Part One

THE EVOLUTION OF PAVEMENT MANAGEMENT

1

Introduction

Many advances in the planning, design, construction, and maintenance of pavements have occurred in the past century. Pavement management, as practiced today as part of overall asset management, has evolved from early rudimentary efforts in the 1960s to a comprehensive technology, economic, and business-based process.

The first two books on PMS were published in the 1970s [1,2] and in many ways were a catalyst for ensuring developments and implementation of pavement management systems worldwide. Related documents include many guides, manuals, reports, and a vast array of publications, most of which can be accessed on agency websites.

Quite recently, the Canadian Pavement Asset design and Management Guide [3] has provided a valuable tool for practitioners and for college and university level instruction.

The last major PMS book, *Modern Pavement Management*, published in 1994, is comprehensive in scope and content and is still used in both university and professional environments [4]. In universities it is used as a text for senior and graduate level classes. Professionals use it to study the broad concept of pavement management systems, either by self-study or in a workshop environment.

Since 1994, there has been a transition in application of pavement management systems. Large agencies at the national and state level continue to use pavement management systems as a vital part of their asset management strategy in fulfilling their responsibility to society. This practice has also been transmitted to local and city agencies with pavement and other assets responsibility.

However, application of PMS in all areas of the public sector has migrated from project-level PMS to broader application at the network level.

As a result of this transition, it seemed clear to the authors that this book should deal primarily with the network-level PMS and so it does. Since the basic concepts and approach from 1994 still apply, this book picks up changes, improvements, and application developed since 1994. As a comparison, [4] provides the content for basic PMS studies, while this book updates concepts and applications for advanced studies.

In other words, the authors do not repeat the basic pavement design models and concepts. The reader may obtain those in [4,5]. The design models covered herein relate to MEPDG [6].

This book explains the development of asset management as it stemmed from pavement management in Chapter 46 of [4] but it does not cover asset management details that are presented in a book by [7].

2

Birth and Teen Years of Pavement Management (1967–1987)

Pavement management was born in the mid 1960s largely in response to numerous unanticipated pavement failures on the US Interstate and Canadian Highway Systems. These roads had been designed and constructed using the best known pavement design technology at that time, including the results of the $30 million AASHO Road Test. After an intensive national review of problems observed, the impossibility of making accurate single-point predictions of pavement performance due to national statistical variability of the major inputs became clear. Design methods at that time required as inputs estimated traffic, projected as-constructed materials properties, and estimated environmental conditions for a 20–30 year life of the pavement. These methods did not take into account the effects on performance of pavement maintenance, nor did they consider the life-cycle cost past the initial design period to include one or more overlays and rehabilitation activities, which everyone knew were common practice on heavy duty pavements. In response to this problem the National Cooperative Highway Research Program (NCHRP) funded a major research project (AASHTO) to find the reason and a solution for the problem [8].

A number of prominent civil engineers were involved in the US space program in the early 1960s and in various brainstorming sessions of the pavement "design" and "performance" problem. After many hours of discussion, they recognized the need to integrate planning, design, construction, maintenance, and rehabilitation into a coordinated systematic method for providing the required pavement performance over a 30, 40 or 50 year life. Figure 2.1 was the first input/output diagram developed to describe what has become known as a Pavement Management System (PMS). It illustrates the many important factors that govern pavement performance. A detailed description of the diagram is beyond the extent of this paper [2,4,9].

In a parallel study in Canada, what was then the Roads and Transportation Association of Canada also recognized the concept and produced a comprehensive Pavement Management Guide in 1977 [10]. Critical to both these efforts was recognition of the need to evaluate pavement behavior, pavement distress, and pavement performance steps in design. Prior to this time, design methods had attempted to predict performance directly from materials and weather inputs using empirical evidence such as the AASHO Road Test. These two initiatives in the late 1960s and early 1970s showed that it was essential to measure pavement behavior as an intermediate step since all known theoretical pavement equations do in fact predict behavior in the form of stress, strain, or deformation, but not performance directly. Behavior carried to its limit becomes distress in the form of cracking, permanent deformation, and disintegration. Distress as a function of accumulated traffic loads yields the required performance curve which can be used to judge the effective life of a pavement structure.

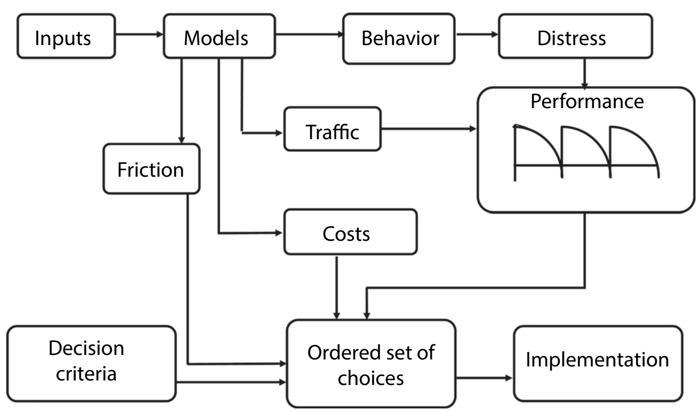

Figure 2.1 Major components of a Project Level Pavement Design System as initially formatted in the 1960s. (These remain true today.) After [9].

These factors properly analyzed can be used to determine required maintenance, overlay, and rehabilitation needs for the pavement including expected time of such interventions and the effect such interventions have on pavement performance life. The complete project level pavement management process then optimizes and compares predicted pavement performance life as a function of total life-cycle costs.

It quickly became clear that these same concepts of behavior and performance could be used to evaluate a group section in a pavement network by evaluating all the factors and developing performance prediction models for each individual section. In turn, the needs for each pavement in the entire set of pavement sections could be compared to determine when to intervene in each individual section and in what priority order to optimize budget expenditures and maximize total performance of the pavement network. All of these activities at both the project and the network level require data that defines the material properties, loads, environment, behavior, distress, and actual performance. The data must be stored in a central data base and be accessible to the entire pavement management process as illustrated in Figure 2.2. As well, the so-called feedback data that describes the actual performance of each individual pavement section of the many sections in the network must be accumulated and used to update the necessary performance and cost models as shown in Figure 2.3. Details about this basic process are described in [2,4,9]. We recommend them for study.

All of the earliest Pavement Management Systems described in the literature FPS (Flexible Pavement System), RPS (Rigid Pavement System), SAMP (Systems Analysis Method for Pavements), and OPAC (Ontario Pavement Analysis and Costs) operated at the project level and provided

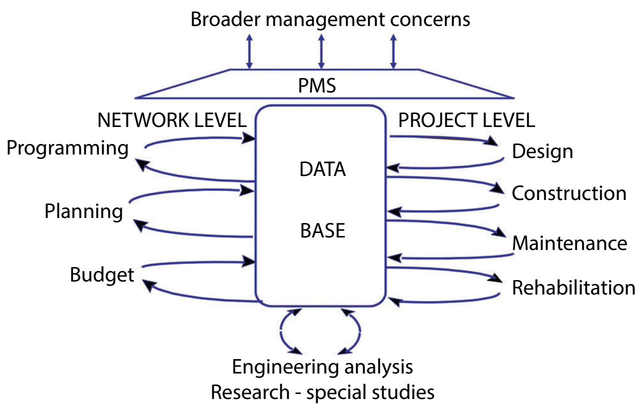

Figure 2.2 Components of a PMS, distinguishing the three levels. After [9].

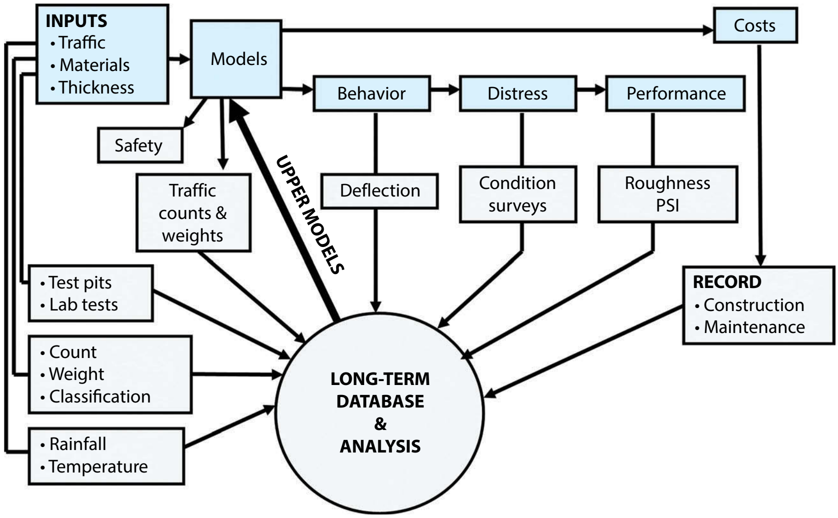

Figure 2.3 Performance and cost models diagram. After [9].

significant improvement in the ability to design, construct, and maintain pavements for adequate performance over time [4]. The functional performance and cost models used in all of these are represented in Figure 2.3.

2.1 Network Level PMS

At the same time many state and provincial DOTs were faced with trying to maintain and operate a large network of existing heavy duty pavements on the US interstate system and the Canadian National Highway System. Their concerns were with the many thousands of miles of the existing pavement network that were failing prematurely. This was the driving force for states such as Arizona, Kansas, and Washington, and several Canadian provinces to embark on the development of functional Network Level Pavement Management Systems [8,10]. Since network level pavement management was of primary interest to transportation executives and chief engineers, the word spread that these network level systems could assist states/provinces in allocating their funds in a more optimal way to maintain their entire network in better condition. These interactions occurred within both the American Association of State Highway and Transportation Officials (AASHTO) of the United States and the Transportation Association of Canada.

Other states began to follow suit and the growth of pavement management from the mid-1970s to mid-1980s advanced toward network-level programs. This was fostered by two National Workshops on Pavement Management sponsored by FHWA and AASHTO in which the Executive Directors of each organization attended.[1]

These workshops basically set the agenda for the next 10 years of development and buy-in of pavement management to other state/executives [11,12,13]. Moreover, this spreading interest led to the first conference in the series in Toronto in 1985 [14]. Because of the rapidly changing landscape of pavement management, a 1987 conference brought together representatives of most US state DOTs, Canadian provinces, and many local agencies, and led to the development of network level PMS in at least 50 of those 60+ agencies in attendance.

Those conferences were also attended by pavement engineers from other nations around the world, and they took the available PMS literature back home to develop their own network level PMS. At the same time undergraduate and graduate courses in pavement management were developed at the University of Texas by Dr. Ronald Hudson and at the University of Waterloo by Dr. Ralph Haas. These courses attracted both national and international students who formed the core cadre of working pavement management engineers around the world. In addition FHWA recognized a major need to reeducate practicing engineers who were working in transportation agencies before the advent of pavement management. In response to this need, FHWA funded an intensive pavement management six-week graduate level course at the University of Texas in Austin with Dr. Ronald Hudson as course coordinator. One hundred eighty-seven engineers from all over the world attended this course over the next three years. Drs. Ralph Haas and Matthew Witzack frequently served as guest lecturers in this course. The engineers attending from approximately 40 states and the FHWA engineers returned to their divisions and central offices and greatly expanded the quality and use of pavement management at the network level.

2.2 The Impact of Lack of Understanding of Software Requirements

As PMS evolved, a common mistake occurred: agencies attempted to develop a PMS in-house even though they lacked the computer and information

[1] The first workshop was held in Phoenix, Arizona, in May 1980, and the second in Charlotte, North Carolina, in September 1980. Drs. Hudson and Haas gave invited keynote addresses to the workshops.

technology skills, statisticians, and support staff to do the job properly. The problem resulted from a shortcoming in the education system of the universities that were teaching engineers in pavement management technology: educators did not adequately delve into the business processes and software needs associated with PMS. Some states and provinces, such as Arizona, Kansas, Minnesota, and Ontario, flourished by employing professionals in the disciplines to develop an appropriate network-level system with crude optimization. Unfortunately, the majority who tried to develop the systems in-house got bogged down or at best got a prioritization system based on worst first pavement condition across the pavement network. A number of these agencies in 2014 are still using these homegrown, self-developed pavement section prioritization methods that should not be called PMS at all. As we will discuss later, from 1997 to 2007, 20 to 30 state/provincial agencies advanced into better developed, more functional PMS with customized software from specialized venders. Similar activities included significant development in Chile as well as implementation of systems in two U.S. state DOTs, Brazil, Parana, Tocantins, and widely across Europe.

2.3 Lessons Learned from the Early Development Years

Pavement management had progressed in 20 years from a concept to a working process. The principles and definitions had been reasonably well formulated and much had been learned from implementation experience at Federal, State/Provincial, and local levels.

These twenty original or "early birth" years of pavement management experience (1967–1987) indicate that the original concept of a comprehensive, systematic process is quite valid. That is, it incorporates in an organized and systematic way all the activities that go into providing and operating pavements: they range from the collection, processing, and analysis of field and other data on various pavement sections; the identification of current and future needs; the development of rehabilitation and programs; to the implementation of these programs through design, construction, and maintenance.

What perhaps has not been so well learned is that just because an agency has carried out all these activities does not mean it has a functional PMS. To have a PMS in the proper definition of the term requires a coordinated execution of these activities, and most importantly, the incorporation of a number of key elements such as performance or deterioration models, lifecycle economic evaluation, etc.

Table 2.1 Some key ideas learned from 20 years (1967–87) of pavement management experience. After [15]

From P.M. Process Itself	From Using the P.M. Process
• The framework and component activities for P.M. can be described on a generic basis. • Existing technology and new developments can be effectively organized within this framework. • The framework allows complete flexibility for different models, methods, and procedures. • P.M. operates at two basic levels: network and project. • Sound technological base is critical to the process and its effective application to the process and its effective application.	• Development and implementation of a PMS must be staged. • Staging allows for understanding and acceptance by various users. • Options almost always exist; they should be evaluated on a life-cycle basis; this means we need models for predicting deterioration of existing pavements and rehabilitation or maintenance alternatives. • P.M. can make efficient use of available funds but it will not "save" a network if funding is below some threshold level. • Good information is essential to the effective application.

Table 2.1 summarizes, in more specific terms, some of the key ideas learned both about the P.M. process itself and about its application. These will be useful to reference during later enhancements in this book.

2.4 Basic Requirements for an Effective and Comprehensive PMS

Pavement management was determined in the early years to be no different in its general requirements than any other area of management. It involves the coordinated direction of resources and labor to achieve a desired end. Decision making at various levels is therefore a primary activity that can only be effective if good data/information is available.

Several additional basic requirements and businesses exist for the effective application of a PMS including the following:

1. Serving different types of users in the organization,
2. Making good decisions regarding network programs and individual projects, and executing these decisions in a timely manner,

Table 2.2 summary of activities and decisions within a complete pavement management structure. After [15].

Basic Blocks of Activities	Network Management Level (Administrative and Technical Decision)	Project Management Level (Technical Management Decisions)
A. Data	1. Sectioning 2. Data a. Field inventory (roughness, surface distress, friction, deflection, geometrics) b. Other (traffic, unit costs) 3. Data Processing	1. Detailed data structural, materials, traffic, climate, and unit costs 2. Subsectioning 3. Data Processing
B. Criteria	1. Minimum serviceability, friction, structural adequacy, max. distress 2. Maximum user costs, maintenance costs 3. Maximum program costs 4. Selection criteria (max. of benefits and max. cost-effectiveness)	1. Maximum as-built roughness; minimum structural adequacy and friction 2. Maximum project costs 3. Maximum traffic interruption 4. Selection criteria (such as least total costs)
C. Analyses	1. Network needs (now) 2. Perf. Predictions and future needs 3. Maint. And rehab. Alternatives 4. Technical and economic eval. 5. Priority analysis 6. Eval. of alternative budget levels	1. Within-project alternatives 2. Testing and technical analyses (performance and distress predictions) 3. Life-cycle economic analyses
D. Selection	1. Final priority program of capital projects 2. Final maintenance program	1. Best within-project alternative (rehab. Or new pavement) 2. Maintenance treatments for various sections of networks
E. Implementation	1. Schedule, contracts 2. Program monitoring 3. Budget and financial planning updates	1. Construction activities, contract control, and as-built records 2. Maintenance activities, Maint. Management, and records

3. Making good use of the existing technology, and new technology as it becomes available,
4. More detailed discussion of these requirements is provided in [2,4,9].

An essential part of fulfilling the foregoing requirements is to have a structure or framework for the various activities of pavement management. Table 2.2 lists the major activities and/or decisions made within such a P.M. structure as summarized in 1987 [15].

Since 1987 we have made great strides in most of these areas and the result is greatly improved PMS software and a better understanding and implementation thereof.

3

Pavement Management Development from 2010

In 1987 the PMS process was generally being developed individually and in-house by state DOTs. All US states and Canadian provinces reported having some type of PMS in place. It has been estimated that of the 90% of these developed in-house, 60% were largely unused and 30% gave only simplistic answers based on condition. This growth of apparent PMS was spurred largely by the US FHWA mandate for pavement management (known as ISTEA) but lacked the guidance and available personnel and resources to truly succeed. Thus good systems were not always developed. Only in the order of 10% of the systems— including Arizona, Kansas, Washington, Minnesota, Alberta, Ontario, and a few others—were successful and used effectively.

At the time, it was not foreseen that private teams of engineers, system analysts, and programmers would recognize the need for effective user-friendly PMS and would step forward to work with several state/provincial DOTs to develop more complete PMS. Many did, and by 2010 approximately 35% of state/provincial DOTs were using commercial off-the-shelf systems successfully, three to four states per year were advancing their technology to improve PMS, and at least three or four agencies per year were adding other management systems (MMS, BMS, etc.), all working toward broader asset management.

In 1987 the subsequent need and development of asset management was also not adequately foreseen. But by 1997 it was receiving serious attention by AASHTO, TAC in Canada [16], FHWA, and in countries like Australia and New Zealand. In some states, asset management was used as an overarching planning tool. By 2010 several states recognized, however, that 90% of the assets to be managed were within the purview of PMS and BMS, pavements and bridges, and supported at the network level by maintenance management (MMS). Many had also expanded to fleet and safety management using commercial off-the-shelf systems [17].

3.1 Data Aggregation and Sectioning

The 1987 contribution also did not adequately foresee the need for improvements in data aggregation and PMS "sectioning." Since that time, individual PMS software vendors in contracts for specific state DOTs have devised sophisticated methods, including dynamic sectioning, for aggregating data that better represent sections or subsections of the pavement network under uniform conditions. This has been made possible by the fact that rapid network optimization analysis procedures have been developed which permit larger and larger networks of sections to be compared and optimized.

3.2 Private Investment

It is encouraging that several PMS providers in cooperation with their state DOT users have made significant investments in PMS software improvements in the last 10 years. While impossible to determine the exact amount, at least 20 state/provincial DOTs have invested approximately $3–4 million each in active pavement management. From this base the software providers have been able to spend significant funds on research and software improvements including clarifying the need for improved data collection methods. Although smaller in magnitude, these investments resemble the private sector investment made by Microsoft, Google, etc. to improve the software technology in their fields of endeavor. Of course, there remains a significant need for public investment in PMS research outlined in the FHWA Pavement Management Roadmap [18].

3.3 Parallel International Developments

There have also been significant parallel developments in the international community. Pavement management has flourished in Chile and to some degree in Brazil and other South American countries under the leadership of Dr. De Solminihac and other colleagues. Significant strides have been made to improve the properties and operating characteristics of the highway design model (HDM-4) under the leadership of the World Bank and carried forward by Drs. Kerali and Snaith, originally at the University of Birmingham, and others.

Significant developments have also been made in the United Kingdom and across Europe where a European PMS conference has been held several times in the last two decades. Pavement management has also spread to China and other Asian countries under the leadership of students who have learned their PMS in US/Canadian universities and returned to their home countries for application. Funding has been provided by such agencies as the Canadian International Development Agency (CIDA) and other nations. Time and resources available for preparation of this paper have unfortunately not permitted a more detailed listing and summary of these individual activities and references.

3.4 Administrative and Public Awareness of PMS

The advancement of asset management (AMS) remains an enigma. In fact, the Hudson, Haas, and Uddin 1997 book argued that Infrastructure Management was a better term than Asset Management or Facilities Management and thus chose it as the title [19]. General pursuit and sales of generic AMS concepts to state DOT administrators in many cases may actually have inhibited the use of PMS. AMS was sold as an overriding planning tool, vaguely outlining that all assets were to be combined and administered effectively. However, rigorous details of how this was to be done remain elusive. On the other hand, progress is being made from the bottom up. As of 2011, several states have adopted not only pavement management systems but have added maintenance management systems and bridge management systems. The combination of these three activities account, in most cases, for about 90% of the budget of state/provincial DOTs. See Figure 3.1. These systems also contain the data needed to do broader asset management. Several state DOTs are also adding safety management systems, fleet management systems, and facilities management

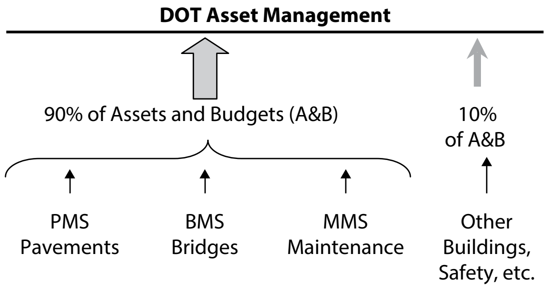

Figure 3.1 Components of Assets Management.

system. Combined with PMS, BMS and MMS, these management systems involve 98% of all the information and analysis needed for good asset management.

There is still need for coordination of the systems at the top, but this is occurring as administrators and agency business processes recognize the true value of bottom up information. Those agencies that are still trying to administer AMS from the top down are lagging in their use of effective management systems. This has occurred to some degree because AMS is sold by some to be a replacement or supplement for "planning." While planning is an important part of asset management, it can only function if the real data on facilities, pavement, bridge condition, and performance is available for analysis. In reality, planning is only one part of AMS.

3.5 Education

The continuing need for broader education in the pavement management field has not been fulfilled to the degree needed. Technical and analytical aspects of an effective PMS are broad and complex. Many DOTs do not have on their staff or even the ability to hire the disciplines needed, particularly statistics, economics, systems, and high quality computer programmers. Nor in general can they afford to develop or attract such employees to their normal staff. That may be best and most economically left to software providers/vendors who do have such personnel and who can apply the resulting technology over several agencies, thus reducing individual cost.

We also need to train existing DOT personnel more effectively. User-based education remains the great need across all state/provincial DOTs, cities, counties, etc. Stated another way, this is also an issue of knowledge management, which requires succession planning/continuity to be effective. Otherwise, like any asset, its value erodes.

The critical and ongoing need for education in PMS is well illustrated by the fact that while 200 practicing engineers trained in PMS from 1982 to 1984 at the University of Texas at Austin, over half took their new systems concepts and applied them in other fields and in turn were promoted to higher levels of responsibility in their agency within three or four years. As of 2011 more than 90% of those people had retired, leaving a major void in state DOT understanding of PMS. Thankfully, however, there are dozens of state DOT personnel who have seen the benefit of PMS and who have self-educated or taken appropriate short courses and/or worked with their PMS software providers to learn more fully the internal workings and benefits of PMS.

3.6 Improvements in Computers and Software Development

In the past 20 years there has been an order of magnitude improvement in PMS software and computers available to support it. In part, this was made possible by rapid advances in computer speed and low cost data storage capabilities. The software developments have been enhanced by a cadre of highly qualified analysts, statisticians, and software engineers who have been attracted into the field by the challenge and the funds made available by software entrepreneurs who have invested in software that they now vend to various state and provincial agencies.

3.7 Other Compatible Management Systems

In 1987 there was a general indication of the broader interfaces under an asset management system (AMS) umbrella. However, what was not foreseen was the increased development and use of modern maintenance management (MMS) which in many states/provinces led the way to later implementation of pavement management. At least 8–10 states/provinces that now use strong PMS started after an active MMS whetted their appetite for high-speed data processing, optimization, and decision making. The success and interface with MMS led those agencies to move more rapidly into PMS and to integrate the two.

3.8 Expansion of PMS Concerns

All of us are beginning to see an expansion of PMS concerns that include noise, societal, and environmental aspects. Terms like "sustainable pavement management" and "sustainable pavements" have been gaining traction, but rigorous definitions are still lacking. The ideas have merit and generally seem to mean trying to produce pavements with greater concern for societal effects such as noise, user costs, user delays, etc. and environmental factors such as consideration of hydrocarbon output, carbon footprint, global warming, etc. Progress is needed in these areas.

No one ever proposed that management systems be used to replace a good estimate of initial design. Indeed the concept has always been to develop the best possible initial design with available inputs and within reasonable budgets, but we must also accept the fact that no matter how well we design, Mother Nature and statistical factors will change in the 20, 30, or 50 years after the initial design and these must be taken into account with management systems.

4

Setting the Stage

Part Three describes the logical next step using data to determine needs and priority programming, rehabilitation, and maintenance. This requires establishing criteria to identify needs deterioration modeling for alternative rehabilitation and maintenance treatments, cost, benefit analysis, and priority programming methodologies. Examples are provided to illustrate the activity.

Part Four describes the Framework and Methodologies for project level design. This involves structural and life cycle economic analysis of available flexible and rigid pavement alternatives. It gives more detailed physical, cost, and other design inputs, the actual analysis models used, and example applications with particular attention to the current Mechanistic Empirical Pavement Design Package. While pavement design is a key part of pavement management, it is stressed in Part Four that good design is not enough by itself; good pavement management has to be practiced as a total process.

Part Five presents a logical sequence of implementation phases in overall pavement management. The steps involved are first defined and then the prominence of software providers is identified. Pavement preservation is described as a key component of pavement maintenance. Since pavement management is implemented within the broader context of asset management, the issues involved are also addressed.

Examples of Working Systems, at both the network and project levels, as described in Part Six, illustrate how pavement management systems are used in practice. There has been an evolution in development and application but basic features of working systems remain constant. Major change in the evolution has been the replacement of in-house development with use of vendors who provide comprehensive software packages. Examples of prominent vendors are given in Part Six. As well, HDM-4 is largely done by consultants. Comprehensive development of city or municipal PMS over the past two decades is noted as the implementation of airport PMS.

Looking ahead is an essential feature of good pavement management. The authors feel that this is still an entirely essential feature and is the focus of Part Seven. The section covers the use of PMS to solve special problems as well as the need to integrate new technologies as they emerge. Although PMS has evolved to a full-function, it is not complete or perfect. Part Seven identifies still needed elements. Finally, the way that PMS has led the way to functional asset management is briefly covered in the final chapter.

The more the engineering community can understand and truly accept Management Systems as the required methodology for the variable real world, the faster we will make progress.

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