Part One

The Pavement Management Process

Chapter 1

Introduction

1.1 HISTORICAL BACKGROUND

We often think of paved highways as beginning with the era of the automobile in the late 1800s. This of course is erroneous, because overland travel has been second only to water travel in the history of the development of the world.

The first real road builders moved southwestward from Asia toward Egypt [1] soon after the discovery of the wheel, about 3500 B.C. It is not surprising that the cradle of civilization was also the cradle of early road building, because roads and population have always gone together.

The Romans were the first scientific road builders, with the *Via Appia*, or the "Appian Way," being initiated in 312 B.C. The oldest, most famous long-distance highway, approximately 1755 miles long, was named the "Royal Road" by the Persians. It was constructed over a 4,000-year period, ending in 323 B.C., across Southwest Asia and Asia Minor. Travel time, according to Heroditus (457 B.C.), was 3 months and 3 days, or an average of 19 miles per day.

The Appian Way was generally 3 to 5 ft thick, made up of three layers. All the work was hand-placed stone, and this type of construction became standard practice for over 2,000 years until it was superseded by MacAdam's light-wearing course surface in the nineteenth century. These early roads had to withstand the wear of hooved animals, and great attention was given to the wearing surface. Speeds were slow, and therefore overall smoothness of the roads was of less importance then than after the introduction of the automobile.

1.1.1 Pioneer Road Builders

Road building became recognized as a profession requiring application of scientific principles in the latter part of the eighteenth century. The main trouble with roads of that day, as well as with many roads of today, seemed to be the lack of adequate drainage and the lack of a hard-wearing surface. Perhaps the real founder of pavement systems management was Pierre Marie Jerome Tresaguet, the first modern highway engineer. He introduced the innovation of relatively light road surfaces designed on the principle that the subsurface of the pavement must be well drained and support the load as opposed to the massive pavements designed by the Romans. More important to pavement system management, however, was the fact that Tresaguet recognized the need for continuous maintenance and was named French Inspector General of Roads in 1775 by King Louis XVI.

Thomas Telford was responsible for the construction in 1816 of the Carlisle-Glasgow Road, said to be the finest road ever built up to that time. It placed emphasis on flat grades and, because of Telford's early training as a stone mason, involved surfacing the road with stones capable of carrying the heaviest prospective traffic of that day.

The most famous of early road builders was probably John MacAdam (1756–1836). He is known as the father of modern pavement construction. His road cross-section design was based on the principle that a drained and compacted base should support the load applied to a pavement, whereas the stone surfacing should act only as a wearing course. The construction techniques involved compaction of the materials by normal traffic and probably would not have been at all satisfactory for modern highways. In 1869 the original steam road roller was used for the first time in New York City. It made compaction of macadam roads better, quicker, and easier. That actually started the modern era of road construction.

In the post-1900 time period, the rapid growth of the automobile and the decline of horse-drawn vehicles and bicycles brought about a major change in pavement construction. The faster automobile began to cause serious dust problems on roads, and the use of oils and other agents to cut down on dust began. This led to experiments in 1905 with coal tars and crude oil in Jackson, Tennessee, to determine their benefit in pavement construction. In 1906, bituminous macadam roads were built in Rhode Island. The conclusion drawn from the experiments was that highways used heavily by high-speed motor cars should be built with bituminous macadam surfaces and that existing roads subjected to similar high-speed traffic should be resurfaced using bituminous materials.

These first bituminous roads were followed closely in 1909 by the first rural portland cement concrete roads built in Wayne County, Michigan. The pavement was 17.8 ft wide with natural earth shoulders and expansion joints every 25 ft.

In 1920, the Highway Research Board was organized and major research efforts in the pavement field began with the objective of improving pavement design and construction methods. This research was highlighted by a variety of theoretical and empirical studies, including the well-known AASHO Road Test in Ottawa, Illinois, in 1958–1961.

1.1.2 Development of Pavement Systems Methodology

In 1966, the American Association of State Highway Officials, through the National Cooperative Highway Research Program, initiated a study to make new breakthroughs in the pavement field. The intent was to provide a theoretical basis for extending the results of the AASHO Road Test. As a result, researchers at the University of Texas [2] in 1968 began a basic new look at pavement design using a systems approach.

Similar, independent efforts were being conducted at the same time in Canada [3, 4] to structure the overall pavement design and management problem and several of its subsystems.

A third concurrent keystone effort in this area was that of Scrivner and others at the Texas Transportation Institute of Texas A&M University as a part of their work for the Texas Highway Department [5].

The work of these three groups provides the overall historic perspective for pavement management systems.

In the late 1960s and early 1970s the term *pavement management system* began to be used by these groups of researchers to describe the entire range of activities involved in providing pavements [6]. At the same time, the initial operational or "working" systems were developed in two major projects. The largest of these was Project 123, conducted by the Texas Highway Department, Texas A&M University, and the University of Texas. A series of reports and manuals have resulted from this research, beginning with 123-1 in 1970 [7]. The project has produced many of the modern innovations in pavement analysis.

The other major continuous research effort in this field was that carried out in NCHRP Project 1-10, as initially reported by Hudson et al. [2]. A second phase was carried out by Hudson and McCullough to develop an actual working system for implementation at the national level [8]. A third phase on implementation was carried out by Lytton et al. at Texas A&M University [9], whereas a fourth phase was continued by Finn et al. at Materials Research and Development, Inc., in California.

1.2 ROLE OF PAVEMENTS IN TODAY'S TRANSPORT SYSTEM

Today's transport system includes marine, highway, rail, air, and pipeline transportation. Of these, only marine and pipeline transportation do not make use of basic pavements. Certainly the major structural load-carrying elements of the highway system are the pavements. For air travel, pavements are required in the form of runways, taxiways, and parking aprons. Likewise, the railroads operate on a form of pavement historically made up of rails, ties, and ballast, not dissimilar to a highway pavement design, although modern design principles show, for example, that the rail can easily be mounted on a properly designed continuous pavement.

It is difficult to define precisely the dollar value of the expenditures in each of these modes of transportation in the United States, in Canada, or in the world. However, it is safe to say that the expenditures in the highway sector in the United States represent the largest amount in U.S. transportation and exceed $20 billion annually. Including maintenance as well as new construction, pavements represent approximately one-half of this total highway expenditure. In effect, pavements, along with bridges and other structures, represent the major investment in fixed facilities of highway transport. It is also important to point out that after the initial development of a highway system, expenditures for right-of-way and other initial costs cease but expenditures on the pavement system continue to grow as maintenance, rehabilitation, and so forth, are required.

Although the function of the pavement varies with the specific user, in modern highway facilities the purpose of the pavement is to serve traffic safely, comfortably, and efficiently, at minimum or "reasonable" cost.

With the relatively large investments involved in pavements, even marginal improvements in managing this investment, and in the technology involved, may effect very large absolute dollar savings. In addition to the direct savings in capital costs and maintenance, the indirect benefits to the road user can be equally significant, although much more difficult to ascertain. Pavement construction in itself will probably not continue to develop as fast in the future as it has since World War II, but the investment we now have in pavements must be protected through various types of upgrading or remedial action. Otherwise, this investment can be lost if pavements are allowed to deteriorate too much.

1.3 TYPES OF PAVEMENTS

Many definitions are applied to the term pavement. In this book, the pavement is considered as the upper portion of the road, airport, or parking lot structure and includes all the layers resting on the subgrade. Additionally, the pavement is considered to have a bound surface and includes the load-carrying capacity of the subgrade.

Many so-called types of pavement are discussed in modern technology. Terms such as *rigid pavement, flexible pavement, composite pavement, asphalt pavement, concrete pavement,* and others are often used. Each of these terms has been developed for a particular reason and each has some useful connotation. Perhaps the most straightforward terminology is the definition of pavement by its structural function or response. Two basic types can be considered: (1) flexible pavements and (2) rigid pavements. These definitions provide a framework to which all others can be related. Rigid pavements normally use portland cement concrete as the principal structural layer. Flexible pavements normally use asphaltic concrete for the surface, and sometimes for the underlying layers.

Pavements can also be defined in terms of the mechanical theory normally used to describe their behavior. In this context, slab analysis is commonly used to define the behavior of rigid pavements, which usually carry their load in bending. On the other hand, layered system analysis is commonly used to analyze the behavior of flexible or asphaltic concrete pavements, which carry their load in shear deformation.

The term *composite pavements* has been introduced from time to time but normally is not a very effective definition. It is intended to describe a pavement that combines rigid and flexible elements, such as a portland cement concrete surface on an asphalt concrete base, or an asphalt concrete surface (usually an overlay) over an old portland cement concrete (rigid) base or over a portland cement treated (rigid) base. A more useful definition is to assign this type of pavement to one of the other two types, depending on the basic load-carrying element and not the visible surface type.

There are many definitions involved in pavement technology and they are provided in various published glossaries, including one in Ref. [2]. Perhaps one of the best sources is various publications of the Transportation Research Board (see their most up-to-date catalogue of publications). The reader may wish to refer to this source for further elaboration.

1.3.1 Rigid Pavements

There are four basic types of rigid pavements. These derive from the combination of reinforcement and load-transfer devices within the concrete. Rigid pavements may be (1) unreinforced, (2) lightly reinforced, (3) continuously reinforced, or (4) prestressed. A typical cross section for any of these types is shown in Fig. 1.1. The basic intent of the diagram is to show that the pavement structure, per se, consists of those layers above the subgrade and not just the slab.

Unreinforced concrete pavements can be placed without joints, but this practice is followed by only a very few agencies today. Therefore, unreinforced concrete pavements are normally jointed and are placed with or without load-transfer devices across the joints. Jointed pavements are also placed with light steel reinforcement between the joints. The purpose of the steel is to hold together the cracks so that the concrete can fulfill its function of carrying traffic loads. These pavements nearly always are placed with load-transfer devices across the joints. Continuously reinforced pavements are usually placed without regular spacing of joints and contain adequate steel reinforcement to carry the load in the cracked

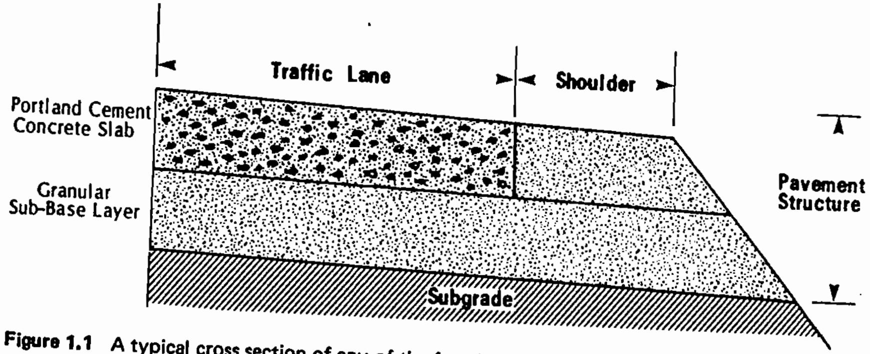

Figure 1.1 A typical cross section of any of the four basic types of rigid pavements.

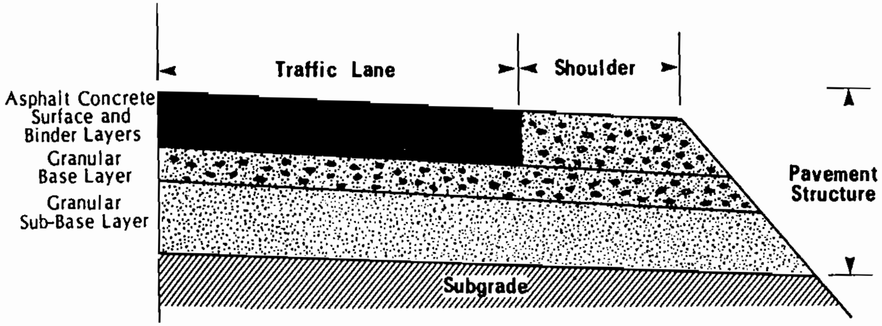

Figure 1.2 A conventional asphalt concrete pavement section.

concrete sections. Prestressed concrete pavements are those pavement slabs that are placed with adequate steel to allow the stressing of the steel. This provides a prestress on the concrete (so that the slab is in compression) and increases its tensile load-carrying capacity in a way similar to other structural applications of prestressed concrete. Such pavements have found only very limited use to date in North America, largely because of the high labor costs involved, but they may have potential for future or certain specialized applications.

1.3.2 Flexible Pavements

Flexible pavements have recently been developed into a wider variety of types than formerly used. A conventional asphalt concrete pavement section, as shown in Fig. 1.2, involves the use of an asphalt concrete surface layer, an asphalt concrete binder or leveling course layer (often of the same material as the surface layer but sometimes with a larger maximum particle size), and one or more base and subbase layers. The granular base and subbase layers may or may not be bound (i.e., with asphalt or some other treatment). Also, the shoulder may or may not be surfaced with asphalt concrete, a surface treatment, and so forth. Often, the shoulder simply consists of the same material as the base.

In recent years, a number of variations of flexible pavement types have appeared. Two of the best-known types are Full Depth^R and Deep Strength^R.[1] The former refers to an asphalt pavement in which asphalt mixtures are employed for all courses above the subgrade, whereas the latter term refers to an asphalt pavement in which the base layer, in addition to the surface, is constructed of an asphalt mixture.

1.4 PAVEMENT MANAGEMENT PRIMER

The performance of a pavement certainly depends in part, but not exclusively, on the design concepts that were used. The success of any design is also largely

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[1] These are terms registered by The Asphalt Institute with the U.S. Patent Office.

dependent on subsequent construction, maintenance, and rehabilitation. Historical studies by many agencies show that the concept of a 20-year new pavement design is generally fictitious. Most such pavements provide adequate service for up to 10 or 12 years, and sometimes less, without major maintenance or rehabilitation. At that time, however, they are often overlayed, sometimes more than once, to provide a total of 20 or 25 years performance or total service life. Consequently, many agencies have recognized the need to link together explicitly the activities of planning, designing, constructing, and maintaining pavements. In other words, they have recognized the need to "manage" the technology of providing pavements on a comprehensive basis.

After development of the basic pavement systems concepts in 1967 and 1968, it became more and more obvious that these concepts should in fact be applied not only to design but to the entire process of providing pavements, from planning and design to construction and maintenance. Nowhere was this more clearly shown than in December 1970, when the Federal Highway Administration-University of Texas-HRB Conference on Structural Design of Asphalt Pavement Systems was held [10]. As a result of this conference, it became clear that pavement systems technology was here to stay and that, in fact, the concept of pavement management systems was the basis on which technology could move forward in an efficient manner.

Unfortunately, however, it has also become common to use the "systems" terminology in the pavement field in a generic way, such as employing *joint system* to mean, presumably, all the joints and associated physical details in a particular rigid pavement. Alternatively, the terminology can become a sales gimmick, such as in the "Ace Asphalt Testing System." Usage of this sort has made skeptics of many potential users of true systems methodology. Most of the existing pavement technology has been developed on a trial-and-error basis. This approach has provided a wealth of experience that forms the basis of our current practices and also of our current theories, which codify experience.

Design technology for pavements has traditionally been both prescriptive and deterministic. It has been prescriptive in the sense that designers have set limits on such factors as deflection, stability, or other parameters in an attempt to avoid premature failure, rather than to predict the type and degree of failure that might occur and the time at which it might occur under a specified set of conditions. It has been deterministic in the sense that the equations or models predict a single answer and do not account for statistical variation or reliability factors.

The concepts of pavement performance developed in the late 1950s and early 1960s in association with the AASHO Road Test and studies in Canada provide the necessary system output function for pavement management systems. Without this performance concept, it is relatively difficult to understand and relate the improvements or differences from one pavement approach or strategy to another.

It has been only recently that "design" itself has been elevated from the concept of specifying an initial structural section to that of a "strategy" where the strategy is an optimized design involving not only the best initial construction and structural section but also the best combination of materials, construction policies, maintenance policies, and overlays. This concept will be fully explored in subsequent chapters, but basically design must involve more than just the initial construction to be carried out.

The technology of designing, constructing, and maintaining pavements has been considerably enhanced in recent years by research into the fundamental characteristics of pavement materials. We are now better able to understand how materials behave when subjected to a variety of loads under various climatic or environmental conditions and the effects of time and loading.

Another thing that has markedly aided the development of pavement technology is the use of computers. Computers have enabled us to process large volumes of data and to perform complex and extensive calculations on the response of pavements as simulated by layered systems, slab analysis, and so forth.

The disparate atmosphere in which pavements are financed, constructed, and maintained has tended to fragment the development of codified pavement management policies over the years. Many administrative levels are involved in the process, and these administrative levels, with different reporting functions, provide a wide variety of input into the process. This does, however, inhibit the codification of data into a single body of knowledge.

To summarize, the reader should keep in mind the variety of considerations and detailed inputs that have affected the development of pavement management systems throughout history. A great deal of work has been done to overcome some of the resulting problems, but there is also scope for considerable improvement in all areas of pavement technology.

Chapter 2

General Nature and Applicability of Systems Methodology

2.1 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 structuring the state of knowledge on an existing system or modeling 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 number of efficiently and systematically conducted projects [11].

There are two main, interrelated uses of systems methodology [12]:

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

These uses are complementary and interrelated; one is insufficient without the other. The framing of a problem is usually too generalized by itself to achieve a useful operational solution, whereas the application of analytical techniques to an inadequately structured problem may result in an inappropriate solution [13].

2.2 STRUCTURE OF THE SYSTEMS METHOD

The structure or framework of any problem-solving process should provide for 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 2.1 presents the major phases and components of such a process. In this general form, it is applicable to a wide variety of engineering and other problems. The diagram illustrates that the recognition of a problem comes from some perceived inadequacy or need in the environment. It leads to a definition of the problem that involves a more in-depth understanding. This provides the basis for proposing alternative solutions. These alternatives are then analyzed in order to predict their probable outputs or consequences. Evaluation of the outputs is the next step in order that an optimal solution may be chosen. Implementation involves putting this solution into service, and its operation. Feedback for improving future solutions, or checking on how well the system is fulfilling its function, is provided by periodic performance measurements.

The process of Fig. 2.1 is continuous and iterative. It is applicable to both the overall problem being considered and to its many component subproblems, basically at three levels:

1 The systems approach
2 Systems analysis
3 Systems engineering

Generally, these levels increase in complexity and utility. The systems approach often means nothing more than broad consideration of a problem, or as many aspects of the problem as convenient. In terms of Fig. 2.1, we might say that the systems approach involves only the problem-recognition phase, and the problem-definition phase in an initial manner, with perhaps a cursory look at the generation of alternative strategies.

Systems analysis encompasses the systems approach and extends it to a more complete consideration of alternate strategies. More important, it provides a methodology for analyzing and optimizing these alternatives.

Finally, systems engineering is a more complete manifestation of the systems method, with design, implementation, and performance evaluation aspects given strong attention.

2.3 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, stresses, etc.). They, together with the constraints, usually represent information that must be acquired by problem solvers. Objectives also represent necessary information, but they must usually be developed or specified by

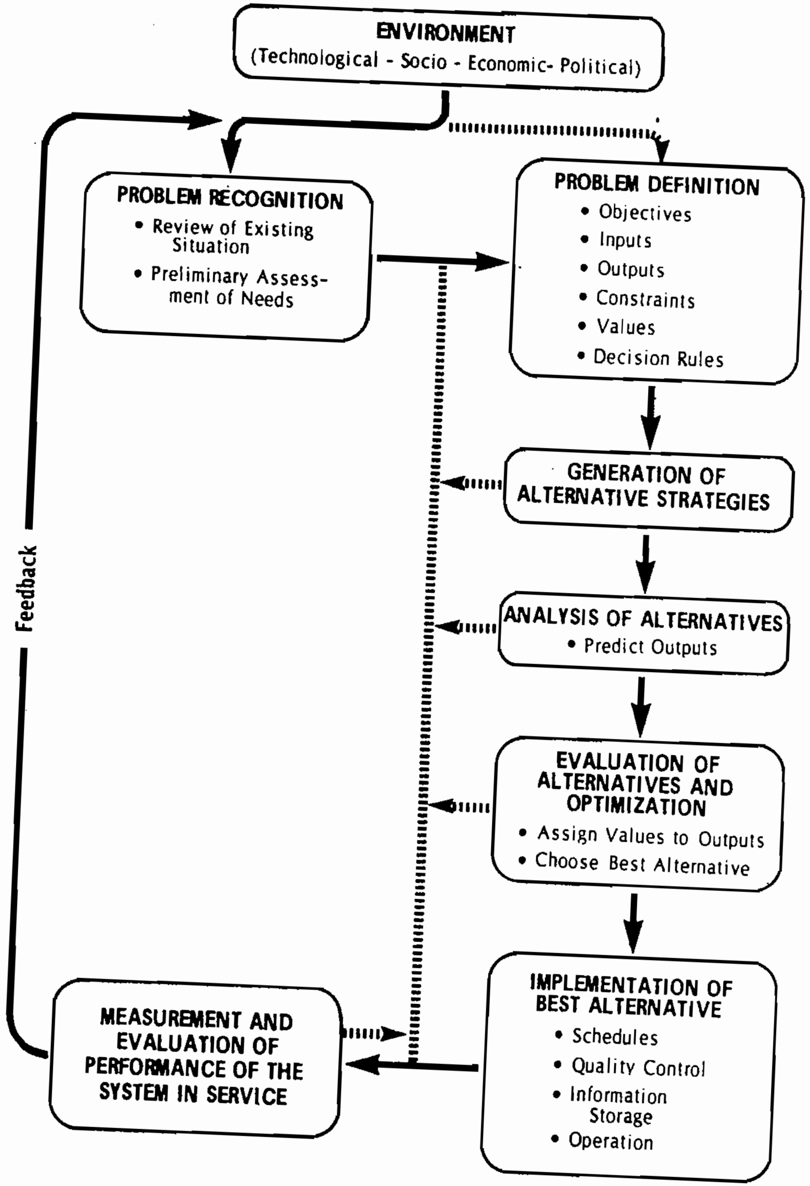

Figure 2.1 Major phases and components of the systems method.

problem solvers. Similarly, they must decide as a part of this problem definition what outputs will be of concern when they subsequently analyze alternative solutions, and what output prediction models they will use. They should additionally specify what types of values they will place on these outputs, what sort of function they will use to combine them, and what decision rule they will eventually use to choose the best solution. These aspects have been discussed in more detail, particularly with respect to the highway and pavement field, in a number of sources, including Refs. [2, 3, 6, 7, 12, 14–16].

It is important that the "system" under consideration be clearly recognized and identified; otherwise there can be confusion in determining the inputs and in specifying the applicable objectives, constraints, and so on. 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.

Chapter 3 extends the foregoing generalizations to some more specifically defined concepts for the pavement management field.

2.4 SOME PRECAUTIONS IN APPLICATION

The general systems method of problem-solving, as shown in Fig. 2.1, models the logical, systematic pattern that is used by efficient problem solvers. It must, however, be used with full recognition that there are certain limitations.

First, successful application of the systems method inherently depends on the capabilities of the people involved. The method is no substitute for poor engineering, and it does not represent a framework for only classifying all the factors pertinent to a problem.

Second, the point of view of the individual or agency involved must be clearly recognized and identified. Otherwise, confusion and contradiction can be the result. For example, a materials processing problem for a public works project might well be viewed differently by the contractor than by the government agency involved. They could have competing objectives, and they would undoubtedly have different constraints.

Third, the components or extent of the system under consideration should be clearly identified. For example, the term *parking system* might mean the actual physical parts of the parking lot, such as pavement, curbs, gates, and so forth, to one person; to another it might mean the method used to operate the facility; and to still another person it might mean a combination of the two. Without such clear identification of the extent of the system, inconsistency among objectives, constraints, inputs, and outputs can result.

A fourth point concerns the oversimplification imposed on many problems by considering the system as a black box, with an arrow on the left labeled inputs and one on the right labeled outputs. This is a convenient conceptualization for certain hardware problems, but it is quite inadequate for most other problems.

A fifth point concerns the inherent danger of generating precise solutions to an imperfectly understood problem. That is, the problem has been recognized but not yet rigorously defined. It is, of course, common to perceive some general solutions in the problem-recognition phase of Fig. 2.1. However, these may be inadequate or incomplete if the problem solver does not go on to define the problem.

2.5 SOME ANALYTICAL TOOLS

The structuring of a problem is usually too general to be used alone to find a useful, operational solution, and the application of analytical techniques to an inadequately structured problem may result in an inappropriate solution. In other words, the analytical techniques that are used as part of the systems methods for solving problems have maximum usefulness when the problems are well formulated or structured; otherwise, they can be an exercise in mismanagement.

There is a large variety of available techniques (or tools, or models) that can be used in applying the systems method to the solution of a problem. It might be noted that these techniques are also applicable to what is commonly known as the operations method. Basically, the operations method and the systems method differ only in the scope and nature of the problems solved, rather than in the form of the methodology. This section of the book provides only a "catalogue" of some of the more widely used systems and operations methods. These methods have varying degrees of potential applicability to the pavement field. The references cited provide a means for further exploration on the part of the reader.

The use of systems or operations models or techniques should facilitate reaching a decision on as objective a basis as possible. The type of "objective function" used depends largely on the available knowledge of the outputs of the system, which can be classified in terms of the three following problem types:

1 Certainty, where definite outputs are assumed for each alternative (i.e., deterministic type of problem)

2 Risk, where any one of several outputs, each of known probability, can occur for each alternative

3 Uncertainty, where the outputs are not known for the alternative courses of action; thus probabilities cannot be assigned

A major amount of engineering practice has treated problems in terms of decisions under certainty (type 1), because of convenience and because of the available information. However, there is considerable current effort being directed toward incorporating probabilistic concepts (type 2) into practice.

Where practical problems are too complex for symbolic representation, they may be modeled on an analogue or a scale basis. Alternatively, it is possible to "force" a solution by experimentation, gaming, or simulation for some types of problems [13].

One of the most widely applied and useful classes of systems models involves linear programming. These techniques have been used in everything from construction to petroleum refinery operations because they are well suited to allocation-type problems [17-20]. A typical problem for linear programming application might involve the determination of how much of each type of material a contractor should produce, given production capacity, the number and capacities of trucks, available materials and their costs, the delivery distance, profits for each type of material, and so forth. There are several variations of linear programming models and several methods of solution, including parametric linear programming, integer linear programming, and piecewise linear programming. The latter is used to reduce a nonlinear problem to approximate linear form.

Nonlinear methods can range from the so-called classical use of differential calculus, Lagrange multipliers (and their extension to nonnegativity conditions and inequality constraints) and geometric programming, to the iterative search techniques [21-24]. These latter techniques start from an initial solution and seek improvements until an acceptable tolerance is reached. They are often applicable where more rigorous methods are impractical.

There are some types of nonlinear problems not easily solved by analytical techniques that may lend themselves quite well to graphical solution. A variety of methods may be used to obtain optimum values. Their applicability and use, which has received comparatively little attention, is directly dependent on the nature of the problem and the way in which it is formulated by the problem solver. For example, Haas et al. [12] have illustrated the use of a simple graphical solution to a construction problem involving a discontinuous cost function.

Problems involving multistage decisions can be represented as a sequence of single-stage problems. These can be successively solved by a method known as dynamic programming [25-27]. Each single variable or single-stage problem that is involved can be handled by the particular optimization technique that is applicable to that problem. These techniques are not dependent on each other from stage to stage and can range from, say, differential calculus to linear programming. Combinatorial-type problems are often well suited to dynamic programming. A typical example might be that of an aggregate producer with several mobile crushers and several sources of raw materials who wants to determine how many crushers should be assigned to each site for a given profit matrix.

Random and queuing models can have a wide range of applicability to systems problems, and there is a large amount of literature available [28-44]. For example, one class of models involves the Monte Carlo methods, which are quite useful when adequate analytical models are not available. These methods require distribution functions for the variables. They are, however, somewhat inefficient and are applied mainly to complex problems that are otherwise unmanageable. There are also a large range of problems to which reliability, random walk, and Markov chain techniques can be applied. The latter can be used to extend stochastic and chance-constrained programming models. Queuing models have been used very extensively in engineering, including various air terminal operations, traffic facility operations, rail operations, and canal operations.

Many systems problems involve the allocation and scheduling of personnel, equipment, money, and materials. Several techniques have found widespread use for these types of problems, including sequencing, routing, and scheduling. Sequencing involves the ordering of various tasks in sequential manner to minimize total time or effort [45, 46]. Routing involves the identification of a path through a network to minimize time, cost, or distance. There are graphical methods and matrix methods available for the minimum path type of routing problems.

Scheduling involves the allocation of time or resources to various tasks whose sequence is fixed but whose cost is time-dependent, to minimize total completion time or cost. There are two well-known types of scheduling methods, the critical path method (CPM) and the program evaluation and review technique (PERT). They have received especially wide application in the construction field during the past decade [47–51]. Single-value time estimates are used for each activity in CPM, whereas PERT uses a range of possible completion times (i.e., including stochastic aspects). Thus PERT has tended to be used more for research and development purposes whereas CPM has found more routine application in construction. Critical path scheduling problems can often be formulated as linear and dynamic programming situations.

This section has only noted the analytical tools that have potential applicability to various aspects of the pavement field. Those desiring more in-depth information may consult some of the many references listed.

Chapter 3

Basic Components of a Pavement Management System

3.1 DEFINITION AND STRUCTURE OF THE SYSTEM

A pavement management system consists of a comprehensive, coordinated set of activities associated with the planning, design, construction, maintenance, evaluation, and research of pavements. This can be represented conceptually as in Fig. 3.1, which shows the logical sequence of activities that would be used by any 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.

It should be recognized that Fig. 3.1 incorporates a number of levels of management. For example, planning activities might be concerned primarily with investment decisions and programming on a network basis, whereas design or construction activities would be concerned primarily with management at the project level.

3.2 MAJOR SUBSYSTEMS

The six major classes of activities or subsystems of Fig. 3.1 (i.e., 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

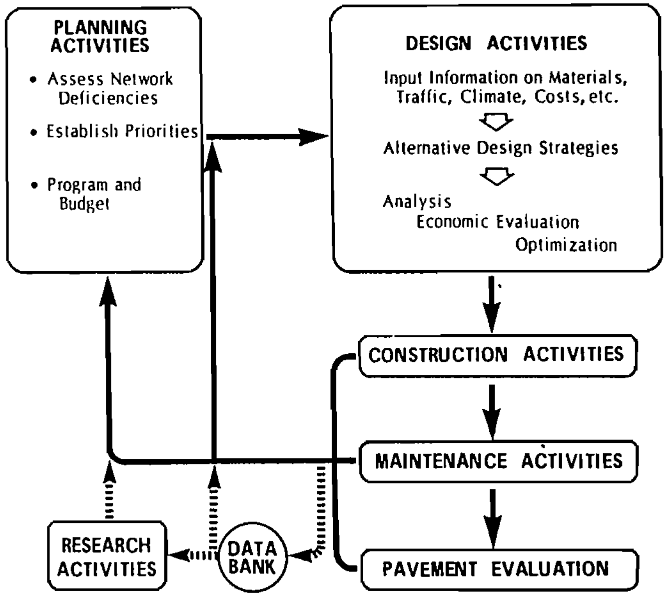

Figure 3.1 Major classes of activities in a pavement management system.

subsystem incorporates a variety of major and minor problems that are amenable to being structured and solved using the general approach of Fig. 2.1. The following paragraphs outline the basic functions of the subsystems.

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

The design subsystem involves the acquisition or specification of a variety of input information, the generation of alternative design strategies, the analysis of these alternatives, their economic evaluation, and finally optimization to select the best strategy. Although the usual operational extent of the designer can be represented by the box in Fig. 3.1, the overall diagram shows how design activities are directly related to all the other activities of the pavement management system.

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

The maintenance phase includes the establishment of a program and schedule of repair work, the actual operations of crack filling, patching, and so forth, and the acquisition and processing of data for transmittal to the data bank.

Pavement evaluation is a phase of the pavement management system that has received considerable attention by a number of agencies during the past decade. It includes the establishment of control or evaluation sections, the actual periodic measurement of such pavement characteristics as structural capacity, roughness, distress, and skid resistance, and the transmittal of data to the data bank. The acquired data can be used for: (1) checking the adequacy with which the pavement is fulfilling its intended function, (2) planning and programming future rehabilitation needs, and (3) improving the technology of design, construction, and maintenance [52].

The data bank has been separately identified in Fig. 3.1. This is done to emphasize its role in acquiring data from all the pavement activities in a centrally coordinated manner, and its concurrent role of being an information base for analyzing the effectiveness of these activities. Data banks can range from simple manual record files to sophisticated, computerized systems [53].

The importance of research in a pavement management system depends on the resources and requirements of the particular agency involved. Research activities can be initiated from problems arising in planning, design, construction, or maintenance, and they usually make extensive use of the information acquired in evaluation. In fact, evaluation can sometimes be considered as research.

The foregoing pavement management subsystems will be considered in more detail in subsequent chapters.

Chapter 4

Planning Pavement Investments

4.1 ROLE OF PAVEMENT INVESTMENT PLANNING

The planning phase of pavement management is concerned with a series of projects within a road network or a region. In turn, it is related to higher levels of planning dealing with overall road needs. This is, in turn, related to a still higher level of planning dealing with overall transport requirements, and so on. Figure 4.1 is a schematic representation of the hierarchy of planning levels that are involved.

The hierarchy begins with the political or administrative jurisdiction level (i.e., federal, state or provincial, municipal), where the major departmental budget decisions are made (i.e., *x* dollars for transportation, *y* dollars for education, etc.). The next major planning or decision-making level is concerned with the total budgets of the various sectors of each department (i.e., some percentage of *x* dollars for roads). At the next major level, decisions must be made for allocating the roads budget to such areas as bridge construction, pavement construction, maintenance, and so on.

The next level of planning, which is of principal interest to this chapter, concerns the decisions to proportion the pavements budget to some series of projects over some selected time span. It must provide answers to the following basic questions:

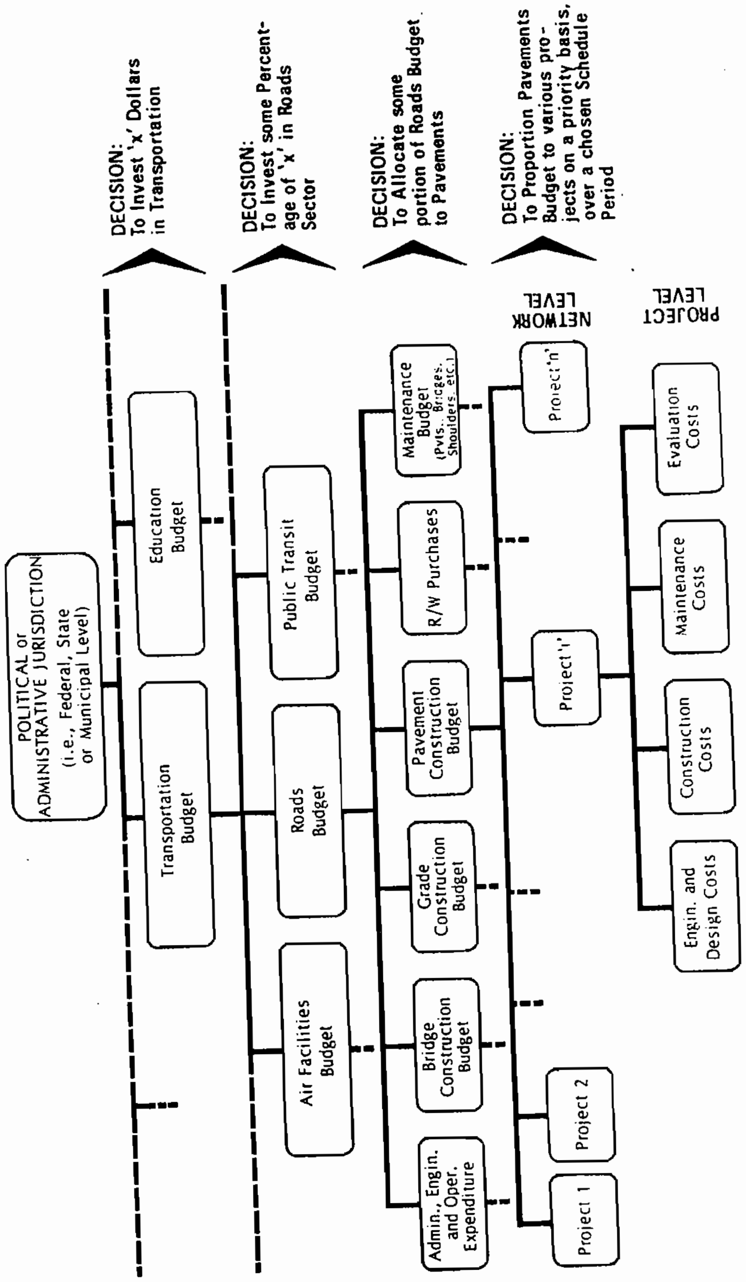

Figure 4.1 The role of pavement investment planning.

1 What are the needs for new pavement construction, and rehabilitation of existing pavements, on the total mileage under the agency's jurisdiction, over the selected time span?

2 How are priorities assigned to these needs?

3 How can the projects be scheduled or programmed according to these priorities and within the total available budget?

The basic information needed to answer these questions comes from roads or transport needs studies where new pavements are concerned, and from periodic pavement evaluation studies for existing pavements.

When a set of projects has been scheduled throughout the agency's network, each individual project then undergoes detailed design and detailed economic evaluation to determine the best within-project alternative.

At the network level, all "candidate" projects should be considered. Because most agencies work under budget constraints, however, some of the candidate projects may have to be delayed even if their benefits exceed the costs. This requires the establishment of some sort of priority programming scheme, based on economic and other cost and benefit considerations.

4.2 NETWORK-LEVEL NEEDS: SELECTING "CANDIDATE" PROJECTS

The establishment of pavement needs at the network level is conducted on some sort of annual assessment and "formula" basis by some agencies, on periodic evaluation of existing pavements combined with road need studies for new pavements by other agencies, or on the basis of some combination of the foregoing.

Most agencies have a scheme for identifying their road networks by section and subsection. A new pavement project, or a rehabilitation project, might cover several such sections. The rationale used to designate sections can vary widely, including changes in subgrade soil type, changes in traffic volume, changes in surface type, changes in geometric characteristics, and so on. For example, an urban arterial street section might go from the intersection of one collector street to the intersection of another arterial street, with uniform traffic being the rationale for designation (assuming that there are no major changes in geometric and subgrade soil type over the section). As another example, a rural highway section might run for several miles, until there is, say, a major change in subgrade soil type. Many highway departments start or end sections at the corresponding start or end of the original contract for grade construction.

The "formula" type of assessment usually consists of subjectively selecting candidate projects and then assigning weights to various pavement surface conditions or distress measurements and traffic volumes. A numerical index-type rating is assigned to each project, and they are ranked according to these ratings. The budget constraint determines how many of the projects will be done. Those that are of lower priority and fall below the budget cutoff become candidate projects for the following year. This method is common for many urban municipalities and a number of state highway departments.

The method of periodic evaluation of existing pavements combined with road needs studies for selecting candidate pavement projects is essentially only an extension of the formula type of method and is used mainly by larger highway departments. In addition to surface condition measurements, it is common to take measurements of roughness or riding comfort, structural capacity, and skid resistance on existing pavements. The candidate projects for existing pavements are usually selected on the basis of roughness or riding comfort, but the other measurements are also usually used to complete the assessment of priority. New pavement projects result from the overall road needs study; in other words, the decision is made on the road project as a whole, and the pavement is simply a part of the project.

4.3 BASIC ECONOMIC AND COST-BENEFIT CONSIDERATIONS FOR PAVEMENT INVESTMENT PLANNING

The basic principles for planning investments in pavements, either at the network level or at the detailed level of within-project evaluation of alternatives, should be that the economic analysis provides information for decisions but does not represent a decision within itself, that all possible alternatives should be considered, and that comparisons of alternatives should be over the same time period.

These principles are discussed in more detail in Chap. 16, along with the methods of economic analysis that consider costs, or costs and benefits.

The basic notion of a cost-benefit type of analysis at the project level is relatively straightforward. Benefits should exceed costs for the project to be economically feasible.

Planning pavement investments, on a priority basis, goes one dimension further. Not only should costs and benefits be determined for all projects under consideration, but also the timing of the investments should be considered.

Benefits are difficult to determine for pavement projects. Some can be approximately quantified in monetary terms, whereas others are extremely difficult to quantify. These other nonquantifiable benefits are usually excluded from decision making, even though they can sometimes be important.

The cost and benefit considerations for pavements, as they concern the road user, the public agency, and the public in general, in terms of the consequences of improvements, may be listed as follows:

1 Road user: Pavement improvements can have the following consequences to the user:
   a Changes in travel time
   b Changes in vehicle operating costs
   c Changes in accident costs
   d Changes in user comfort costs

   Some quantification of the first two factors has been tentatively established (see Sec. 4.5 and chap. 16), but accident and discomfort costs are very difficult to quantify for pavements alone; no acceptable methodology has yet been developed for relating these latter two cost factors to pavement improvements. Consequently, it is only practical at the present time to consider savings in travel time and vehicle operating costs as quantitative benefits of pavement improvements.

2 Public agency: The public agency concerned can be directly affected by the following consequences of pavement improvements:
   a Changes in maintenance costs
   b Changes in future construction costs (associated with rehabilitation)
   c Changes in public "attitude" and complaints
   d Changes in accident measures or policies required

3 Public in general: The public in general can be affected by pavement improvements in the following ways:
   a Commercial sector—traffic volumes, prices for goods, employment opportunities, etc., can change
   b Environment—noise, pollution, vibration, etc. may occur during construction; as well, the actual materials used may be scarce and/or valuable in place; therefore, their removal may constitute a harmful impact
   c Aesthetics—appearance may be improved

Although direct agency costs and user benefits in terms of savings in travel time and vehicle operating costs are easier to identify, the nonquantifiable factors may become important in some situations. In addition, most public agencies find it necessary to allocate certain minimum annual expenditures to each district, region, area, ward, and so on, aside from priorities based strictly on monetary benefits. This can be built in as a constraint in any formalized priority programming method for pavement investments.

4.4 EXISTING METHODS OF INVESTMENT PLANNING FOR HIGHWAYS

Public agencies usually prepare their capital expenditure programs for highways as a whole, including bridge construction, grade construction, new pavement construction, reconstruction or rehabilitation of existing pavements, right-of-way purchases, and so on. Although this book is concerned only with the pavements sector, it is necessary to recognize the various existing methods that are used for preparing highway investment programs. A priority programming approach for investments in the pavement sector alone is described in Sec. 4.5.

In preparing priority programs for highway improvements, many public agencies place major emphasis on initial capital costs of construction. This means that certain projects with high capital costs, or alternatives within a project that are initially costly, will not be accepted even though they may have the highest overall benefits. An approach of this type usually occurs when the basic policy of the agency is to spread available funds as far as possible.

Another consideration involves the procedures used for selecting candidate projects within the various categories (i.e., bridges, grade construction, resurfacing existing pavements, etc.) and preparing cost estimates. For smaller agencies, this can be a central or head office function. For larger agencies, this is often a district function, with overall coordination at the head office level. Cost estimates for candidate projects are approximate, often on a per-mile basis, using construction cost information from previous projects.

In selecting the list of candidate projects and making cost estimates for, say, the forthcoming year's capital construction program, precedence is a very useful guideline in most agencies. In other words, unless major policy changes occur, this program is based largely on budgets and priority programs from the current and previous years.

4.4.1 Ranking Method

The most common method used by highway agencies is to prepare a list of capital improvement expenditures for either one or more years with priorities based on one of the following:

1 Ranking all the candidate projects on a subjective basis (sometimes only by class, i.e., first priority and secondary priority), using judgment

2 Ranking all the candidate projects using the ratio for each of present worth of benefits to capital costs of the improvement

3 Ranking all the candidate projects in descending order of rate of return

The candidate list of projects usually comes from highway needs studies, with annual updating.

When the available budget has been exceeded by this method, the lower-ranked or secondary-priority projects are shelved and put on the candidate list for the following year.

This method is very straightforward, but it has two major disadvantages. First, the potential advantages or benefits occurring through rescheduling projects (i.e., speeding up or delaying candidate projects within the program period) are not considered. In other words, variations in costs and benefits associated with timing of the investment are not considered. Second, benefits associated with pavement improvements are not explicitly taken into account, except in a subjective way or within the highway project as a whole. Moreover, the benefits of the highway project as a whole are usually calculated on the basis of travel time and/or distance, and do not include the pavement per se.

Despite the foregoing disadvantages, the use of sound judgment in preparing the priority program may give a ranking that is little different from that established by more sophisticated procedures.

4.4.2 Benefit-Maximization Method

The benefit-maximization method is based on calculating the optimum timing of each project, using maximum benefits as the criterion. A list of optimum investment times for all projects is determined and these, together with the associated costs, are then compared with the budgets available. A linear programming model can be used to rearrange the timing of projects so that the total benefit loss (from the optimum investment timing) is minimized, subject to the budget constraint.

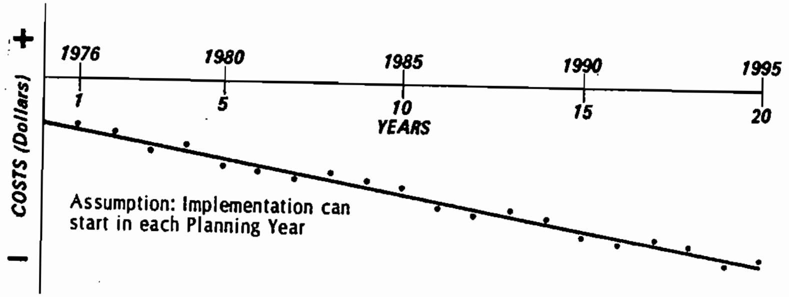

Figure 4.2 Typical cost stream (present-day dollars) for a highway improvement for each possible year of implementation.

The procedure for this method can be described schematically, starting with Fig. 4.2. Here, the cost of an improvement, in present-day dollars, is shown for each possible year of implementation. Similarly, in Fig. 4.3, the benefits accruing from the improvement, in present-day dollars, are shown for each possible year of implementation.

The operation of the linear programming model is shown schematically in Fig. 4.4. The "Input" portion of the diagram places the improvements into their maximum benefit year and shows the total costs for each year over the time period. Also shown is the total expected budget line. It indicates, for example, that in 1975, the total costs of the improvements exceed the available budget; in 1976, however, there are not enough improvements to exhaust the budget. The linear program rearranges the timing of the improvements and produces an "Output" (lower portion of Fig. 4.4) that is within the budget constraint for each year but

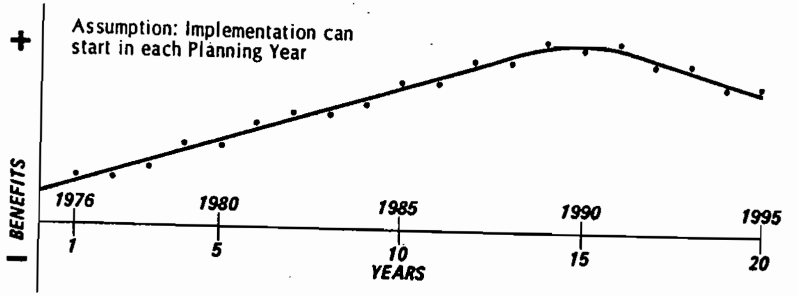

Figure 4.3 Typical benefits stream (present-day dollars) for a highway improvement for each possible year of implementation.

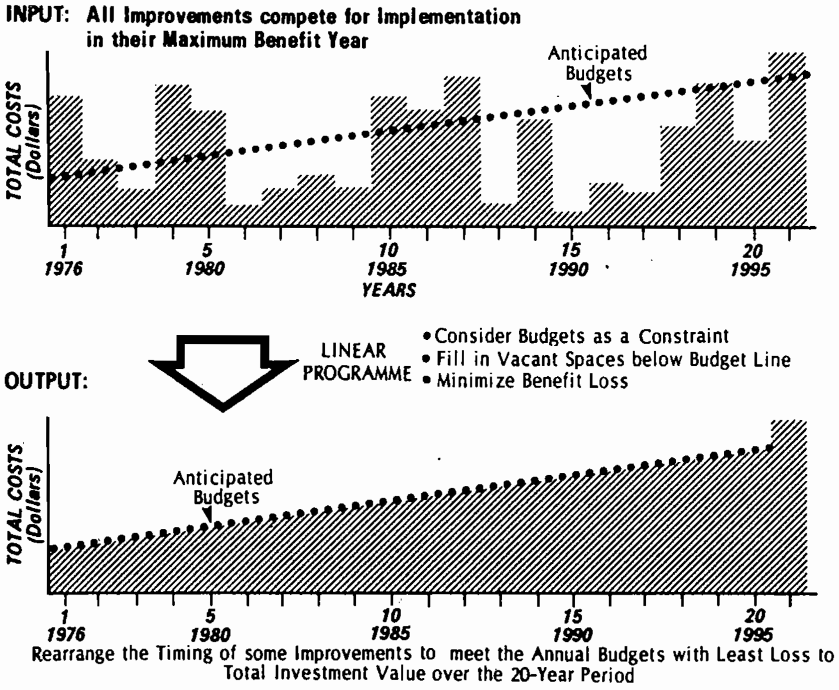

Figure 4.4 Schematic representation of linear programming method for rearranging optimum investment times for improvements so that total benefit loss is minimized and budget constraints are not exceeded.

minimizes the total benefit loss. Because the actual budget may vary from the anticipated budget, annual updating is required.

The benefit-maximization method as summarized in the foregoing paragraphs was developed basically for programming all types of highway improvements by the Ontario Ministry of Transportation and Communications [54, 55]. However, in using this method, constraints may have to be placed on such considerations as allocating minimum portions of the budget by district or region and allocating minimum portions of the budget to the various sectors of the highway (i.e., bridges, new grade construction, pavements, etc.); otherwise, the tendency would be to place major emphasis on capacity improvements for high-volume facilities.

4.4.3 Cost-Minimization Method

The cost-minimization method works basically the same as the benefit-maximization method, except that the benefits of the improvements are not considered. In other words, the optimum set of improvements is that which results in the least fiscal cost to the agency involved. Again, a linear programming model can be used, and the budget constraint is applicable.

This method does not, however, necessarily result in an optimum set of

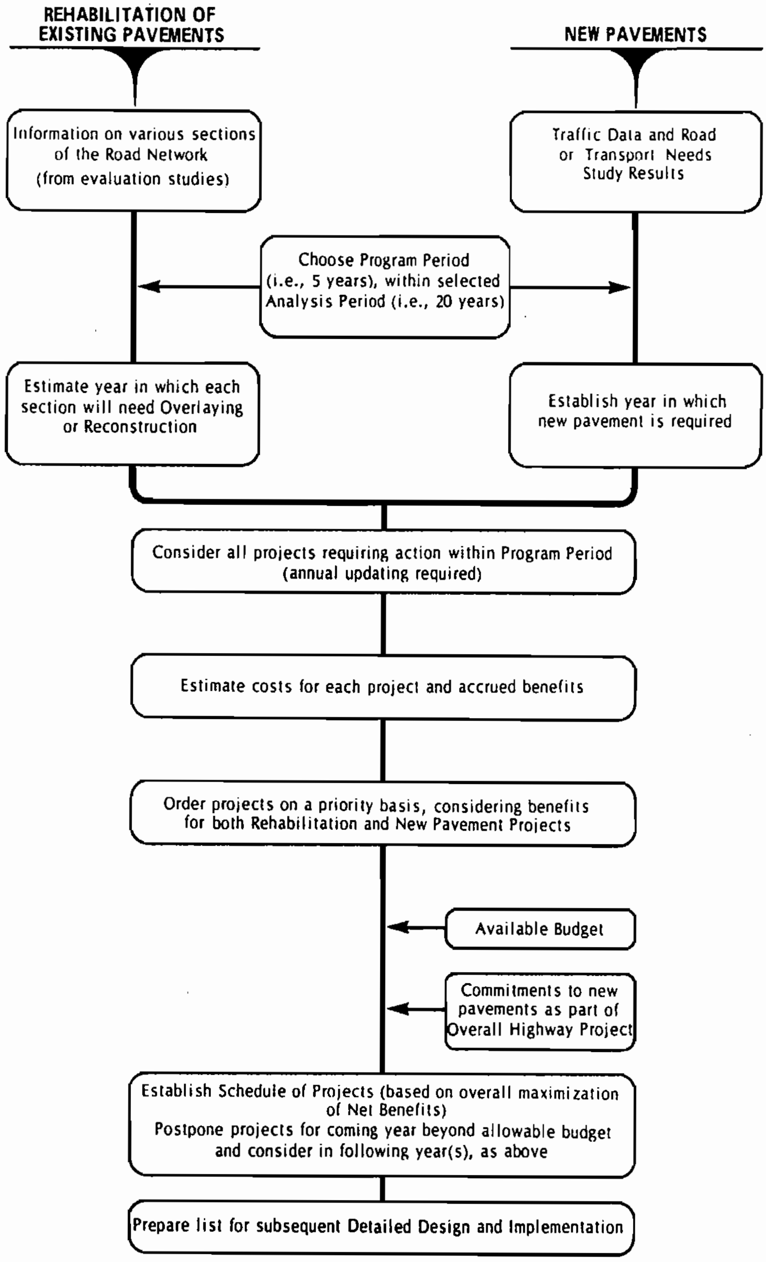

Figure 4.5 Steps in planning pavement investments over chosen program period.

Table 4.1 Example List of Pavement Improvement Projects

1976 First-priority projects

Project no.	Description	Functional class and no. of lanes	Length, miles	A.D.T.		Expected PSI[a] before improvement	Proposed improvement	Expected initial service life, years	Expected PSI[a] after improvement	Total capital cost	Total maintenance cost	Annual cost per mile	Annual user savings per mile	Net annual savings per mile	Remarks
				At time of construction	At end of service life										
76-401-10	Hwy. 401; jct. Hwy. 25 to jct. Hwy. 6	Rural fwy., divided 4 lanes	8.8	10,000	20,000	2.6	3.5 in. overlay	12	3.1	1,030,000	70,000	10,400	85,890	75,490	
76-13-1	Hwy. 13; jct. Hwy. 17 to McCay Rd.	Rural arter., 2 lanes	10.3	5,000	10,000	2.4	3 in. overlay	10	3.1	600,000	25,000	6,068	54,600	48,532	
76-28-2	Hwy. 28; Rally city limits to 8.6 mi north	Rural arter., 2 lanes	8.6	–	8,500	–	New pvt.	12	4.0	1,650,000	–	–	–	–	Overall hwy. improvement determines priority
76-97-3	Hwy. 97; jct. Flac Rd. to jct. Oly Rd.	Rural collector, 2 lanes	6.2	3,500	4,500	3.0	Seal coat	8	3.0	68,000	–	–	–	–	Safety improvement for skid res.

1976 Second-priority projects

Project no.	Description	Functional class and no. of lanes	Length, miles	A.D.T. at time of construction	A.D.T. at end of service life	Expected PSI[a] before improvement	Proposed improvement	Expected initial service life, years	Expected PSI[a] after improvement	Total capital cost	Total maintenance cost	Annual cost per mile	Annual user savings per mile	Net annual savings per mile	Remarks
76-33-10	Hwy. 33; jct. Hwy. 14 to 5.3 mi south	Rural collector, 2 lanes	5.3	3,000	5,000	2.0	15 in. overlay	13	2.4	700,000	50,000	10,900	17,500	6,600	
76-22-1	Hwy. 22; jct. Blem Rd. to 8.1 mi north	Rural arter., 2 lanes	8.1	2,200	3,800	2.6	Seal coat	10	2.6	94,000	–	–	–	–	Existing surf. extensively cracked and patched

1977 First-priority projects

Project no.	Description	Functional class and no. of lanes	Length, miles	A.D.T. at time of construction	A.D.T. at end of service life	Expected PSI[a] before improvement	Proposed improvement	Expected initial service life, years	Expected PSI[a] after improvement	Total capital cost	Total maintenance cost	Annual cost per mile	Annual user savings per mile	Net annual savings per mile	Remarks
77-24-2	Hwy. 24; jct. Hwy. 5 to jct. Hwy. 94	Rural arter., 2 lanes	7.2	2,000	5,000	1.4	Pave exist. gravel rd.	15	2.6	400,000	10,000	3,800	45,000	41,200	
77-7-8	Hwy. 7; Branton city limits to 4.8 mi east	Rural arter., 2 lanes	4.8	5,500	8,000	2.2	Partial reconstr. of exist. pvt.	11	2.9	1,000,000	30,000	19,500	48,750	29,250	

1977 Second-priority projects

Project no.	Description	Functional class and no. of lanes	Length, miles	A.D.T. at time of construction	A.D.T. at end of service life	Expected PSI[a] before improvement	Proposed improvement	Expected initial service life, years	Expected PSI[a] after improvement	Total capital cost	Total maintenance cost	Annual cost per mile	Annual user savings per mile	Net annual savings per mile	Remarks
						etc.	etc.								

[a] PSI, Present Serviceability Index, is a measure of the present serviceability of the road surface to the road user, primarily in terms of riding comfort, on a scale of 0 to 5 (see chap. 7 for details).

improvements for the public as a whole. It does have the advantage to the agency of providing a standard against which to measure the added cost associated with priority programming by another method.

4.5 PAVEMENT INVESTMENT PLANNING BASED ON NET BENEFIT MAXIMIZATION

There are a number of steps involved in determining a list of pavement improvements, on a priority basis, and scheduling them over the chosen program period. Figure 4.5 summarizes these steps.

The diagram uses two basic classes of improvements; new pavements and rehabilitation of existing pavements (i.e., overlays, seal coats, partial or full reconstruction, etc.). For each class, the year in which the improvement is required should be estimated. This is done over the chosen program period—say 5 years.

Then, those projects requiring improvement next year, and in the following years (i.e., the planning should be done in advance), are evaluated for benefits and costs. These benefits and costs are approximate, with the assumption being that detailed project design and economic evaluation is still to be done (see chaps. 14 through 19). Such detailed design and economic evaluation, and of course the actual construction costs that occur, will not only require annual updating but may also result in one or more projects of lower priority being dropped.

4.5.1 Example Set of Pavement Improvement Projects

Table 4.1 contains an example list of pavement improvement projects for investment planning purposes. It contains two classes of priority—first-priority projects and second-priority projects—for each improvement year. Those second-priority projects that cannot be financed in any given program year move into the following year and "compete" with both the first- and second-priority projects of that following year. Table 4.1 uses three ways to assign priorities to pavement improvement projects:

1 Calculation of net annual user savings (employing vehicle operating costs only) when such savings can clearly be based on the effect of the improvement

2 Subjective identification of priority based on nonquantifiable benefits, such as those resulting from a safety improvement (see Sec. 4.3)

3 Priority "fixed" through the pavement improvement being part of an overall highway project, when benefits of the project as a whole might be determined on the basis of capacity and/or route improvements

In actual practice, most highway agencies would have a list similar to Table 4.1 for capital expenditures that would include not only pavement projects but also bridge projects, grade construction projects, and so on. Nevertheless, because past practice has generally not included the assignment of any benefits to pavement improvements, a Table 4.1 type of listing for pavements alone, and the basis on which it is determined, can be most beneficial and can be used as input to a higher level of financial planning in the agency.

4.5.2 Basis for Net Benefit Calculations for Pavement Improvements

The basis for the user savings calculations of Table 4.1 is the relationship between vehicle operating costs and pavement serviceability, for various speeds, of Fig. 4.6, and the operating speed guidelines of Table 4.2. Figure 4.6 is a graphical representation of vehicle consumption rates translated into very approximate costs. These consumption rates and costs have been synthesized from Refs. [56-62] for North American conditions. They should be recognized as being very rough estimates only and applicable primarily to the network type of investment planning analysis shown in Table 4.1.

Table 4.2 also represents some very approximate estimates and again is applicable primarily to the Table 4.1 type of analysis. The basis for the Table 4.2 estimates is Refs. [62-64]. To use Table 4.2 in conjunction with Fig. 4.6, it is necessary first to select the operating speed corresponding to the PSI or RCI of the pavement surface from Table 4.2. This same PSI or RCI value is then located along the horizontal axis of Fig. 4.6, and the operating speed selected is located vertically from this point (interpolation may be necessary). Finally, the average user operating cost is determined by going horizontally to the vertical axis.

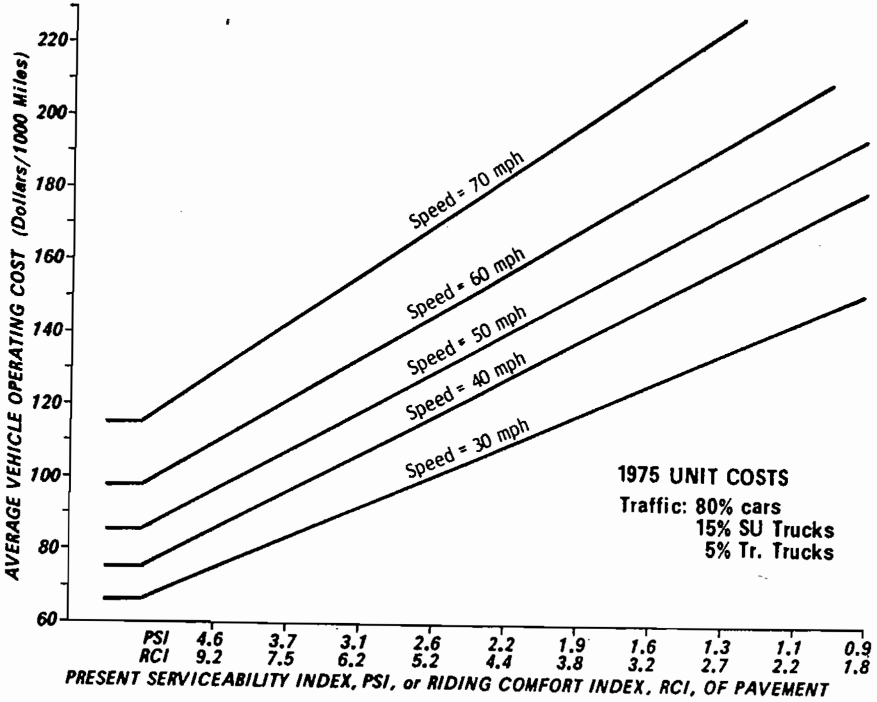

Figure 4.6 Approximate vehicle operating cost as a function of pavement serviceability and speed under rural, free-flow conditions.

Table 4.2 Guidelines for Selecting Approximate Average Highway Operating Speed, Under Free-Flow Conditions, for Various Levels of Serviceability

PSI[a] range	RCI[b] range	Approximate average speed for roads with following speed limits[c] 50 mph	55 mph	60 mph	65 mph	70 mph
0–0.5	0–1	30	30	30	30	30
0.5–1.0	1–2	42	42	42	42	42
1.0–1.5	2–3	46	48	50	50	50
1.5–2.0	3–4	48	53	55	57	58
2.0–2.5	4–5	50	55	58	62	65
2.5–3.0	5–6			60	65	68
3.0–3.5	6–7					70
3.5–4.0	7–8					
4.0–4.5	8–9					
4.5–5.0	9–10	50	55	60	65	70

[a] PSI, Present Serviceability Index, is a measure of the present serviceability to the road user, primarily in terms of riding comfort, of the pavement surface, as developed at the AASHO Road Test. It is measured on a scale of 0 to 5 (see chap. 7 for details).

[b] RCI, Riding Comfort Index, is the Canadian equivalent of PSI, but measured on a scale of 0 to 10 (see chap. 7).

[c] A maximum speed limit of 55 mph was instituted in the United States in 1975. Consequently, the last three columns are not applicable where this situation occurs.

For example, suppose that an existing pavement section with Present Serviceability Index (PSI) of 1.6 and AADT of 3,000 is to be a candidate project for an overlay. The overlay is expected to have a service life of 10 years (i.e., at the end of 10 years, the PSI of the pavement will be back down to 1.6). Immediately after construction, the PSI is expected to be 3.1. Consequently, the average PSI over the 10 years would be $1.6 + (3.1 - 1.6)/2 = 2.3$. These conditions will result in the following speeds and average vehicle operating costs:

PSI	Average operating speed (Table 4.2), mph		Average vehicle operating costs per 1,000 vehicle miles (Fig. 4.6)
1.6	53		\$167
2.3	55		\$144
		Savings	\$ 23

If the AADT is expected to increase linearly to 4,000 at the end of 10 years, the average AADT over the 10 years is 3,500. So the average annual user savings due to the improvement are $23/1{,}000 \times 3{,}500 \times 365 \simeq \$29{,}000$ per mile. The net annual savings, or benefits, would then be calculated by subtracting the average annual cost of construction plus maintenance from these savings, as shown in Table 4.1 for the projects listed.

The foregoing analysis involves a number of approximations and simplifying assumptions:

1. It is assumed that if no improvement occurred, routine maintenance could keep the serviceability level constant (i.e., at a PSI of 1.6 for the example) over the service life of the improvement. In actual fact, of course, maintenance costs would probably increase drastically if the improvement continued to be delayed. Thus, it could be argued that savings in maintenance costs as a result to constructing the improvement should in fact be added to user savings to obtain total benefits. However, leaving out the maintenance cost savings, at least at the network level of investment planning, is conservative and simplifies the analysis. At the detailed project level of design (see Part Three and Chap. 16), the economic analysis might well include such factors.

2. An average traffic composition, applicable to many highway conditions in North America, has been to derive the plotted relationships in Fig. 4.6. There can, of course, be fairly wide variations from these conditions. Nevertheless, this simplifying assumption should be reasonably representative for most highway conditions and sufficient for analysis at the network level of investment planning.

3. The investment planning analysis described does not satisfy the desirability of using the same time period of analysis for all projects (see Sec. 4.3). Without this simplification, however, the analysis could become much too detailed and time-consuming for network investment planning purposes. For most of the new and rehabilitation type of tentative pavement designs used by highway agencies at the network stage of planning, where expected initial service lives usually range from about 10 to 20 years, this simplification does not normally affect the relative priority ranking of projects. At the detailed project level of design, where within-project alternatives are being considered, it is essential, however, that the economic analysis use the same time period for all alternatives (see Part Three and Chap. 16).

4. The analysis described also considers annual costs per mile, and annual user savings per mile, as averages over the service life of the improvement, with no provision for the time value of money (i.e., future costs, or savings, are not discounted to present value). This simplification makes the calculations very easy and, although certainly not economically "correct," it will provide the same relative priority ranking for most network planning situations as would a procedure that incorporates the time value of money. Again, at the detailed project level of economic analysis, this must, however, be included (see Part Three and Chap. 16).

5. The analysis uses only vehicle operating costs to determine user savings. This simplification provides a conservative estimate because user time savings due to the improvement have not been included.

These approximations and simplifying assumptions are considered warranted for the network level of investment planning for two basic reasons: (1) Pavement improvements are not always justified by highway agencies on the basis of benefits to be derived from the pavement itself; that is, they are often either a predetermined part of a larger highway project, or the benefits cannot be quantified. In fact, it has only been very recently that a few highway agencies have begun to consider pavement improvements explicitly in terms of benefits attributable to the pavement itself. (2) The objective of network investment planning is basically to assign priorities to candidate projects for improvement; it is not to determine the optimum within-project strategies.

Finally, the analysis described for network investment planning of pavement improvements can easily be computerized both for the cost and benefit calculations and for the annual updating required. As well as the computerization, some of the approximations and simplifying assumptions that have been used could either be improved or eliminated. The form and extent of such computerization and modifications depend on the agency involved and its particular requirements.

Chapter 5

Pavement Research Management

5.1 IDENTIFYING RESEARCH NEEDS

Although it is not widely known, some of the earliest work in pavement systems development was done to provide a rational framework for organizing and coordinating existing knowledge on pavements and for projecting future research needs. Because of the many details involved in pavement design, construction, and maintenance, large agencies have often found themselves working at cross purposes, internally, without proper coordination on pavement research.

When the Texas pavement group began their Project 123 [7], one of the primary objectives of the study as stated was "to delineate additional profitable areas of research in the design, construction, maintenance and economics of pavements." In current pavement management terms it could be said that the objective was to provide a systematic plan of research for continued development of a pavement design system in order to provide for optimum utilization of funds and personnel.

The NCHRP pavement systems project [2] also showed that systems methodology provide an ideal way of structuring research needs.

5.2 SYSTEM PARAMETERS AND THE STATE OF THE ART

If the pavement system and its subsystems were completely understood, a perfect, invariate set of parameters that defined the system could be developed. Each of these parameters would be a function of space, time, geometry, and other variables. The model would be extremely complex but, if it were available, work to solve it could proceed. Such is not the case, however; knowledge of the system is not now complete and is not likely to be in the near future. This knowledge will come only from continued study of details of the system, the development of relatively more simple models, the application of these models, and the feedback of information to improve the models.

At the present time, the parameters that must be considered in a pavement management system are highly dependent on the state of the art for:

1 The model being used

2 Past experience on which to base knowledge of pavement behavior and the significant factors involved

3 The quality of the instrumentation or measurement techniques available to determine the parameters to be considered in the system

4 The quality of the information and data storage retrieval system that must be used in the continuous improvement of the pavement system

5 The quality control or variability that is inherent in the system and that governs the amount of data required to define the parameters adequately

These five factors constitute much of the problem in developing improved pavement design and management systems. In fact, the term *design system* itself is misleading, because it has traditionally excluded consideration of maintenance and evaluation. Thus, a term such as *pavement management system* should be used to represent the entire process of providing pavements.

It is not entirely possible to isolate the various subsystems involved in pavement management, although many attempts have been made in the past to do so. An example of such attempts would be trying to solve the complete system by considering only the environment and its effect on pavement failure. The interaction of the environment, for example, with material properties can give very misleading results with this type of approach.

Another example of subdividing the problem has been to develop pavement design methods for immediate use from the more complete design methods for future use. Usually, the attempt to develop a "quick" state-of-the-art method is made at one level of an organization while at another, usually in the research section, an attempt is being made to solve the problem by providing a sophisticated theory to give perfect answers. Often this theory ignores or abandons that which is currently being used or developed, calling it an "empirical approach." Obviously, such a method of subdivision is wasteful and cannot possibly lead to a comprehensive, efficient, and economical design method.

In reality, the problem will ultimately best be solved through a cyclic process, as shown in Fig. 5.1, and improvement will come in gradual steps, not in quantum increases, as portrayed in Fig. 5.2. Step 1 in this process involves considering methods currently being used. Also, the current state of the art should be used in the initial, perhaps crude, systems model. Then sensitivity analyses can be performed and work to improve the system can be done on a continuing, step-by-step basis (Fig. 5.2).

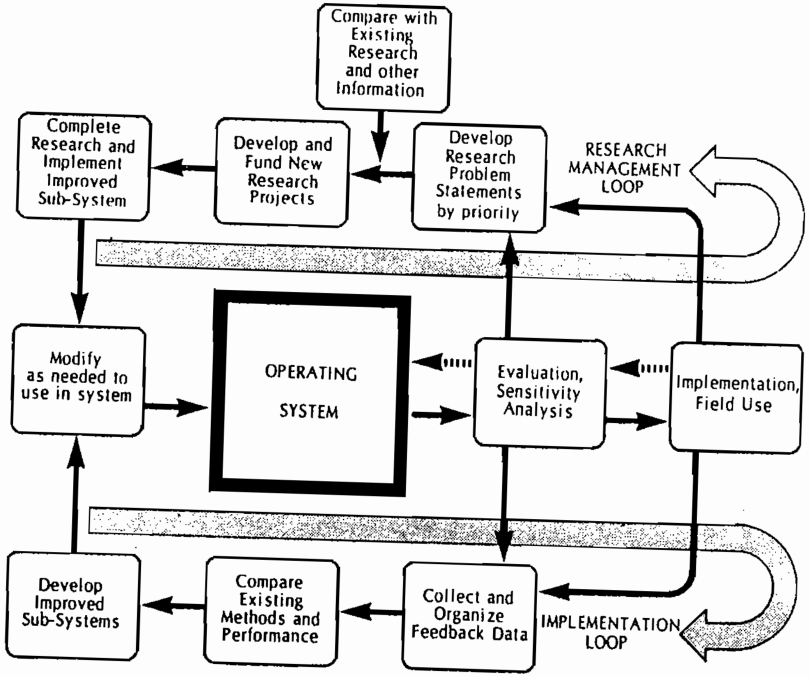

Figure 5.1 Cyclic improvements of pavement design and management systems.

Thus, the way model building, selection of parameters, and the entire system development relate to each other begins to become apparent. In some components, such as traffic, it seems easy to define the significant parameters. However, there are questions as to the form in which the data are to be provided in the model and the way they should be summarized. For example, the AASHO Road Test models involved equivalent 18-kip single-axle loads; however, the original data also provide information on vehicle load, placement, and other factors such as tire pressure and tire width.

Environmental variables have historically been rainfall, temperature, and depth of frost penetration. In all cases, however, except for a few theories such as those for slab restraint, the models have involved crude correlations. The use of these correlations often causes problems in developing general pavement models because the experiment and the data used to develop the correlations were basically applicable only to a particular situation or locale.

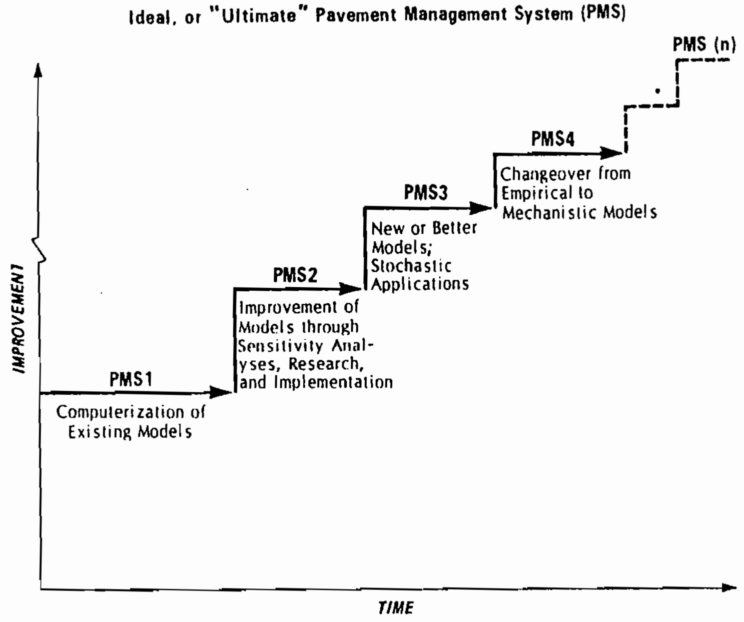

Figure 5.2 Step-by-step improvements in development of pavement management systems.

5.3 ESTABLISHING PRIORITIES

One of the important parts of research management is the task of establishing priorities for work to be done. Almost no research budget is adequate for attacking all perceived problems. Too often in the past the priorities have been set by the main interests or abilities of existing research staff rather than by the needs of the job. This can be overcome to a large degree with a well-developed pavement management system, including an initial operating system with which to work. Sensitivity analyses can be run with the working system to determine the areas or parameters in the model that seem most to affect the output of the system. These results can be compared with estimates of the accuracy with which these parameters, or models, as the case may be, are known or can be determined. By combining this information a priority list of important factors can be determined. This priority list can be compared to research costs and potential payoff or benefit to establish actual research program priorities.

5.4 IMPLEMENTING RESEARCH RESULTS

There is a great deal of concern in the scientific community about implementing research results. This concern has carried into the transportation and specifically the highways area. It is well founded and important. Unfortunately, the reaction to the concern is often inappropriate to correct the problem. In many cases the concern over implementation has resulted in the formation of special organizations called *implementation groups*, and so on. These groups are often set up as autonomous, organizational units peripheral to the research process and also peripheral to the operational process within the agency.

Proper implementation of any research results is best begun at the time that the research is first formulated. This implementation should directly involve (1) the operating agency or "research consumer," and (2) the research agency. Proper structuring of the problem by the operating agency and proper understanding of the problem by the research agency is essential. When this has been accomplished, an automatic mechanism for implementation of the research has been created, a priori.

In the pavement field the pavement management system provides the required organizational structure for both defining research needs and providing a mechanism for implementation of research findings. When the problem is originally structured, a comparison of the initial working system against the conceptual system can immediately show missing links in the chain. The interaction of these missing links or subsystems with adjacent subsystems, including the form of required inputs and outputs, can readily be determined and thus a specific research problem can be formulated and attacked. If proper scheduling and funding of these needs is also observed, then the results of the research program will feed back into the pavement management system to update the appropriate subsystem. Priorities and needs must, of course, be observed as outlined in the preceding section.

Certainly it may be appropriate to have people specifically charged with implementation of results even within the staff of the pavement management system. However, these people must work closely with the research team and with the operating team of the management system, and they cannot be successful if they are working independently of these groups. Such an implementation group can be responsible for preparing the necessary manuals, documents, and forms for putting the revised system into practice. However, here again the pavement management system concept makes this relatively easy, because the working system will be operational on a computer of some type and will of necessity have appropriate documentation in user manuals. Thus the implementation process merely involves changing the appropriate computer software and providing updated manuals or corrections to the operator and revised user manuals to the appropriate users of the working system.

Throughout this book, as many of the principal parts of the pavement management system are discussed, the research needs of each subsystem are also considered. As well, in the last chapter of the book, several major research priorities are considered directly. However, in a book of this type it is not appropriate to discuss all the specific, detailed research needs and priorities, because they can change very rapidly as innovations and findings are brought forth by the pavement research community.

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Part Two

Pavement Evaluation and Performance