluation is the output of the alternative strategies shown in Figure 14. Strategy a represents a strong, well-designed, and well-constructed pavement; strategy i represents a less durable initial design that is later strengthened by resurfacings. For purposes of comparing alternative design and maintenance strategies, the economic analysis must produce meaningful relative costs. The measure selected here is the present value of the total costs of both construction and the subsequent maintenance and overlays needed to keep the pavement to minimum standards during a stated period. The present values of future costs are calculated at a suitable discount rate, currently considered to be 6 percent.

An example of the method of presenting the results of the analysis is shown in Figure 15. Here 2 design strategies are considered: Strategy a represents 2 alternative designs [10-in. (254 mm) asphalt concrete, no base, 9-in. (228.6 mm) subbase and 5.5-in. (139.7 mm) asphalt concrete, 6-in. (152.4 mm) base, 13.5-in. (342.9 mm) subbase] with 15 ± 2 years initial surface life and an overlay life ranging between 4 and 8 years. Strategy b represents 2 other alternative designs [10-in. asphalt, no base, 13.5-in. subbase and 5.5-in. asphalt, 6-in. base, 18-in. (457.2 mm) subbase] with 20 ± 2 years initial surface life and an overlay life ranging between 6 and 9 years. The 20-year conventional design is economical and has a smaller spread in costs and therefore smaller risks.

At this stage, the costs that are taken into account are construction costs, admin-

Figure 11. Loss of serviceability and axle load repetitions curves for pavements of different deflections.

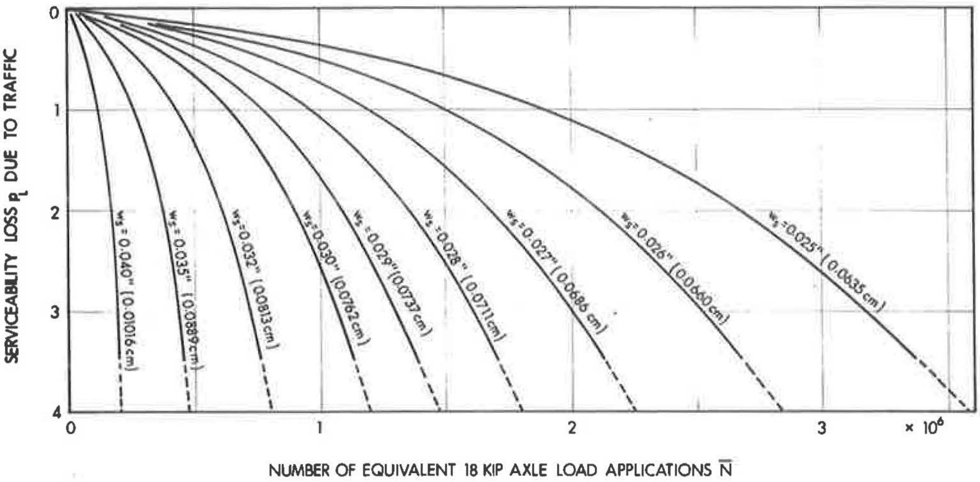


Figure 12. Curves for estimating life of pavement overlays.

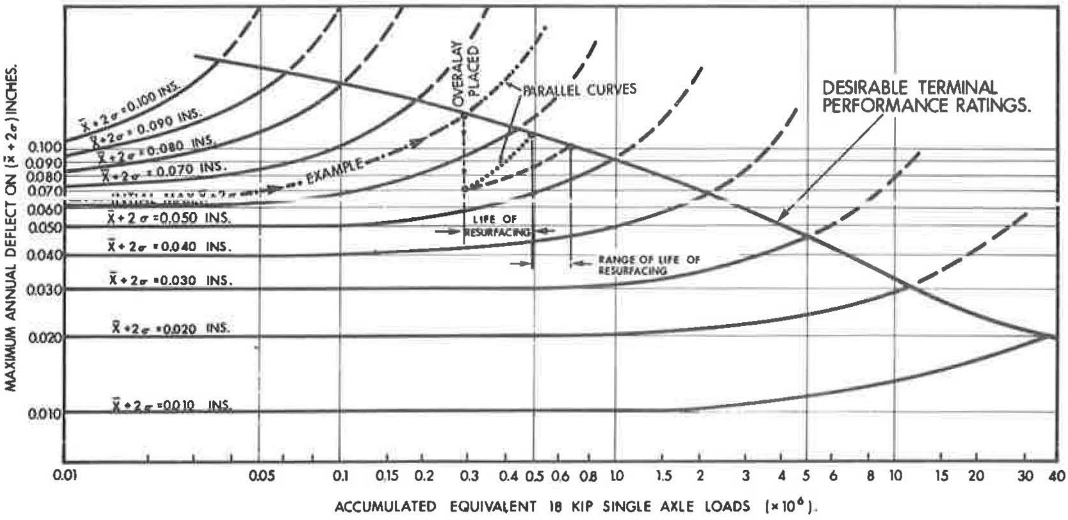


Figure 13. Overlay thickness deflection curve.

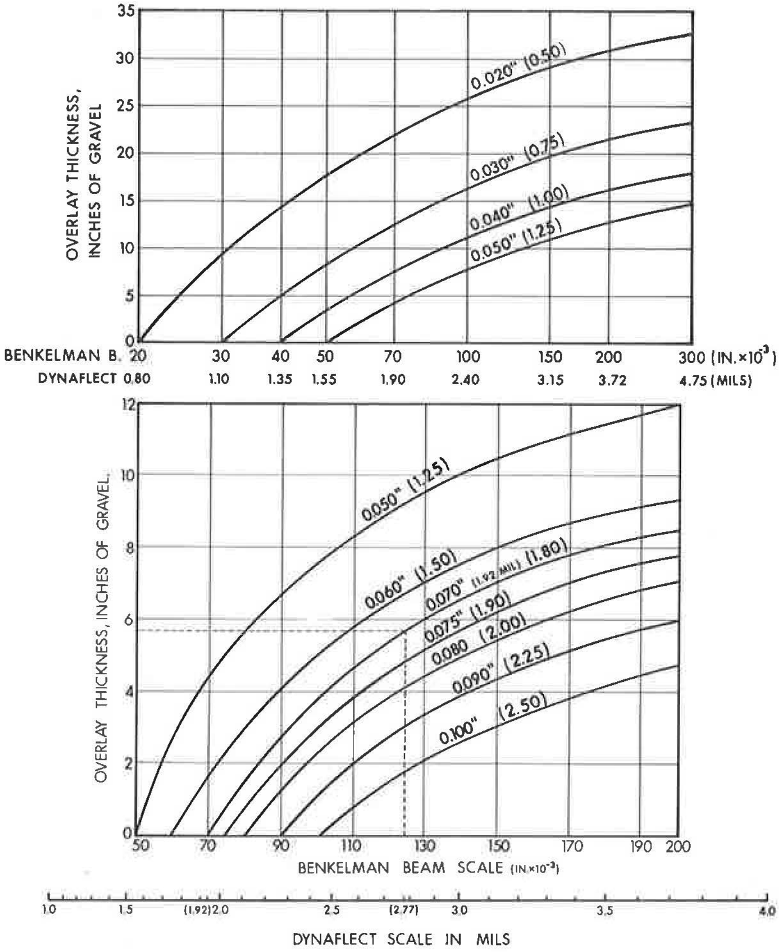


Figure 14. Projected serviceability and age histories of alternative pavement design, construction, and maintenance strategies.

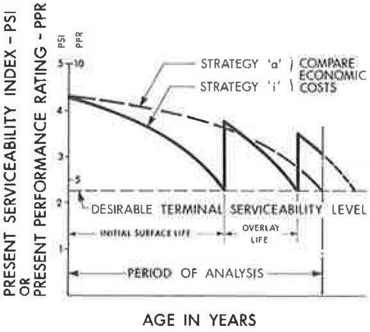
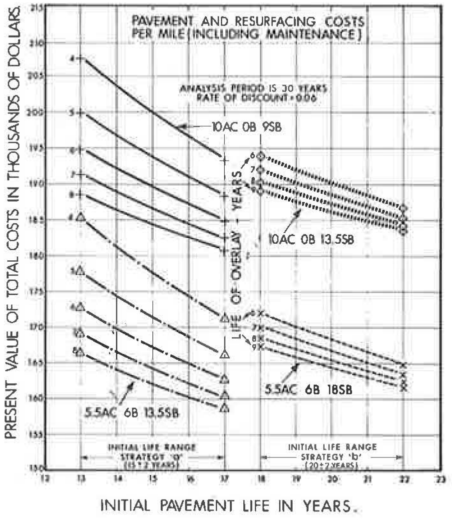


Figure 15. Economic cost evaluation of 4 alternative designs.



istrative costs for the design and supervision of overlays, overlay costs, and annual maintenance costs. At some later stage, cost of traffic detours and control during overlay construction, cost of overlays including premiums for night work where necessary, cost to users due to traffic delays during overlay construction, and some constraints defining public acceptability of the periodic inconveniences involved may be added to complement the basic economic analysis.

When this is done, it may become practical to answer questions regarding the conditions under which the initial pavement should be built to last a long time or a short time, the best time to overlay a pavement (which is not necessarily when it reaches terminal serviceability), and the most appropriate scheduling for stage construction.

DIRECTION OF FUTURE PAVEMENT DESIGN METHODS

Present developments in transportation in Ontario indicate that more effort and funds will go into the provision of public transit facilities in future years. The enlarged transportation responsibility of the Ministry is likely to result in a further tightening of money supply for the highway sector. We must, therefore, explore all avenues by which maximum benefits can be gained for funds expended. Whereas previous pavement design methods were aimed at providing adequate pavements, future design methods must be tailored so that, together with appropriate economic analysis, they serve as sensitive management tools.

Shrinking aggregate supplies may result in use of different materials, so there is the need to provide in future designs for the use of unfamiliar materials. The future design methods must therefore be capable of handling new materials.

Because of the tightened money supply, there is likely to be a limitation on new highways and a corresponding increase in rehabilitation of old pavements. The future method of overlay design must adequately account for deterioration of the existing pavement.

As materials and construction methods change in the future, there will be an urgent need to have a design method that will accommodate the experience gained with these new materials and methods. A computerized data bank that can provide the feedback information for this purpose appears to be very desirable.

CONCLUDING REMARKS

The pavement design procedures in Ontario are designed to take maximum advantage of the experience of the staff. The design guidelines express current experience in thickness design.

In spite of the bias in the procedures toward experience, they are sufficiently flexible to allow new design methods to be introduced. Efforts are under way to provide acceptable new design methods with features that are suitable for future needs. As part of this program, an alternative tentative elastic layer analysis procedure is proposed.

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FLEXIBLE PAVEMENT ANALYSIS SUBSYSTEM

W. J. Kenis and T. F. McMahon, Federal Highway Administration

This paper presents an outline of the analysis techniques proposed for use in a pavement design check procedure that has been developed in the federally coordinated program of highway research on new methodology for flexible pavement design. The concepts and formulations used in the method have been developed in the National Cooperative Highway Research Program and by staffs of the Federal Highway Administration and the state transportation and highway departments. The techniques presented reflect current knowledge, and changes will be made as new information becomes available. The proposed structural analysis subsystem is based on the assumption that portions of the pavement act as viscoelastic elements, others as plastic elements, and others as elastic elements. The method also accommodates the important concept of element responses altered with temperature and loading rate fluctuations. The subsystem is incorporated in a procedure by which it is possible to check existing designs for structural adequacy to resist pavement damage due to cracking, rutting, and roughness. Eventually this subsystem will be integrated with a pavement management system that will allow consideration of optimum design concepts with respect to the planned used and life of the proposed roadway.

•THE FEDERAL Highway Administration's research program in flexible pavement design was planned and developed as part of the National Program of Research and Development in Highway Transportation (since replaced by the Federally Coordinated Program of Research and Development in Highway Transportation). With minor changes in emphasis, this program has been followed to the present time.

The major objective of the research program developed by the Pavement Systems Group of the Structures and Applied Mechanics Division, Office of Research, is a new structural subsystem for flexible pavements that will reliably predict in-service performance by a rational analysis of material properties, traffic loadings, and environmental conditions. This subsystem in the form of a pavement design check procedure will be available to the states on a trial basis. The procedure will be set forth in a users manual that will be supplemented by a completely documented computer program.

A great deal of effort by many research agencies has provided basic information that permits the presentation of this outline of the proposed design-analysis procedure. The outline relies heavily on concepts and work accomplished at the Massachusetts Institute of Technology (1, 2, 3, 4, 5, 6) and uses much of the work accomplished at the University of California (7, 8, 9, 10, 11, 12). Research efforts at Georgia Institute of Technology, Ohio State University, and Texas A&M University are being considered as refinements (13, 14, 15). Current work includes studies at the University of Utah, Materials Research and Development, Austin Research Engineering, Inc., and Pennsylvania State University.

As a long-range goal, the structural analysis subsystem is to become an integral part of an overall pavement design-management system, which will provide for total life planning. Pavement maintenance and economic factors will be integrated with the structural subsystem to provide a capability for optimizing the structural design. A schematic outline of the design-maintenance system is shown in Figure 1.

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

CONCEPTUAL CONSIDERATIONS

A structural subsystem deals with the analysis of the structural response of the pavement system. It may be composed of one or more subsystem models and in general provides information about the primary and limiting responses of the pavement. Before entering on a discussion of the various models of the structural subsystem, the reader must understand the concepts behind the developments incorporated in this subsystem.

For more than 2 decades, pavement design engineers have been developing concepts and methodology by which pavement design can be transformed from an art to a science in which physical measurements of material properties, load applications, and environmental factors may be used to predict the performance of a pavement in place. This transformation requires that the measurements taken and the performance predicted be compatible with all rules of science and mathematics germane to the problem.

Therefore, the first phase of the research endeavor concentrated on the solution of boundary value problems and the development of constitutive equations. The researcher investigated size, shape, and makeup of the pavement layered system and developed formulations that attempted to predict its response when subjected to external influences. This research showed that the pavement response is manifested by both recoverable (elastic) and permanent (viscous and plastic) deformation, which eventually results in cracking and rutting. Portions of the response are time dependent (viscoelastic) and therefore partially nonrecoverable because of the time of the load applications on the pavement system and because of the effects of temperature on this response. In addition, laboratory tests were developed to investigate the behavior of the layer materials. Various configurations of material specimens were tested under different loading and environmental conditions. Procedures for characterizing the behavior of these materials led to the formalization of several types of laboratory tests that determine the material characteristics for use in predicting pavement response.

A second phase of the research was concerned with the development of formulations that allow a stochastic or probabilistic approach to the design problem. Variation is important in materials and in construction practices; therefore, the design-analysis system must take variability into account.

A third phase was concerned with the fatigue of flexible pavements. Currently the only available method for predicting fatigue life is an empirical on based on fatigue testing of sawed or formed beams and extrapolating those data to the fatigue of the pavement. The extrapolation procedure correlates the stress on the underside of the pavement, the expected temperature regime, and the fatigue test results. Fracture mechanics concepts have also been applied to the pavement-cracking problem. A predictive method is not yet available, but progress is being made. The concepts of viscoelastic fracture mechanics appear to have the best promise of a solution to fatigue cracking of flexible pavements.

The efforts of this work result in a rational analysis method for evaluating flexible pavement designs. This is a method in which all responses of the pavement can be stated in terms of the geometry of the pavement system, the physical properties of the materials, and the effect of climate and load on these properties.

STRUCTURAL SUBSYSTEM

The structural subsystem is composed of 3 separate sets of models: primary response, damage indicator, and performance. Each model depends on separate input variables and on interrelations of input and output among the models (1, 2, 3, 4, 5, 6, 18). For instance, the distress to the pavement incurred through the associated failure mechanisms is transformed into numerical values indicating the levels of serviceability of the pavement. A view of these interrelations is shown in Figure 2.

To account for the uncertainties and variabilities associated with the operations of a pavement system, computer programs allow inputs and outputs to be described in terms of probabilistic distributions instead of single-valued estimates. The methods of approach to the formulation of probabilistic models may be divided into simulation procedures and direct probabilistic procedures. The current version of the analysis incorporates Monte Carlo simulation techniques for the computation of primary response;

Figure 1. Design-management system.

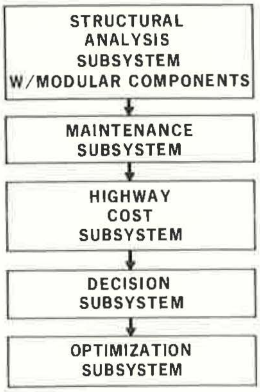


Figure 2. Structural subsystem.

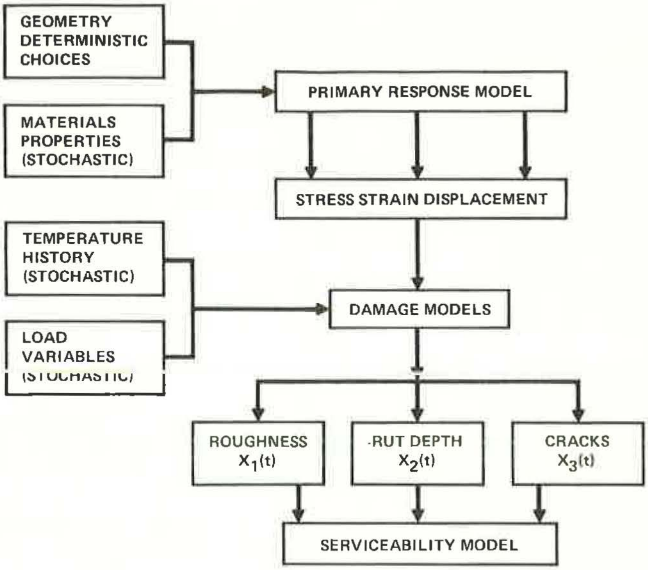
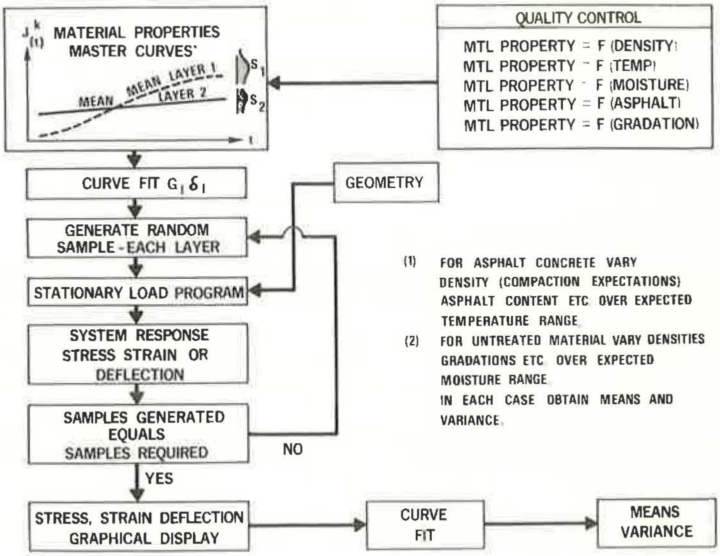


Figure 3. Primary response model.



(1) FOR ASPHALT CONCRETE VARY DENSITY (COMPACTION EXPECTATIONS) ASPHALT CONTENT ETC. OVER EXPECTED TEMPERATURE RANGE.

(2) FOR UNTREATED MATERIAL VARY DENSITIES GRADATIONS ETC. OVER EXPECTED MOISTURE RANGE.

IN EACH CASE OBTAIN MEANS AND VARIANCE.

direct, closed-form probabilistic procedures are used to compute the pavement's response to random loading. Variability in estimates of future traffic and in the properties of the layer material components can be accounted for, but the user must provide the computer programs with those data.

Primary Response Model

The primary response model is a mathematical model of the pavement structure in the form of computer program solutions to stationary (static) load conditions (1, 2). It now consists of a 3-layer linear viscoelastic boundary value problem that incorporates a probabilistic solution to account for the stochastic nature of input variables (3, 4). Output from this model consists of distributions of the mean value and variance of the resilient (elastic) and accumulative (time-dependent) stresses, strains, and deformations at any point in the pavement due to a stationary load applied at the pavement's surface. The components of this model are shown in Figure 3. The solution to the static load condition is similar to that described by Burmister except that the moduli of the material layers are allowed to behave as viscoelastic (rate-dependent) materials as well as elastic ones. In addition each material layer is assumed to be incompressible (Poisson's ratio 0.5). The computer program inputs provide for pavement geometry, magnitude and size of the statically applied load, and linear viscoelastic creep or elastic compliance function for each layer. The compliance function represents the material characterization of the layer materials to be used in the primary response model. (These properties are determined from the results of laboratory tests conducted on individual samples of each pavement layer.) It is expressed in terms of stress and strain as

$$D(t) = \frac{e_{zz}(t)}{\sigma_{zz} - 2\mu(t)\sigma_{rr}} \qquad (1)$$

where

$D(t)$ = modular creep compliance function,
σ_{zz} = axial load in a tension or compression test with or without confinement,
σ_{rr} = confinement pressure,
e_{zz} = axial strain, and
$\mu(t)$ = Poisson's ratio.

For an elastic material, D(t) is defined as the inverse of the elastic modulus or, as it is known today, the resilient modulus.

The modular creep compliance function is represented mathematically within the computer program by the exponential series

$$D(t) = \sum_{i=1}^{n} G_i \exp \delta_i t \qquad (2)$$

where

G_i = constant coefficients determined by the series curve fit program, and
i = constants prescribed within the program.

Damage Indicator Models

A highway pavement is a structure built for use during a given period of time. During its design life, the structural integrity of the pavement may weaken and its inability to resist the imposed loadings and environment will give rise to accumulations of cracking and permanent deformation.

The factors that primarily influence these manifestations include properties of materials in each layer; magnitude, duration, and number of repetitions of load; and environmental factors such as moisture and temperature. Since each of these factors cannot be measured or specified in an exact form, their variations should be accounted for in the design-analysis procedure. For example, the quality of the material of each layer has certain variations that can be described statistically in terms of means and variances. The fluctuation of temperature and the randomness of traffic can also be described by means and variances. The structural subsystem has been uniquely formulated to account for these random parameters. By using stochastic procedures, the predictive capabilities of the system inherently include the interactions of these parameters. In addition the variation of the material properties along the roadway will give rise to longitudinal variations of the rut depth and cause longitudinal profile changes or roughness. In the computation of the distress indicators of the subsystem, 3 independent load-associated failure mechanisms are assumed (4, 5): fatigue failure, accumulative deformation in the wheel paths, and longitudinal roughness. The damage indicator models are shown in Figure 4.

Fatigue Failure Submodel—Cracking is a phenomenon associated with the brittle behavior of materials. A fatigue mechanism is assumed to cause progression of cracks in pavements. This distress mechanism is accounted for by a phenomenological approach, namely, a modified stochastic Miner's law for progression of damage within materials. Miner's law is given by the following equation:

$$C = \sum_{i=1}^{m} \frac{n_i}{N_i} \tag{3}$$

where

n_i = number of load applications at the strain state i, and
N_i = number of cycles to failure for that same strain state i.

When the amount of damage C reaches the value of 1, failure is said to have occurred. When C reaches any value less than 1, that value represents the percentage of pavement life used up. The number of cycles to failure N is related to the strain amplitude by the following relation:

$$N_i = K_1 \left(\frac{1}{\Delta \epsilon_i}\right)^{K_2} \tag{4}$$

where

$\Delta \epsilon_i$ = tensile strain amplitude at the underside of the asphalt concrete layer directly under the wheel load, and
K_1, K_2 = material characteristics of the fatigue model.

The values of K_1 and K_2 are usually determined in laboratory fatigue tests on beam specimens of the layer in which it is assumed fatigue cracking takes place (7, 8, 9). The deterioration of the pavement is computed through a probabilistic formulation of the fatigue equation and Miner's law. In the computer program the coefficients K_1 and K_2 may be statistically correlated; i.e., a coefficient of correlation of -1 means that an increase of K_1 corresponds to a decrease of K_2, and a coefficient of 0 means that K_1 and K_2 are statistically independent of each other. Values of K_1 and K_2 are to be prescribed by the user in terms of their mean value and variance. In general, the coefficients K_1 and K_2 are dependent on the configuration of the family of fatigue curves developed to represent the failure criteria. Recent analysis has shown that the variability of K_2 has a much greater influence on fatigue crack predictions than does the variability of the tensile strain (12). Therefore, for fatigue testing standard laboratory procedures must be developed that realistically reflect fatigue cracking in the pavement.

Rutting Submodel—Rutting distress results from the residual or permanent deformations occurring in the layers because of repeated load applications in the wheel paths. These accumulative deformations may occur in all layers; however, the mechanisms will be different for different materials. The rutting may be due to the viscous behavior of the materials or to compaction and reorientation of the individual particles

Figure 4. Damage indicator models.

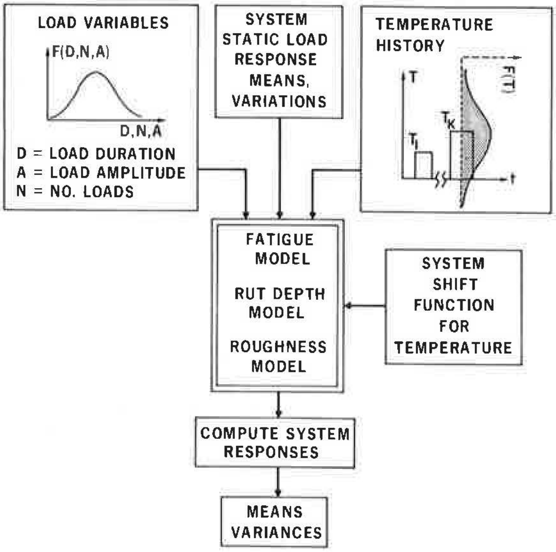
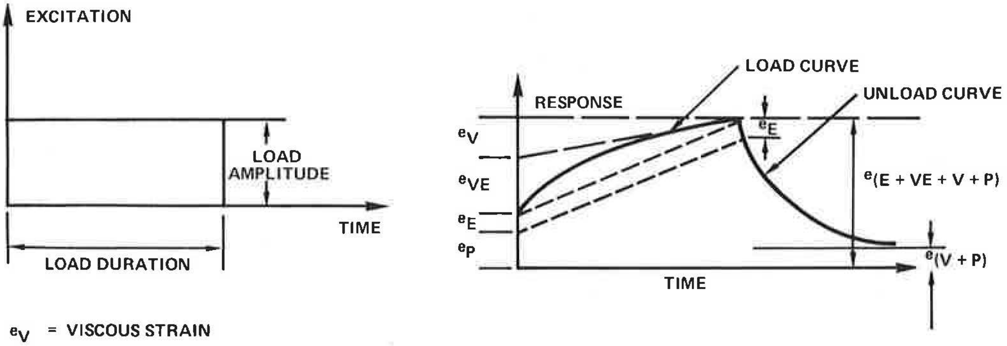


Figure 5. Material response.



e_V = VISCOUS STRAIN

e_{VE} = VISCOELASTIC STRAIN

e_E = ELASTIC STRAIN

e_P = "PLASTIC" STRAIN

upon application of wheel loads. Figure 5 shows the response of a material body and its rebound upon unload. Its true behavior could not have been known without a knowledge of the rebound curve. The permanent deformation is composed of a viscous part and a plastic part (the use of the word "plastic" denotes permanent deformations due to causes other than viscous flow), whereas the elastic and viscoelastic components are considered to be fully recoverable.

In general, the viscous component is of greater significance for asphalt-bound materials, and the plastic component has a greater effect on the development of permanent deformations in granular type materials. Fine-grained materials exhibit a predominantly elastic behavior when their moisture contents are below optimum values. As moisture contents are increased above optimum, viscous and plastic behavior becomes more predominant.

The rutting submodel of the program computes the amount of vertical deformation occurring in the wheelpath because of repeated traffic. The operational techniques used to predict pavement rutting have been programmed and are included in the random load program. The current version of this program computes rut depth by using the linear superposition integral. This operation is essentially a process where residual deformations are summed over many applications of a repeated load. The accumulative deformation, of course, will be a function of the duration of each load, the number of loads, the time between arrival of each load, the magnitude of each load, and the response behavior of the pavement system itself. A single load application is expressed mathematically as follows:

$$F(\tau) = A \sin^2 \omega\tau, \ 0 < \tau < \text{duration } F(\tau) \qquad (5)$$

The function $F(\tau)$ is shown in Figure 6. The amplitude A and frequency take on random values associated with the traffic characteristics, which are prescribed by the user.

Roughness Submodel—This distress component defines the deformation along the longitudinal profile of the roadway. The rut depth along the wheelpath is assumed to vary in a random manner as a result of both quality control measures and construction techniques. For instance, if the materials along the roadway were placed during radical changes in environment or if a wide variety of construction practices were used or if different material sources were used, then one might expect the structural integrity to vary at different points along the roadway. In this submodel the roughness is expressed by the AASHTO definition for slope variance. It is computed both from a knowledge of the frequency distribution of rut depth and from an autocorrelation function that is a measure of the variation of material properties along the roadway. This function, however, must be determined from actual field measurements on existing roadways so that it reflects the in-place variations inherent in the pavement structure.

Performance Model

The performance of a pavement in a given environment is its ability to provide an acceptable level of serviceability with a specified degree of reliability at an assumed level of maintenance. Inability of the pavement to provide the necessary services in a given locale may then be considered as pavement failure. When viewed in this context, failure becomes a loss in performance; it is the extent to which the pavement is unable to render itself serviceable as a result of accumulation of damage during a given time period.

When a pavement constructed of known materials and geometry is subjected to an operational environment, the damage model predicts the distribution of each major distress component. One can use the expected values of these components to predict the expected value of the road serviceability after a given time period, provided one knows the relation between serviceability and damage components. The AASHTO serviceability model is assumed to be valid. Thus, the outputs of the damage indicator models are used in the following equation:

$$SI = a_0 + a_1(C) + a_2(RD) + a_3(SV) \qquad (6)$$

Figure 6. Excitation and pavement response functions.

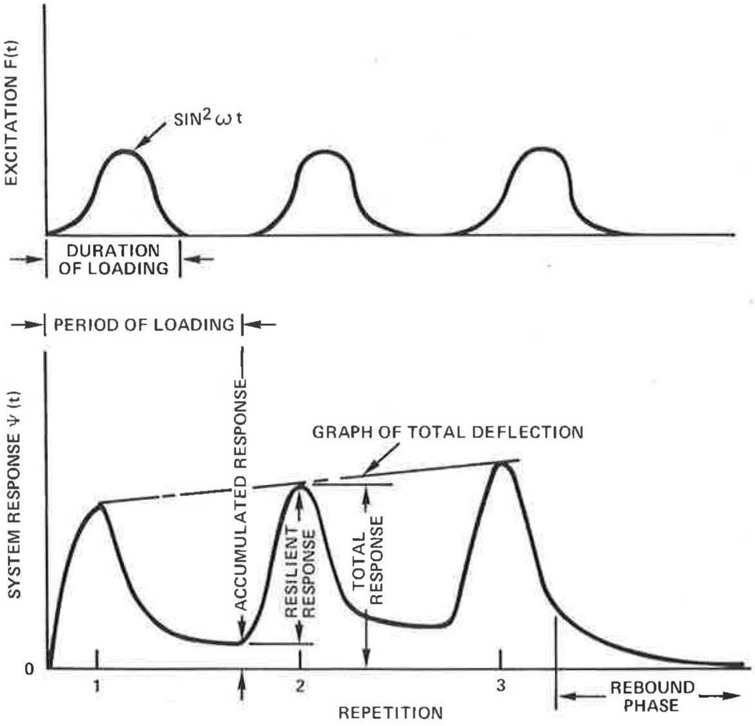
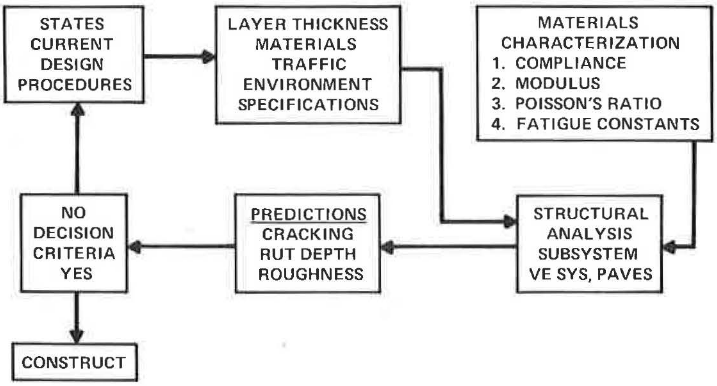


Figure 7. Design check procedures.



where

SI = present serviceability normalized with respect to its initial value (it is described by its distribution function, which can be used to determine the reliability of the system),
C = damage caused by pavement cracking,
RD = damage caused by change in the transverse profile, and
SV = damage caused by change in the longitudinal profile.

This estimates the change in serviceability due to accumulation of damage caused by the interaction between the pavement and the traffic in a given environment.

DESIGN CHECK PROCEDURE

The structural subsystem will be used initially as a check procedure for analysis of state pavement designs as shown in Figure 7. In general, the use of this package will involve the following:

1. Pavement sections are designed according to state's normal procedures;
2. The computer program (6) is used to analyze the design section;
3. If the structural analysis indicates that one or more of the failure mechanisms (cracking, roughness, or rutting) will occur at a more rapid rate than is thought to be tolerable, the original design is modified and evaluated by the computer program (step 2 above) until an acceptable design is obtained; and
4. After the pavement is constructed, performance measurements are taken and compared to the predicted values (as experience is gained, feedback information will indicate where the structural design subsystem may need modification).

COMPUTER PROGRAM

Input

Four input categories are used by the programs in predicting pavement performance: system geometry, material properties, traffic characteristics, and temperature history. In addition, spatial correlation coefficients must be prescribed for the roughness model. These coefficients range from 0 for a very rough pavement to 1 for a smooth pavement and are based on the history of material and construction control in the state. Until more precise data become available, coefficients based on information gained in quality assurance research have been incorporated in the program for initial trials.

System Geometry—In the current program, system geometry is expressed in terms of the thickness of the first and second layers.

Material Properties—The material properties are divided into 2 categories: those expressing the stress-strain relations of each layer of material and those describing a failure characteristic. The stress-strain relations require determination of the creep compliance function for rate-dependent materials and elastic moduli for rate-independent materials. The rate-dependent properties are obtained from creep tests. Values of the modular creep compliance, as described by Eq. 1, are plotted versus time on log-log paper. Care should be taken in testing materials to ensure that test results reflect the effects of stress state, temperature, moisture content, and conditions corresponding to those of the in situ pavement. When asphalt-bound samples are tested, a sufficient number of tests at different temperatures should be run to establish the master creep compliance curves and hence the time-temperature shift factor a_T.

Since the programs will also handle variations in the material properties, the user has the option of specifying those significant variations in the properties that he or she expects in the field. A very simplified method of estimating anticipated variations of material properties is presented by Kenis in another report (16). Figure 8, from that report, shows how the estimated standard deviations of creep compliance vary for different points in time. An average coefficient of variation can be obtained from these values for input to the programs. In practice, the user need only punch selected values from the mean compliance curve and the average coefficient of variation of this curve

Figure 8. Material variation.

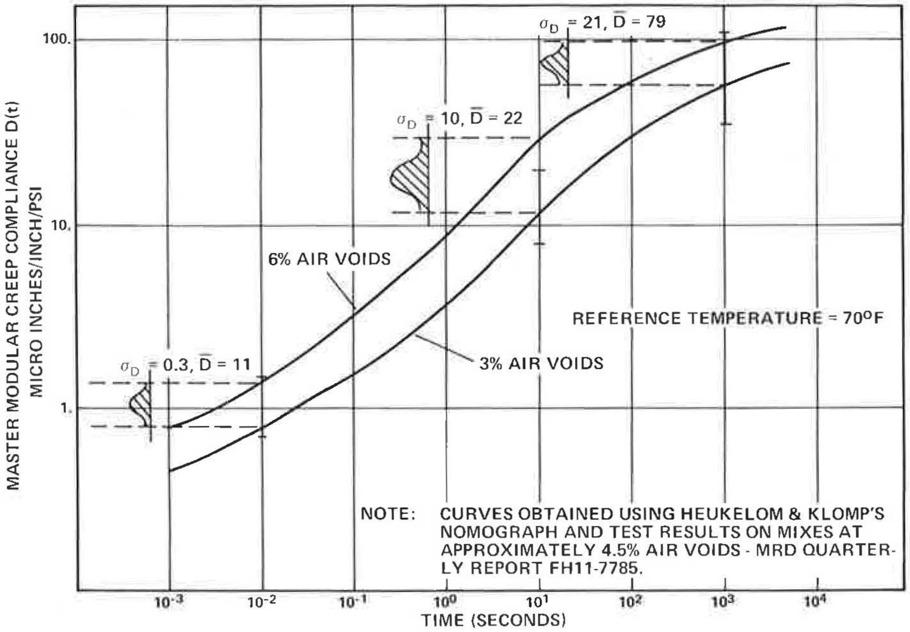
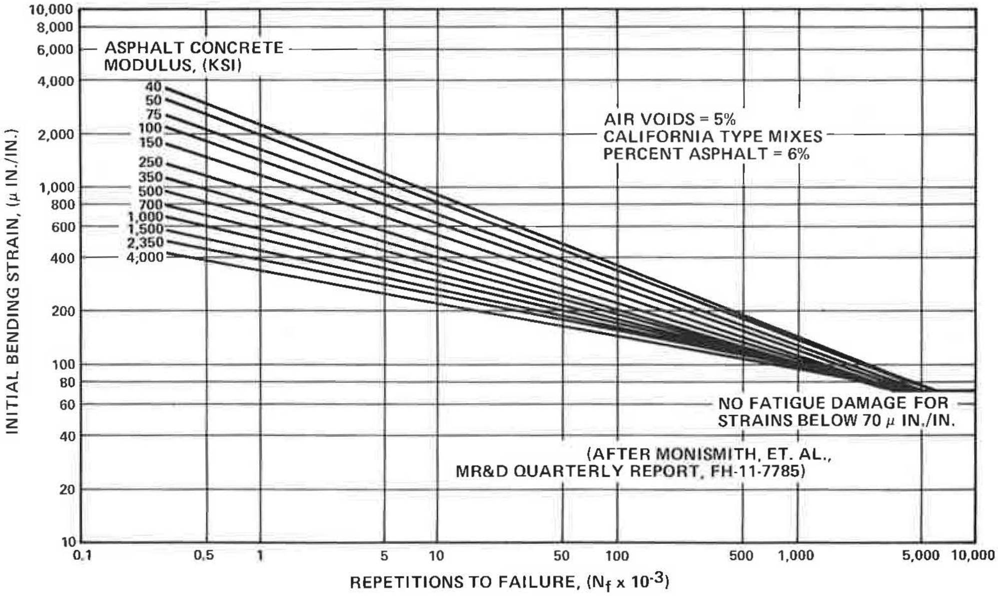


Figure 9. Fatigue failure criteria.



onto computer cards and insert them in the deck.

The elastic or resilient modulus can be obtained for granular or cement-treated materials from complex or dynamic modulus tests, or the instantaneous elastic response occurring in the creep test can be used. The use of an elastic modulus for any given layer would indicate that this layer exhibited an insignificant amount of creep under long-term loading. When the modulus depends on the state of stress, such as in a granular base course, it may be desirable to use the following relation:

$$M_R = A_1 \phi A_2 \tag{7}$$

where M_R is the resilient modulus, ϕ is the first stress invariant, and A_1 and A_2 are constants determined from laboratory tests (7, 10, 12, 13, 19, 20).

Certain fine-grained materials will also exhibit rate-dependent properties and may be characterized as such (21, 22). Tests to establish material properties are being further developed and will be standardized by ASTM. However, current methods have been adopted by many of the researchers and will be recommended for use in conjunction with the check procedure.

When fatigue failure properties are established, fatigue curves similar to those shown in Figure 9 are customarily developed. In computing fatigue life, the computer makes use of 2 constants, K_1 and K_2, which are developed from the curves shown in and are related to Eq. 4. Mathematically K_1 can be expressed as the intercept b raised to the -1/m power (b-1/m), and K_2 is the reciprocal of the slope of the curve (-1/m). These constants play a significant role in the computation of fatigue life; therefore, the variance of the values of K_1 and K_2 plays an important role in the reliability of the computations.

Traffic Characteristics—Figure 10 shows statistical characteristics that have been assumed to represent the loading conditions for a typical highway. The loading of a pavement system is assumed to be a process of independent random arrivals. Vehicles arrive at some point on the pavement in a random manner both in space and in time. The arrival process is modeled as a statistical distribution, a Poisson process, with a mean rate of arrival. It is assumed that a logarithmic-normal distribution is suitable to represent the scatter in load amplitudes. Means and variances of load amplitudes are also used to represent this scatter.

The load duration, a function of vehicle speed on the highway, is also a random variable. In a typical highway, for example, speeds may vary from 40 to 70 mph. Accordingly, the load duration is assumed to have a statistical scatter represented by its mean and variance from distributions obtained by traffic studies.

The load variables must be determined for specific conditions and are used as input to the computer program. The mean and the standard deviation of each variable are determined by the user. The lateral distribution of traffic must also be known. In this program it is assumed that 75 percent of the traffic is channelized. A summary of the loading variables is as follows:

1. Radius of the applied loads, in inches;
2. Intensity of loads, in pounds per square inch;
3. Duration of the loads, in seconds; and
4. Rate of load applications per month and the proportion of channelized loads.

Temperature History—The current version of the programs automatically accounts for annual temperature variation. The variations in pavement response during the year from one temperature period to another are determined through application of the time-temperature superposition principle. One can choose the temperature periods in such a way that averaging temperatures within these periods is justified. The present computer program allows for the study of hourly, daily, weekly, monthly, quarterly, or yearly intervals of time. Application of the time-temperature superposition principle has demonstrated that the relation

$$\log a_T = 0.09(To - T) \tag{8}$$

Figure 10. Distribution of load characteristics.

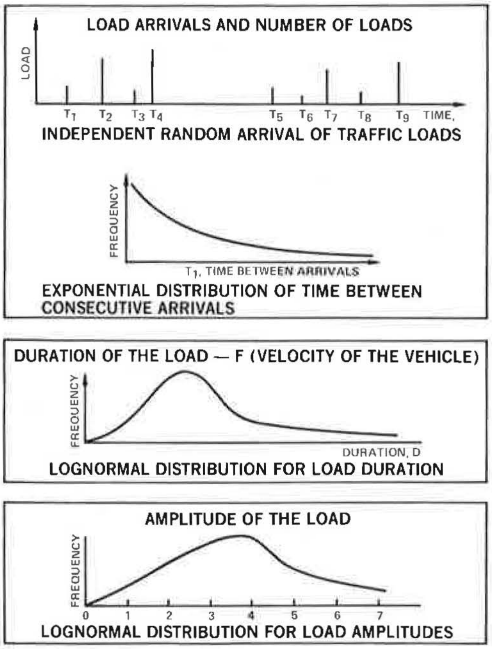


Figure 11. Temperature shift factor.

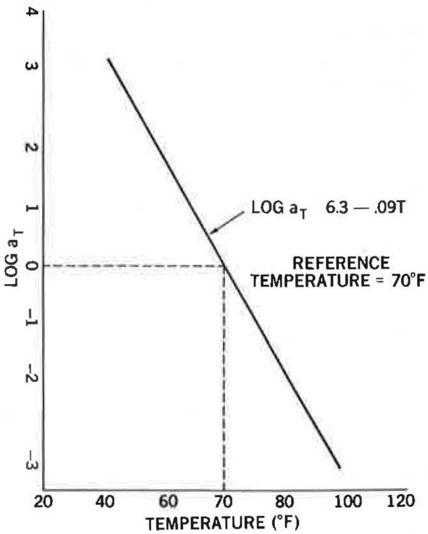
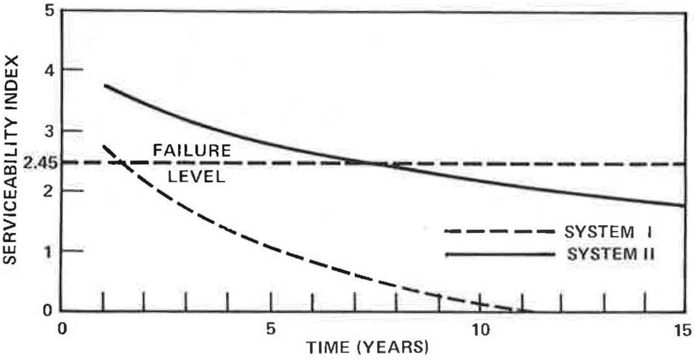


Table 1. Response history of 2 pavement systems.

	Rut Depth		Slope Variance		Cracks	
Years	Expected Value	Variance	Expected Value	Variance	Expected Value	Variance
System 1						
1	0.1058124 D-04	0.7016140 D-11	0.8957364 D-09	0.3189094 D-19	0.2545644 D-02	0.3626053 D-02
3	0.1363651 D-04	0.7362124 D-11	0.9353431 D-09	0.3330551 D-19	0.7636933 D-02	0.1087816 D-03
6	0.1567957 D-04	0.7507012 D-11	0.9468578 D-09	0.3371604 D-19	0.1527387 D-03	0.2175632 D-03
10	0.1740845 D-04	0.7628664 D-11	0.9530464 D-09	0.3393539 D-19	0.2545644 D-03	0.3625053 D-03
12	0.1805977 D-04	0.7679161 D-11	0.9548168 D-09	0.3399763 D-19	0.3054773 D-03	0.4351263 D-03
15	0.1884290 D-04	0.7747835 D-11	0.9565659 D-09	0.3405849 D-19	0.3818466 D-03	0.5439079 D-03
System 2						
1	0.7749276 D-05	0.3763186 D-11	0.4804291 D-09	0.9242749 D-20	0.3366507 D-02	0.6420968 D-02
3	0.1000001 D-04	0.3950931 D-11	0.5019319 D-09	0.9657749 D-20	0.1009952 D-03	0.1926290 D-03
6	0.1149962 D-04	0.4029092 D-11	0.5081370 D-09	0.9777295 D-20	0.2019904 D-03	0.3852581 D-03
10	0.1276699 D-04	0.4094688 D-11	0.5114631 D-09	0.9840995 D-20	0.3366507 D-03	0.6420968 D-03
12	0.1324438 D-04	0.4121933 D-11	0.5124144 D-09	0.9859065 D-20	0.4039809 D-03	0.7705161 D-03
15	0.1381838 D-04	0.4159002 D-11	0.5133544 D-09	0.9866735 D-20	0.5049761 D-03	0.9631451 D-03

Figure 12. Serviceability index.



is reasonably valid for a wide variety of asphalt mixes (11). In this expression a_T is the time-temperature shift factor, and To and T are the reference and prevailing temperatures respectively. This curve is shown in Figure 11 for a reference temperature of 70 F.

Output

The output of the computer programs provides information dealing with both pavement response and its relation to pavement performance. Values are presented as means and variances of the following:

1. Rutting in the wheelpath at the pavement surface in terms of accumulated deformation of the component layers;
2. Pavement roughness in terms of slope variance resulting from the variance of rut depth in the wheelpath;
3. Strain in the wheelpath on the underside of the asphalt layer;
4. Fatigue damage in terms of cracked surface area that is related to percentage of pavement life; and
5. Present serviceability index, as defined by AASHTO, at specified points in time.

Typical computer output for 2 pavement systems is given in Table 1. The material properties of the 2 systems were varied while all other inputs were held constant (4). System 1 has less cracking but more rutting and roughness. This comparison is intended to emphasize that, although a given system may reflect adequate structural integrity in one failure mode, it may not resist another. Serviceability index for the 2 systems is shown in Figure 12. This view indicates that the serviceability index as defined by AASHTO is less influenced by the amount of cracking than it is by roughness and rutting. These comparisons are only included to indicate the capabilities of the systems. Numerical values are dependent on realistic inputs from experimental field observations. As experimental and field data become available, the structural subsystem models will be adjusted accordingly.

SUMMARY

A brief overview of the research accomplishments emanating from the federally coordinated research project on new methodology for flexible pavement design has been presented. The use of a structural subsystem as a design check procedure was described. More research is under way not only to improve and refine the methods presented but also to develop and test a complete system that will incorporate maintenance, economics, and decision theory as integral parts of a design-management system.

ACKNOWLEDGMENT

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IMPLEMENTATION OF A SYSTEMS APPROACH TO PAVEMENT DESIGN

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ABRIDGMENT

A systems analysis model for pavements has been implemented in Florida, Kansas, and Louisiana. A computer program for the design of flexible pavements using the AASHO Interim Guide as a structural subsystem has been developed and can be implemented within any state. It incorporates most of the major variables involved in pavement design in a realistic way. Revisions required to accommodate the unique factors of each state can usually be made with a minimum of reprogramming effort. Collateral improvements such as construction cost simulation and pavement feedback data systems are required to provide reliable input data and, in the long run, to verify the assumptions made in design.

•NCHRP project 1-10, Translating AASHO Road Test Findings: Basic Properties of Pavement Components, commenced in 1966 and was completed in 1970 (1, 2). The work resulted in an increased interest and use of computerized systems approaches to pavement design, and NCHRP funded an additional project to determine whether the systems analysis model for pavements (SAMP5) could be implemented in states other than the one where it originated (3).

The main aims of the project were to test an overall system with a strategic approach to the pavement design process and to get an in-depth evaluation of the approach by the cooperating states. The state highway departments of Florida, Kansas, and Louisiana agreed to cooperate in the project. Major revisions made to the SAMP5 program to satisfy the design requirements of the states resulted in SAMP6, a new version of the program.

The major finding of this project was that SAMP6 is a working systems model for pavements. The states in which the computer program was tested expect to use it in their design system: Louisiana for design; Florida for design studies and as a building block for a future, more mechanistically oriented design system; and Kansas as a supplement to its current design system. States that currently use the AASHO Interim Guide as a design method can use the SAMP6 computer program directly. Other states that wish to use some other structural subsystem must use one that predicts the decrease of serviceability index (SI) with time and traffic. Then, their structural subsystem can be inserted directly into the SAMP6 computer program as it now stands. The effort required to implement the SAMP6 system within any state has been reduced to a minimum by providing the following:

1. SAMP6 in modular, distinct subsystems that can be replaced or reprogrammed with a minimum of effort;
2. A users' guide, 2 program documentation decks, and flow charts;
3. These programs on magnetic tape;
4. All equations used in SAMP6 assembled in the appendix to the final report of the project.

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The main problems encountered in implementation are the following:

1. Organization. How the state is organized to design pavements is important, i.e., whether it has a centralized or decentralized organization and whether a single person or section has primary responsibility for technical details of pavement design or whether a committee has this responsibility. The more dispersed the responsibility is, the more extensive are the required implementation efforts.
2. Confidence in the model. There is a greater tendency for pavement designers to use the program if they know what is in the program, if they trust and agree with the models used, if they believe that all or most of the pertinent factors are included, and if the predicted results on conventional pavements match what their experience indicates is a successful design.
3. Reliable data. Sometimes too much data are collected for some subsystems and not enough for others. The SAMP6 program provides a framework within which the right amount of data can be collected. As experience is gained, the reliability of the data can be improved.

Figure 1 shows the operation of the SAMP6 program. The present program includes all of the features shown except a consideration of seal coat and skidding accident costs for which few reliable data are currently available. The SAMP6 program can consider the costs of all materials in the cross section, including the shoulders, and can allow these costs to vary with the volume of material placed. Full cross-sectional design and variable costs have proved to have significant effects on optimum pavement strategy.

BENEFITS OF USING THE SYSTEMS APPROACH

The systems approach may be used to satisfy a variety of pavement design objectives, including the following:

1. Minimization of the total cost of the pavement during a given analysis period,
2. Minimization of construction costs,
3. Reconsideration of the optimal overlay strategy throughout the life of the pavement, and
4. Determination of optimum design strategies in periods of inflation and cost fluctuation such as those due to the energy crisis.

An example of this latter use is a typical run for Florida in 1973 when the asphalt cost was estimated to be 18 cents per gallon. SAMP6 was run again in 1974 with the same data except that the asphalt cost was estimated to be 36 cents per gallon. The results are given in Table 1.

Pavement designs using thick asphalt surface courses or sand-asphalt hot-mixed base courses generally remained in the top 30 designs but lost an average of 3.3 positions in the rankings. On the other hand, designs using water-bound limerock base moved up in the rankings by an average of 2.4 positions. The general trend is obviously to use less asphalt.

The ability to make routine studies of this sort can result in a fine-tuning of pavement design practice to the current market situation. The management and financial benefits to the highway department and the public are readily apparent.

REMOTE TERMINAL APPLICATIONS

The SAMP6 program and several others developed for the Texas Highway Department are available for use in an interactive mode in which a remote terminal can be acoustically coupled by telephone with the IBM 360/65 computer at Texas A&M University. A list of compatible terminals is available on request from the authors.

The interactive mode is a self-teaching arrangement that takes the person using the program through all of the steps of data input, piece by piece, explaining each step and giving typical values of input data. All of the data can then be stored in the user's data set. The user who wishes to run a similar problem sometime later can display the stored data set, make any desired changes, and rerun the problem. This capability

Figure 1. Operation of SAMP6.

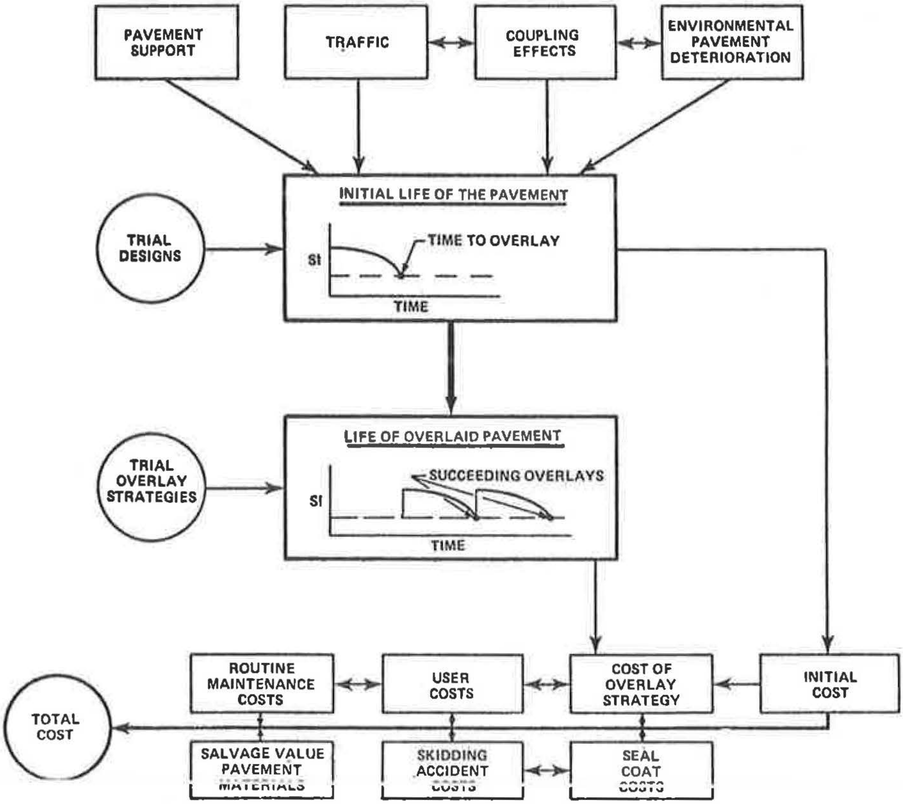

Table 1. Effect of energy crisis on optimum pavement strategy.

Category	Before Energy Crisis	After Energy Crisis
Optimum pavement thickness, in.		
Asphaltic-concrete surface course	4	1
Limerock base course	–	4
Type B stabilized subbase course	–	8
Number of overlays (40-year period)	9	4
Average thickness of best 30 designs, in.	10.5	11.6
Minimum total cost, dollars/yd^2	7.18	7.94
Increase of cost, percent	–	+10.6

makes a sensitivity analysis a simple matter. The system programs that are currently available on remote terminal in the interactive mode are as follows:

1. AASHO Interim Guide flexible pavement system (SAMP6),
2. Texas flexible pavement design system (3),
3. Texas flexible pavement design system using 3-layer elastic theory (4),
4. Texas rigid pavement system (5), and
5. Texas overlay design (6).

All of these systems analysis programs have been implemented to some extent within a state highway department. One of these, the flexible pavement design system, is in common use in 10 of the 26 districts of the Texas Highway Department.

FUTURE IMPROVEMENTS

The following suggested improvements are based on evaluations by the cooperating states and the research team of the current capabilities and limitations of the SAMP6 computer program. System improvements to be recommended can be incorporated within the SAMP6 program itself. The collateral improvements to be suggested are entirely separate computer programs or data systems.

System Improvements

A systems program should be able to consider different designs along a single stretch of road. The designer is normally faced with variations in subgrade type as well as transitions from cut to fill along the length of a project. Although each of these sections could be considered separately by the current version of SAMP6, the separate design of pavement sections, which are built in series, may not be the optimum design. For example, the designer may wish to match depths and material of each of the pavement sections as well as possible. The use of such nearly standard details may result in an overall savings in construction cost. In addition, a systems program should be capable of considering pavement sections in parallel, such as is the case when the pavement width must be expanded to carry more traffic. The optimum material and layer combinations for a widened pavement to be built 10 or 15 years in the future may be different from those combinations that are optimum if the pavement is built now. A long-range improvement of SAMP6 is the development of a rigid pavement system similar to the flexible one so that both concrete and asphalt pavements can be considered side by side in the same program. In addition, there is a need to develop decision criteria on the weighting of various costs. Still unsettled is the question whether the following costs should be considered equally in determining the total cost of the system: initial construction; maintenance and rehabilitation; user costs such as traffic delay due to rehabilitation, roughness, and accidents; salvage value; and inflation and time value of money. Finally, there appears to be a need to develop another measure of system performance. A serviceability index measures riding quality, and perhaps a safety index is needed also.

Collateral Improvements

Three major developements will aid the operation and reliability of a pavement design and management system such as SAMP6. These are feedback data systems whether they are computerized or not, construction cost estimation by computer simulation, and maintenance rating systems. The pavement feedback data system is used most efficiently if it is part of an overall maintenance management system as is the case in Louisiana and Florida. Construction cost estimation by computer simulation can be done with existing programs (7) and can show areas where improved operations can save substantial costs. A maintenance rating system should be composed carefully so as to provide numerical values for various forms of pavement distress.

Subsystem Improvements

A number of improvements in the subsystems currently in SAMP6 fall into the areas of the structural subsystem, environmental serviceability loss subsystem, user cost and maintenance costs subsystems, and safety. In the structural subsystem, the models to be developed should be based on mechanics but should not be so complicated as to require extensive computer running time. Any new structural subsystem for SAMP6 should be capable of predicting pavement riding quality and safety deterioration due to traffic. Each of these is affected differently by distress mechanisms such as cracking, roughness, rutting, and polishing. These same kinds of distress can be caused by a hostile environment. Cracking can be caused by thermal cooling, thermal fatigue, and shrinkage. Roughness can be caused by cracking, frost heave, and expansive clay.

A currently funded Federal Highway Administration project is expected to produce results that will be applicable in the user cost subsystem. There is a continuing need to keep the unit costs within that subsystem up to date. The maintenance cost models within SAMP6 could be improved to include important variables such as traffic and temperature, which are not now included in a satisfactory way.

Many experienced engineers think that seal-coating extends the service life of a pavement and upgrades the skid resistance of the surface. This potentially beneficial effect of seal coats on the performance of a pavement needs to be considered.

SUMMARY

The SAMP6 program has been implemented in 3 states and has proved to be a practical, working systems model for pavements. Its implementation requires attention to numerous details of design technique and policy and its improvement, which is desirable in certain areas, will be a simple task. A variety of financial benefits can be derived in using it as an aid in making strategic pavement design and management decisions. It is readily available for use by all pavement designing organizations.

ACKNOWLEDGMENT

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DEVELOPMENT AND USE OF A PAVEMENT DATA SYSTEM

Marion F. Creech and Stephen N. Runkle, Virginia Highway Research Council

This paper details the development of a pavement data system that can be used in combination with other data systems to provide useful information to the Virginia Department of Highways for the purpose of planning maintenance resurfacing, skid resistance research studies, and pavement durability studies. The paper includes a general outline of the pavement data system, a discussion of the collection of historical data and the implementation of a data collection system for field personnel, and a discussion of the software development required to handle the data. A brief discussion is made of the integrated use of the pavement data with other data systems for the purpose stated above.

•THE CONSTRUCTION of the Interstate Highway System and the dual-laning of the arterial system have ushered in a new highway era in Virginia. This great upsurge in construction activity has generated thousands of pieces of data that have been collected and stored in the various offices of the highway department throughout the state. The original purposes for which the data were collected have been served well, but in the past few years difficulties have been encountered in retrieving these data for other applications. For example, planning for maintenance resurfacing is becoming an increasingly complex and important function. The increasing highway mileage and traffic volumes and the need to maintain a minimum skid resistance require that many variables be considered so that maintenance resurfacing funds are most efficiently allocated. Likewise, many variables must be considered in evaluating the skid resistance properties of various types of aggregates and mixes or in evaluating the performance of materials and pavement designs. Because of the large amounts and the complexity of the data required for various applications, the most feasible systems for handling the data are integrated, automated systems.

The purpose of this paper is to describe the development of a pavement data system that can be used in combination with other data systems to provide useful information to the Virginia Department of Highways for the purpose of planning maintenance resurfacing, skid-resistance studies, and pavement performance studies. In addition to describing the development of the pavement data system, the paper includes a brief discussion of the planned integrated use of the pavement data system with other systems. The paper covers only the work performed prior to August 31, 1973.

PAVEMENT DATA SYSTEM DEVELOPMENT

The most specific uses in mind during the development of the pavement data system were those for maintenance resurfacing planning, skid resistance studies, and pavement durability studies including the evaluation of pavement designs. The total data required to meet these needs were determined by several committees composed of personnel from the Virginia Highway Department; the final judgment was made by a task group composed of top level personnel from the Materials, Maintenance, Construction, Traffic and Safety, and Data Processing Divisions, a district office, and the Research Council. The data agreed to be required are given in Table 1.

Columns 1, 2, and 3 in Table 1 comprise the data in the pavement data system de-

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veloped. The data shown in the remaining columns are contained in either existing automated systems or systems under development.

The pavement data system has 2 basic characteristics:

1. The basic unit in the new system is a surface mix section, which is defined as a length of roadway for which the surface mix type, age, materials data, and other descriptive data remain constant.
2. The locational method used in the system is the milepost as derived from the graphic logs maintained by the Traffic and Safety Division. The use of some locational method such as the milepost is the only effective way of correlating data from several computer systems, and the milepost is the most acceptable method used by the Virginia Department of Highways.

The desired location and descriptive data define the exact location of each surface mix section and provide a general description of the section. Highway system refers to the interstate, arterial, and primary systems and allows analysis of data for each system separately. District, residency, county, city, town, route, direction, lane, and beginning and ending mileposts define the location of the surface mix section and allow outputs to be generated by district, residency, county, city, or town. Descriptive beginning and descriptive ending are included to aid field personnel in their use of the output from the system. Maintenance section is the section used for the allocation of maintenance costs and is included so that projected resurfacing needs can be shown by the maintenance section. Highway type indicates the number of lanes and can be useful in several ways, particularly in determining how many surface mix sections exist across the highway at any point. For instance, the north-south, 4-lane, divided highway may require separate surface mix sections for the northbound and southbound lanes. Also, highway type permits data to be summarized by lane-mile rather than centerline-mile. Length and width are necessary for maintenance purposes to determine the area to be resurfaced (length, of course, can be determined from beginning and ending mileposts). Mix type indicates that the surface is portland cement concrete, surface treatment, slurry seal, mix-in-place, or bituminous concrete (for bituminous concrete the particular mix type such as S-5 is required). Special feature refers to particular characteristics about the surface such as grooved pavement and will be most useful in selecting data for future research studies. Age is required so that output can be provided by age or age and mix type and is determined by including the date of the last resurfacing.

The materials and construction data are desired so that estimations can be made about the useful life remaining for surface mix sections and to facilitate research work on the performance of materials. For instance, surfaces containing limestone aggregates likely will become slippery sooner than those containing other aggregate types and therefore require resurfacing sooner. Also, these data may show that aggregates from certain sources do not perform well from a structural standpoint. The aggregate information is required for each aggregate used in the surface mix.

Data on mix type, depth and percentage of cement, lime, or asphalt for each layer under the surface, and 18-kip equivalent design volume are desirable for several reasons, but principally to indicate the maximum 18-kip equivalent volume the pavement was designed to carry, to aid in the evaluation of the performance of pavement designs, and to aid in deciding what type and rate of resurfacing to apply.

GENERAL SYSTEM OUTLINE

A general outline of how the pavement data system works, independent of any interaction with other systems, is shown in Figure 1. Initially, the data forms should be filled out as explained in the code manual by either the inspector or project engineer assigned to the resurfacing or new construction job. Input form 1 (Fig. 2) is filled out for each job, and input form 2 (Fig. 3) is filled out whenever the job involves the placement of subsurface layers. If no code exists for certain data (for instance, a new quarry source), field personnel are instructed to submit the data in question in written form attached to the data form.

The forms are reviewed in the residency office and submitted with the contract or schedule finals to the district computer's office. The district materials engineer's

Table 1. Data required for highway system.

Section Location and Descriptive Data	Surface Mix Materials and Construction Data	Subsurface Layers and Design Volumes for Each Layer	Dynaflect Data for Each Lane	Skid Data for Each Lane	Accident Data	Volume Data	Resident Engineers' Comments
Highway system District Residency County City and town Route Maintenance section Highway type Direction and lane Beginning milepost Descriptive beginning Ending milepost Descriptive ending Length Width Surface mix type Special feature Age	Application rate Aggregate size Aggregate type Aggregate source Aggregate percentage	Mix type Depth Percentage of cement, lime, and asphalt 18-kip equivalent design volume	Spreadability mean Standard deviation Sample size Date of test	Mean PSDN Standard deviation Sample size Date of test Test vehicle	Total accidents Total fatal accidents Wet accidents Wet fatal accidents Percentage of wet accidents Accident rate	Average vehicles daily Trucks 2 axle, 4 wheels 2 axle, 6 wheels 3 axle Trailer trucks Buses	Date of review Estimated remaining life Reason for resurfacing

Figure 1. Pavement Data System.

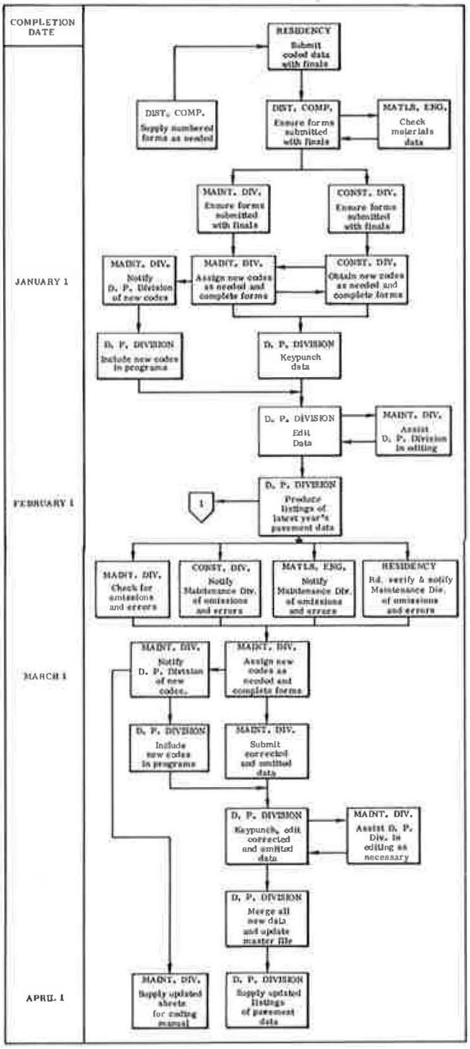
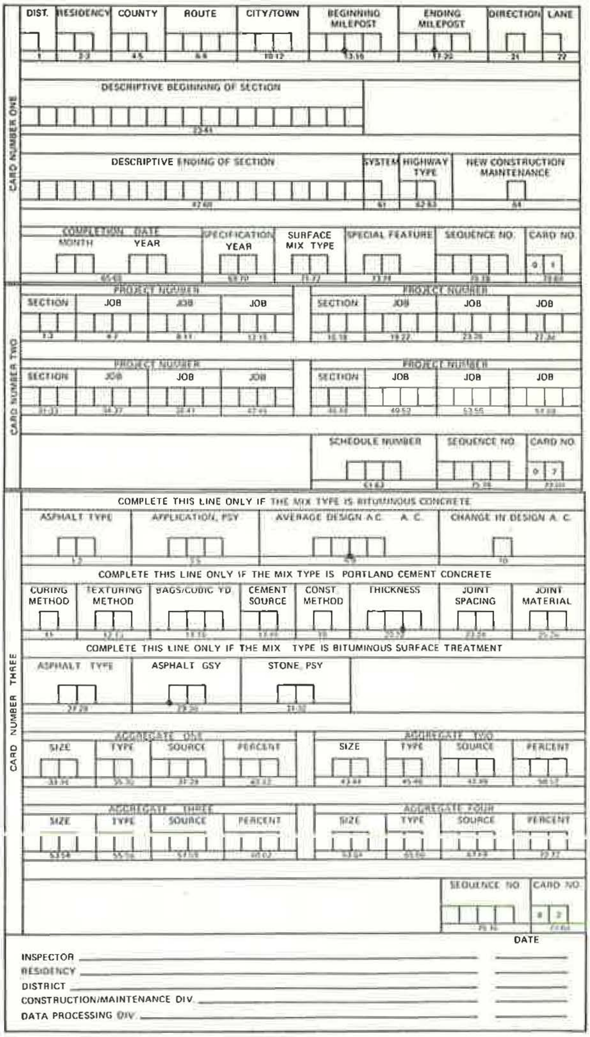


Figure 2. Pavement descriptive information, input form 1.



CARD NUMBER ONE

DIST. | RESIDENCY | COUNTY | ROUTE | CITY/TOWN | BEGINNING MILEPOST | ENDING MILEPOST | DIRECTION | LANE

DESCRIPTIVE BEGINNING OF SECTION

DESCRIPTIVE ENDING OF SECTION | SYSTEM | HIGHWAY TYPE | NEW CONSTRUCTION MAINTENANCE

COMPLETION DATE MONTH YEAR | SPECIFICATION YEAR | SURFACE MIX TYPE | SPECIAL FEATURE | SEQUENCE NO. | CARD NO. 0 1

CARD NUMBER TWO

PROJECT NUMBER: SECTION | JOB | JOB | JOB — PROJECT NUMBER: SECTION | JOB | JOB | JOB

PROJECT NUMBER: SECTION | JOB | JOB | JOB — PROJECT NUMBER: SECTION | JOB | JOB | JOB

SCHEDULE NUMBER | SEQUENCE NO. | CARD NO. 0 7

CARD NUMBER THREE

COMPLETE THIS LINE ONLY IF THE MIX TYPE IS BITUMINOUS CONCRETE

ASPHALT TYPE | APPLICATION, PSY | AVERAGE DESIGN A.C. A. C. | CHANGE IN DESIGN A. C.

COMPLETE THIS LINE ONLY IF THE MIX TYPE IS PORTLAND CEMENT CONCRETE

CURING METHOD | TEXTURING METHOD | BAGS/CUBIC YD | CEMENT SOURCE | CONST METHOD | THICKNESS | JOINT SPACING | JOINT MATERIAL

COMPLETE THIS LINE ONLY IF THE MIX TYPE IS BITUMINOUS SURFACE TREATMENT

ASPHALT TYPE | ASPHALT GSY | STONE PSY

AGGREGATE ONE: SIZE | TYPE | SOURCE | PERCENT — AGGREGATE TWO: SIZE | TYPE | SOURCE | PERCENT

AGGREGATE THREE: SIZE | TYPE | SOURCE | PERCENT — AGGREGATE FOUR: SIZE | TYPE | SOURCE | PERCENT

SEQUENCE NO. | CARD NO. 0 2

DATE

INSPECTOR

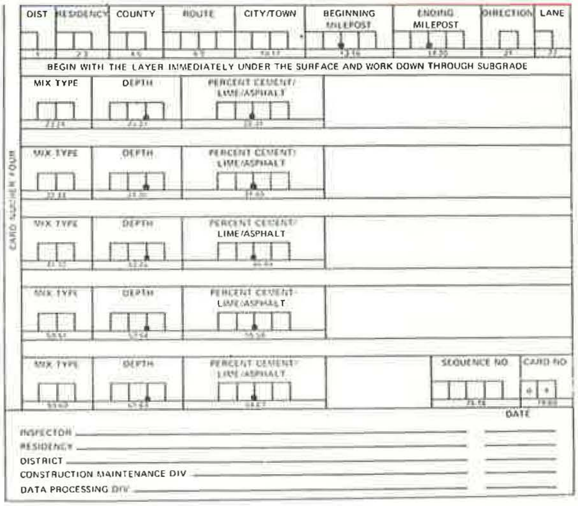
RESIDENCY

DISTRICT

CONSTRUCTION/MAINTENANCE DIV.

DATA PROCESSING DIV.

Figure 3. Pavement descriptive information for subsurface layers, input form 2.



CARD NUMBER FOUR

DIST | RESIDENCY | COUNTY | ROUTE | CITY/TOWN | BEGINNING MILEPOST | ENDING MILEPOST | DIRECTION | LANE

BEGIN WITH THE LAYER IMMEDIATELY UNDER THE SURFACE AND WORK DOWN THROUGH SUBGRADE

MIX TYPE | DEPTH | PERCENT CEMENT/LIME/ASPHALT

MIX TYPE | DEPTH | PERCENT CEMENT/LIME/ASPHALT

MIX TYPE | DEPTH | PERCENT CEMENT/LIME/ASPHALT

MIX TYPE | DEPTH | PERCENT CEMENT/LIME/ASPHALT

MIX TYPE | DEPTH | PERCENT CEMENT/LIME/ASPHALT | SEQUENCE NO | CARD NO

DATE

INSPECTOR

RESIDENCY

DISTRICT

CONSTRUCTION MAINTENANCE DIV

DATA PROCESSING DIV

office checks the forms for the accuracy of the materials and construction data. The forms are then submitted with the finals to the Maintenance Division or Construction Division, depending on whether the work is maintenance resurfacing or new construction. These divisions check to ensure that the correct number of forms are submitted with the finals and then forward them to the Data Processing Division for keypunching.

In addition to checking to ensure that the correct number of forms are submitted, the Maintenance and Construction Divisions assign new codes as necessary. If the work is new construction, the Construction Division obtains a code from the Maintenance Division and completes the form. If the work is maintenance, the Maintenance Division assigns the new code and completes the form. The Maintenance Division is responsible for notifying the Data Processing Division of new codes so that they may be included in the computer programs developed to handle the pavement data.

The reason for including the forms with the finals for a project or schedule is to ensure that forms are submitted when work is completed. A major weakness in previous manual systems was that there was no way to ensure that forms were submitted as work was completed, and consequently much work was completed without any data of the type discussed thus far ever being submitted.

The work described thus far involves all resurfacing and new construction completed from December 1 of one year to December 1 of the following year. A 1-month period (until January 1) is allowed each year to complete forms for work completed prior to December 1 and to submit them to the Data Processing Division. Between January 1 and February 1, the Data Processing Division edits and produces listings of the latest year's data (Fig. 4).

The listings are sent to the Maintenance Division, Construction Division, districts, and residencies for a final check for errors and omissions before the master pavement data file is updated. By March 1 the Maintenance Division is notified of corrections and omissions and submits them to the Data Processing Division along with any new codes assigned. The Maintenance Division is also responsible for supplying to the field updated sheets for the code manual as required by the assignment of new codes.

After receiving the corrections, the Data Processing Division keypunches and edits the data and updates the master pavement data file with the past year's data. Listings of the updated pavement file can then be issued to the field offices and divisions as desired. However, listings containing additional data from other files, as will be discussed later, are more useful for field and central office personnel.

Installations of computer terminals in the district offices may eventually effect a change in the system as described. At present, terminals are in 7 of the 8 districts and are used in a batch-operating mode, principally for design work. However, further work will involve studying the possibility of updating and accessing the pavement data system on a continual basis at the district level by the use of the terminals.

One important feature of the pavement data system not shown in Figure 1 is the periodic review of the system including evaluation by users of its overall usefulness and decisions to omit or add or both certain data elements. The Maintenance Division has the responsibility to ensure that this review is conducted at least each 2 years and more frequently if required.

Development and implementation of the pavement data system involved basically 3 separate functions: collection of historical data, implementation of a new data collection system for field personnel, and computer software development to handle the data. Progress on each of the functions is discussed below.

Collection of Historical Data

The decision was made to collect historical data for the interstate and arterial systems only; data on the interstate, arterial, and primary systems were submitted from the field for new construction and maintenance resurfacing beginning in 1972. Collecting historical data about the subsurface and 18-kip equivalent design volume was impossible.

The collection of the historical data needed as original input for the pavement data system turned out to be a formidable task. Investigation revealed that several sources in the state contained information desired in the study: highway residencies, construction district offices, Research Council, and several divisions of the central office. The methodology selected for collecting the historical data was to compile the information obtained from the highway department's maintenance plant mix forms and construction forms. The collection and compilation involved the use of data contained at each of the offices mentioned above, none of which had complete information. Some of the records of surface mixes were excellent; others were very poor. An advantage of going to the field office was that when records were missing there was usually someone (an engineering clerk or inspector) with knowledge of when the road was surfaced. That knowledge made it possible to obtain information for sections for which records were missing. Information could not be obtained for considerable road mileage and was provided by the authors based on knowledge they obtained while collecting historical data. It may seem unusual that the source of materials can be verified from the road, but the familiarity gained during the study, the somewhat limited number of nonpolishing sources of aggregate in the state, the fact that aggregates can be clearly seen 3 months after the mix is placed, and the fact that one of the authors is a geologist all combined to make this possible.

When all of the information available had been collected, the data were put in order by milepost, and field verification was made in a car equipped with a special survey speedometer to check end-point locations of the sections and the authenticity of the recorded information.

To date, collection of historical data has been completed for the interstate and arterial systems with the exception of the subsurface data and 18-kip equivalent design volume as indicated above. Maintenance section and width also have not been collected for each section, but are readily available from the graphic log. The historical data were coded on the forms designed for input into the pavement data system (Figs. 2 and 3); the code manual designed for this purpose was used. The total effort required to collect and code the historical data was 30 person-months. The authors instructed field personnel in the correct methods of submitting data for the pavement data system.

Implementation of Field Data Collection

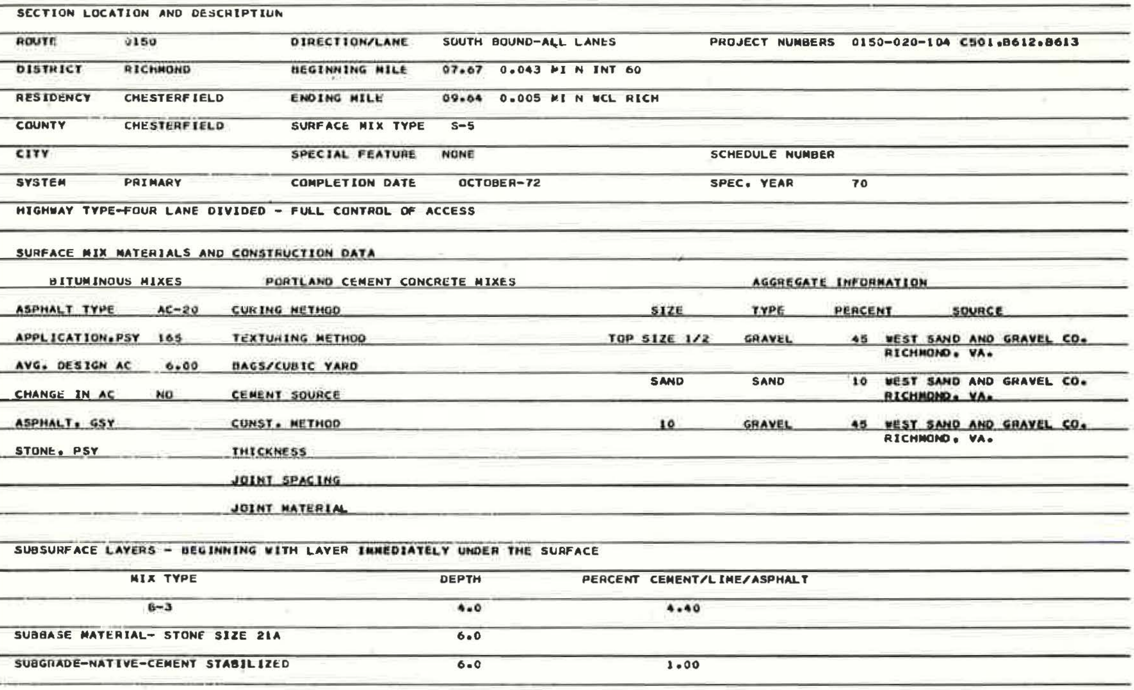
Field implementation of the data collection procedures was accomplished by conducting schools in the department's 8 construction districts. All personnel who have a part in collecting, coding, or checking the data—inspectors, project engineers, maintenance supervisors, residency engineering clerks, district computers, and district materials engineers—were requested to attend. In addition, supervisory personnel such as resident engineers and their assistants and district engineers and their assistants were invited to attend. During the schools the use of the code manual and forms was explained, and several examples of both resurfacing and new construction were coded. In addition, an overview of how the pavement data system works was given. The district materials engineers, in conjunction with the Materials and Maintenance Divisions, have the responsibility of conducting refresher schools in coding as they are required.

The sessions were lively and resulted in much discussion of various items, and several suggestions were made and incorporated in the final version of the code form and manual. Setting up and teaching the schools required about 1 month of time of each of the authors, including the time required for several visits to various residency offices for the purpose of teaching a second school for some of the personnel.

A review of the forms submitted for work completed during 1972 indicates that, in general, a relatively low number of errors occurred. Also, most of the errors seem to be concentrated in 1 or 2 districts. The authors believe that with some limited amount of additional schooling in some districts the data collection will be very satisfactory.

Software Development

The initial work in the development of the software was devoted to the code manual and data forms. The development of this material was handled by the Data Systems and Analysis Section at the Research Council, and the items were reviewed several times by representatives of the Data Processing Division. Care was taken to ensure that the igure 4. Pavement information for latest year.

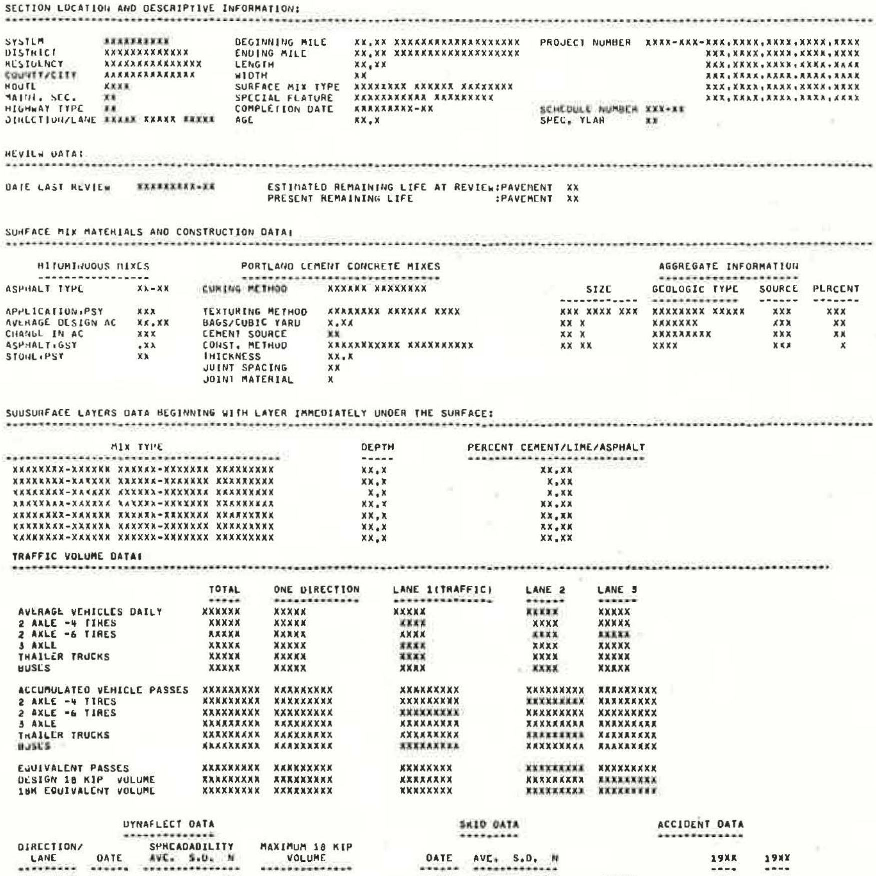


```
SECTION LOCATION AND DESCRIPTION
ROUTE        0150           DIRECTION/LANE    SOUTH BOUND-ALL LANES        PROJECT NUMBERS  0150-020-104 C501.B612.B613
DISTRICT     RICHMOND       BEGINNING MILE    07.67  0.043 MI N INT 60
RESIDENCY    CHESTERFIELD   ENDING MILE       09.64  0.005 MI N WCL RICH
COUNTY       CHESTERFIELD   SURFACE MIX TYPE   S-5
CITY                        SPECIAL FEATURE   NONE                         SCHEDULE NUMBER
SYSTEM       PRIMARY        COMPLETION DATE    OCTOBER-72                  SPEC. YEAR       70
HIGHWAY TYPE-FOUR LANE DIVIDED - FULL CONTROL OF ACCESS

SURFACE MIX MATERIALS AND CONSTRUCTION DATA
   BITUMINOUS MIXES        PORTLAND CEMENT CONCRETE MIXES                          AGGREGATE INFORMATION
ASPHALT TYPE     AC-20   CURING METHOD                                SIZE          TYPE      PERCENT       SOURCE
APPLICATION.PSY  165     TEXTURING METHOD                      TOP SIZE 1/2      GRAVEL         45  WEST SAND AND GRAVEL CO.
                                                                                                    RICHMOND. VA.
AVG. DESIGN AC    6.00   BAGS/CUBIC YARD
                                                                      SAND          SAND        10  WEST SAND AND GRAVEL CO.
CHANGE IN AC     NO      CEMENT SOURCE                                                              RICHMOND. VA.
ASPHALT. GSY             CONST. METHOD                                 10          GRAVEL        45  WEST SAND AND GRAVEL CO.
                                                                                                    RICHMOND. VA.
STONE. PSY               THICKNESS
                         JOINT SPACING
                         JOINT MATERIAL

SUBSURFACE LAYERS - BEGINNING WITH LAYER IMMEDIATELY UNDER THE SURFACE
            MIX TYPE                             DEPTH          PERCENT CEMENT/LIME/ASPHALT
              B-3                                 4.0               4.40
SUBBASE MATERIAL- STONE SIZE 21A                  6.0
SUBGRADE-NATIVE-CEMENT STABILIZED                 6.0               1.00
```

gure 5. Detailed output
f proposed system.



```
SECTION LOCATION AND DESCRIPTIVE INFORMATION:
*****************************************************************************************************************

SYSTEM          XXXXXXXXXX        BEGINNING MILE    XX.XX XXXXXXXXXXXXXXXXXX   PROJECT NUMBER  XXXX-XXX-XXX,XXXX,XXXX,XXXX,XXXX
DISTRICT        XXXXXXXXXXXX      ENDING MILE       XX.XX XXXXXXXXXXXXXXXXXX                            XXX,XXXX,XXXX,XXXX,XXXX
RESIDENCY       XXXXXXXXXXXXXX    LENGTH            XX.XX                                               XXX,XXXX,XXXX,XXXX,XXXX
COUNTY/CITY     XXXXXXXXXXXXX     WIDTH             XX                                                  XXX,XXXX,XXXX,XXXX,XXXX
ROUTE           XXXX              SURFACE MIX TYPE  XXXXXXXX XXXXXX XXXXXXX                             XXX,XXXX,XXXX,XXXX,XXXX
MAINT. SEC.     XX                SPECIAL FEATURE   XXXXXXXXXXX XXXXXXXXX                               XXX,XXXX,XXXX,XXXX,XXXX
HIGHWAY TYPE    XX                COMPLETION DATE   XXXXXXXXX-XX               SCHEDULE NUMBER XXX-XX
DIRECTION/LANE XXXXX XXXXX XXXXX  AGE               XX.X                       SPEC. YEAR      XX

REVIEW DATA:
*****************************************************************************************************************

DATE LAST REVIEW    XXXXXXXXX-XX        ESTIMATED REMAINING LIFE AT REVIEW:PAVEMENT  XX
                                        PRESENT REMAINING LIFE            :PAVEMENT  XX

SURFACE MIX MATERIALS AND CONSTRUCTION DATA:
*****************************************************************************************************************

     BITUMINOUS MIXES              PORTLAND CEMENT CONCRETE MIXES                            AGGREGATE INFORMATION
     ----------------              ------------------------------                            ---------------------
ASPHALT TYPE          XX-XX    CURING METHOD      XXXXXX XXXXXXXX                 SIZE      GEOLOGIC TYPE   SOURCE  PERCENT
                                                                              ------------  -------------   ------  -------
APPLICATION.PSY       XXX      TEXTURING METHOD   XXXXXXXX XXXXXX XXXX        XXX XXXX XXX  XXXXXXXX XXXXX    XXX      XXX
AVERAGE DESIGN AC     XX.XX    BAGS/CUBIC YARD    X.XX                        XX X          XXXXXXX           XXX       XX
CHANGE IN AC          XXX      CEMENT SOURCE      XX                          XX X          XXXXXXXXX         XXX       XX
ASPHALT.GSY           .XX      CONST. METHOD      XXXXXXXXXX XXXXXXXXX        XX XX         XXXX              XXX        X
STONE.PSY             XX       THICKNESS          XX.X
                               JOINT SPACING      XX
                               JOINT MATERIAL     X

SUBSURFACE LAYERS DATA BEGINNING WITH LAYER IMMEDIATELY UNDER THE SURFACE:
*****************************************************************************************************************

               MIX TYPE                             DEPTH        PERCENT CEMENT/LIME/ASPHALT
*******************************************         -----        ---------------------------
 XXXXXXXX-XXXXXX XXXXXX-XXXXXXX XXXXXXXXX           XX.X                  XX.XX
 XXXXXXXX-XXXXXX XXXXXX-XXXXXXX XXXXXXXXX           XX.X                   X.XX
 XXXXXXXX-XXXXXX XXXXXX-XXXXXXX XXXXXXXXX            X.X                   X.XX
 XXXXXXXX-XXXXXX XXXXXX-XXXXXXX XXXXXXXXX           XX.X                  XX.XX
 XXXXXXXX-XXXXXX XXXXXX-XXXXXXX XXXXXXXXX           XX.X                  XX.XX
 XXXXXXXX-XXXXXX XXXXXX-XXXXXXX XXXXXXXXX           XX.X                  XX.XX
 XXXXXXXX-XXXXXX XXXXXX-XXXXXXX XXXXXXXXX           XX.X                  XX.XX
 TRAFFIC VOLUME DATA:
 *************************************************************************************************************

                                TOTAL     ONE DIRECTION    LANE 1(TRAFFIC)    LANE 2     LANE 3
                                -----     -------------    ---------------    ------     ------
  AVERAGE VEHICLES DAILY       XXXXXX     XXXXX            XXXXX              XXXXX      XXXXX
  2 AXLE -4 TIRES               XXXXX     XXXXX             XXXX               XXXX      XXXXX
  2 AXLE -6 TIRES               XXXXX     XXXXX             XXXX               XXXX      XXXXX
  3 AXLE                        XXXXX     XXXXX             XXXX               XXXX      XXXXX
  TRAILER TRUCKS                XXXXX     XXXXX             XXXX               XXXX      XXXXX
  BUSES                         XXXXX     XXXXX             XXXX               XXXX      XXXXX

  ACCUMULATED VEHICLE PASSES  XXXXXXXXX  XXXXXXXXX          XXXXXXXXX         XXXXXXXXX  XXXXXXXXX
  2 AXLE -4 TIRES             XXXXXXXXX  XXXXXXXXX          XXXXXXXXX         XXXXXXXXX  XXXXXXXXX
  2 AXLE -6 TIRES             XXXXXXXXX  XXXXXXXXX          XXXXXXXXX         XXXXXXXXX  XXXXXXXXX
  3 AXLE                      XXXXXXXXX  XXXXXXXXX          XXXXXXXXX         XXXXXXXXX  XXXXXXXXX
  TRAILER TRUCKS              XXXXXXXXX  XXXXXXXXX          XXXXXXXXX         XXXXXXXXX  XXXXXXXXX
  BUSES                       XXXXXXXXX  XXXXXXXXX          XXXXXXXXX         XXXXXXXXX  XXXXXXXXX

  EQUIVALENT PASSES           XXXXXXXXX  XXXXXXXXX          XXXXXXXX          XXXXXXXXX  XXXXXXXXX
  DESIGN 18 KIP  VOLUME       XXXXXXXXX  XXXXXXXXX          XXXXXXXX          XXXXXXXXX  XXXXXXXXX
  18K EQUIVALENT VOLUME       XXXXXXXXX  XXXXXXXXX          XXXXXXXX          XXXXXXXXX  XXXXXXXXX

                   DYNAFLECT DATA                                      SKID DATA                ACCIDENT DATA
                   --------------                                      ---------                -------------
  DIRECTION/                SPREADABILITY   MAXIMUM 18 KIP
    LANE        DATE      AVG.  S.D.  N         VOLUME             DATE   AVG.  S.D.  N                          19XX     19XX
  ---------    ------    ---------------    --------------        ------  -------------                          ----     ----
  XX XXXX X    XX-XX      .XX   .XX  XXX        XXXXXX            XX-XX    XX    XX  XX       TOTAL               XXX      XXX
  XX XXXX X    XX-XX      .XX   .XX  XXX        XXXXXX            XX-XX    XX    XX  XX       TOTAL FATALS         XX       XX
  XX XXXX X    XX-XX      .XX   .XX  XXX        XXXXXX            XX-XX    XX    XX  XX       WET                 XXX      XXX
  XX XXXX X    XX-XX      .XX   .XX  XXX        XXXXXX            XX-XX    XX    XX  XX       WET FATALS           XX       XX
  XX XXXX X    XX-XX      .XX   .XX  XXX        XXXXXX            XX-XX    XX    XX  XX       PERCENT WET         XXX      XXX
  XX XXXX X    XX-XX      .XX   .XX  XXX        XXXXXX            XX-XX    XX    XX  XX       ACCIDENT RATE      XXXX     XXXX
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codes developed corresponded to those that exist in other automated systems, which eventually will be used in an integrated manner with the pavement data system. Development of this material required about 2 person-months of time and was completed prior to implementing a final data collecting system in the field or coding historical data.

After work was completed on the code manual and forms, work was begun on the development of computer programs to edit and produce listings of the pavement data. The programming work was handled by the Data Processing Division staff, who had frequent discussions with the authors concerning the requirements to be met in these programs. The programs were written in assembly language and ANSI COBOL languages to be run on the IBM 370-155 computer operated by the Data Processing Division.

A sample of the output produced by these programs is shown in Figure 4. No codes are printed as part of the output. The authors were insistent that coded output not be allowed, for they felt it would greatly diminish the use of the output. Blank spaces occur on the output when a particular data item is not applicable to the section, such as those items shown in Figure 4 under portland cement concrete mixes. To date the programs have been used to provide initial listings of all historical data as well as separate listings of data submitted by the field for work completed during 1972.

Work is under way by the Data Systems and Analysis Section to develop programs for data corrections and updating. Initially these programs will be used to make corrections to the historical data and 1972 data and then to update the master file (historical data) with the 1972 data. These programs are being written in IBM compatible FORTRAN IV and ANSI COBOL. The installation in the near future of a terminal at the Research Council will permit access to the IBM 370 operated by the Data Processing Division and will facilitate the implementation of these programs.

Thus far the program for corrections has been completed and tested and is being used to enter corrections of the 1972 and historical data in preparation for the initial update.

The update program represents a major programming effort for several reasons. First, on occasion the update record will not correspond to the beginning and ending points of an existing section, but instead will overlap 2 or more existing sections or be within an existing section. In addition, the update information may refer to all lanes in both directions or any group of lanes in either direction. For all of these reasons, an update at times is likely to have the effect of creating several new sections. The procedure may be complicated even further if the update reflects new construction that could be the replacement of existing roadway or completely new roadway. A further complication is that historical data are retained for each section of the surface.

The programming effort expended thus far has amounted to 5 or 6 person-months. Additional software is under development for the integrated applications.

INTEGRATED USES OF PAVEMENT DATA SYSTEM

Some of the anticipated uses of the pavement data system are for maintenance planning, skid resistance research studies, and pavement durability studies. Each use will require that pavement data be integrated with the other types of data given in the last 5 columns of Table 1. These data can be divided into the 5 categories of Dynaflect data, skid data, accident data, traffic volume data, and resident engineers' comments. Before discussing the intended uses, we should first discuss what data bases exist for these 5 categories and what work will be done to further develop these data bases.

At present, all Dynaflect data are collected by the Pavement Section of the Research Council. These data are collected on particular construction projects for research purposes and, at times, on pavements requiring resurfacing to gain an indication of what type and thickness of resurfacing to apply. There is no automated system to handle Dynaflect data, but plans are to develop and implement one suitable to the requirements of maintenance planning and pavement evaluation.

Skid data are also collected by the Research Council. The Maintenance Section uses both a stopping distance car and skid trailer to obtain data and at present has more than 30,000 test results. An automated system has been developed by the Data Systems and Analysis Section to handle skid data. This system is compatible in all respects with the pavement data system. In addition, a new skid trailer is being purchased by the highway department to be operated by the Materials Division as a survey vehicle. Data obtained with this new trailer will be included in the skid data base.

Accident data are maintained in an automated system by the Data Processing Division. These data are located by county, route, and milepost and thus can be associated directly with pavement surface mix section and skid data.

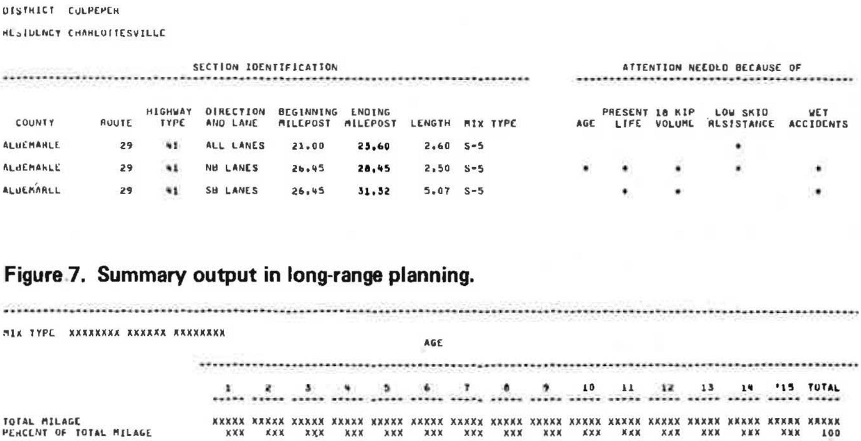
Traffic volume data are also maintained in an automated system by the Data Processing Division. However, these data are located not by milepost but by traffic sections. A determination will be made of the most appropriate method of obtaining traffic volume data, including the consequences of assigning beginning and ending mileposts to the traffic sections or the possibility of building a separate file compatible with the other data files discussed thus far.

Resident engineers' review data do not yet exist, but will be collected on the basis of pavement surface mix sections. Development of the materials necessary to implement this system will involve further discussions with personnel from the Research Council, field offices, and divisions regarding what data are appropriate to collect.

Although data bases are not so complete as desired, we can make use of the data that are available and proceed with developing the integrated applications.

The integrated use of the pavement data with data from the other systems discussed above is best illustrated in terms of what output will be provided. Most of the work thus far has been to develop outputs for planning maintenance resurfacing. These outputs include a detailed output (Fig. 5), an exception output (Fig. 6), and a summary output (Fig. 7). Present plans are to provide each type of output annually to the residencies and districts for the counties they include and to the Maintenance Division for the entire state. The detailed output is intended primarily as a reference; the other 2 outputs are the primary maintenance resurfacing planning tools. The exception output is obtained

Figure 6. Output by exceptions.



```
DISTRICT   CULPEPER

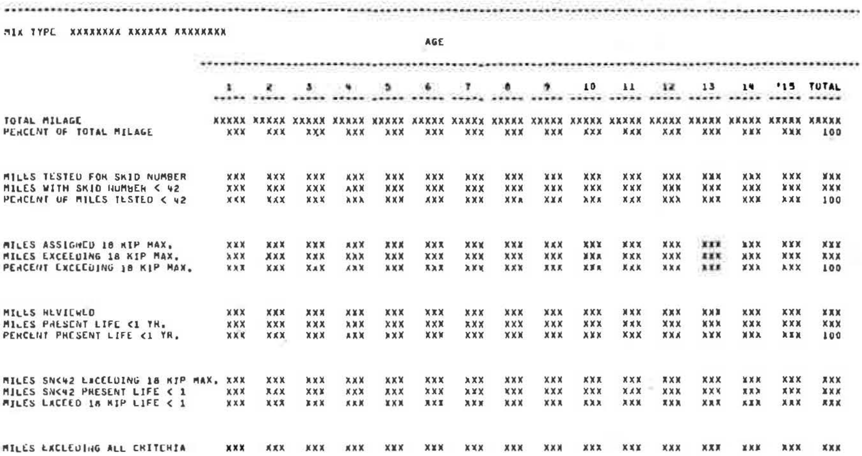
RESIDENCY CHARLOTTESVILLE

                           SECTION IDENTIFICATION                                        ATTENTION NEEDED BECAUSE OF
*********************************************************************           ****************************************

                         HIGHWAY  DIRECTION  BEGINNING  ENDING                               PRESENT  18 KIP   LOW SKID     WET
  COUNTY          ROUTE    TYPE   AND LANE   MILEPOST   MILEPOST  LENGTH  MIX TYPE      AGE    LIFE    VOLUME  RESISTANCE  ACCIDENTS

ALBEMARLE          29      41     ALL LANES    21.00     23.60     2.60   S-5                                     *
ALBEMARLE          29      41     NB LANES     26.45     28.45     2.50   S-5            *      *        *        *           *
ALBEMARLE          29      41     SB LANES     26.45     31.32     5.07   S-5                   *        *                    *
```

Figure 7. Summary output in long-range planning.



```
********************************************************************************************************************

MIX TYPE  XXXXXXXX XXXXXX XXXXXXXX
                                                            AGE

                                 *******************************************************************************************

                                   1     2     3     4     5     6     7     8     9    10    11    12    13    14   '15  TOTAL
                                 ----- ----- ----- ----- ----- ----- ----- ----- ----- ----- ----- ----- ----- ----- ----- -----

TOTAL MILAGE                     XXXXX XXXXX XXXXX XXXXX XXXXX XXXXX XXXXX XXXXX XXXXX XXXXX XXXXX XXXXX XXXXX XXXXX XXXXX XXXXX
PERCENT OF TOTAL MILAGE            XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   100


MILES TESTED FOR SKID NUMBER       XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX
MILES WITH SKID NUMBER < 42        XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX
PERCENT OF MILES TESTED < 42       XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   100


MILES ASSIGNED 18 KIP MAX.         XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX
MILES EXCEEDING 18 KIP MAX.        XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX
PERCENT EXCEEDING 18 KIP MAX.      XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   100


MILES REVIEWED                     XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX
MILES PRESENT LIFE <1 YR.          XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX
PERCENT PRESENT LIFE <1 YR.        XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   100


MILES SN<42 EXCEEDING 18 KIP MAX. XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX
MILES SN<42 PRESENT LIFE < 1       XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX
MILES EXCEED 18 KIP LIFE < 1       XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX


MILES EXCEEDING ALL CRITERIA       XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX   XXX
```

by determining when established criteria for resurfacing are met for one or more of the variables of age, present remaining life as determined by the resident engineers' review, accumulated 18-kip equivalent volume, skid resistance, or percentage of wet accidents. This output is intended to provide guidance regarding what specific sections may need resurfacing during the next resurfacing season. The summary output gives the lane-miles of pavement meeting one or more of the criteria discussed above.

With regard to skid resistance and pavement durability studies, detailed output will be particularly useful in determining what specific programs have been developed, yet it is anticipated that one of the initial programs written will be for the purpose of establishing curves of skid resistance versus accumulated traffic volume for each aggregate source (either solely or in combination with other aggregate sources). Another program anticipated is one to relate the design 18-kip accumulated volume to the actual 18-kip accumulated volume achieved before resurfacing is required. Many other programs will be developed to meet particular needs, especially as the data bases become more complete.

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