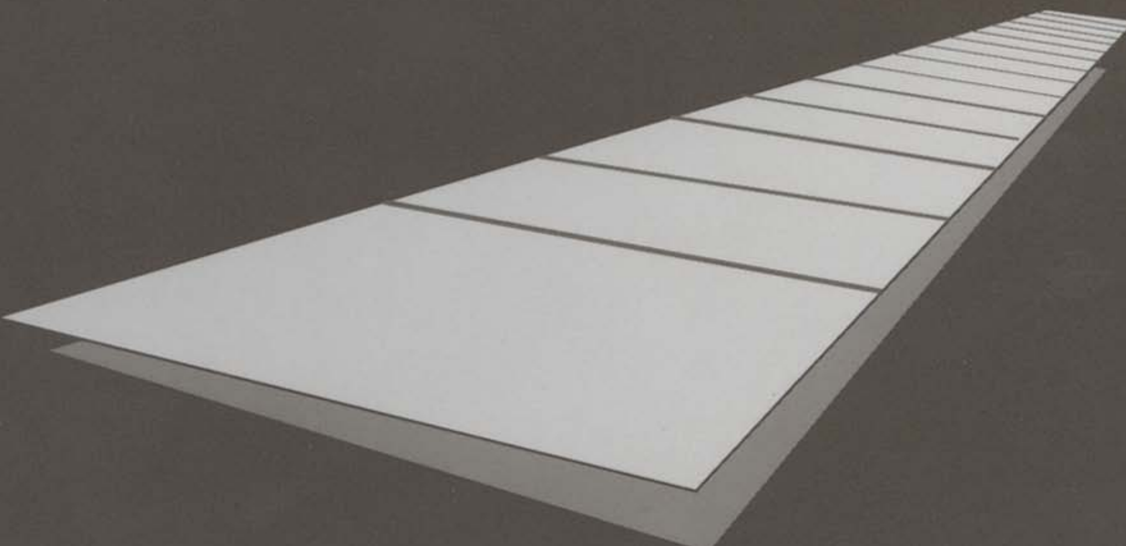
Pavement Management Implementation



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Pavement Management Implementation

Frank B. Holt and Wade L. Gramling, editors

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Peer Review Policy

Each paper published in this volume was evaluated by three peer reviewers. The authors addressed all of the reviewers' comments to the satisfaction of both the technical editor(s) and the ASTM Committee on Publications.

The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of these peer reviewers. The ASTM Committee on Publications acknowledges with appreciation their dedication and contribution to time and effort on behalf of ASTM.

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Foreword

This publication, *Pavement Management Implementation*, contains papers presented at the symposium of the same name, held in Atlantic City, NJ on 26–27 June 1991. The symposium was sponsored by ASTM Committee E-17 on Pavement Management Technologies and its Subcommittee, E17.41 on Pavement Management. Frank B. Holt of Eckrose/Green Associates in Madison, WI and Wade L. Gramling of Pasco USA, Inc., in Mechanicsburg, PA, presided as symposium co-chairman and are editors of the resulting publication.

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Overview

During the past twenty years, there has been significant progress made in applying system management principles to the complex problems in maintaining infrastructure. Agencies responsible for the street and highway networks have been faced with decreasing buying power and increased needs. The maintenance of aging networks is complicated by increased weights and volumes of traffic accelerating deterioration, coupled with intense competition for limited budgets.

The development of pavement management methods has been widely recognized as one of the tools in the economic planning and maintaining of systems. Increased power of computers, available at reasonable costs, and the development and maturing of pavement management system technology will facilitate and accelerate the adoption of Pavement Management Systems by a wider community.

The purpose of this symposium on Pavement Management Implementation was to review and capitalize on progress to date, and provide focus and direction for pavement management in the 1990s. The requirement of the Federal Highway Administration for States to have a Pavement Management System in place by 1933 raised many questions as to the form and requirements of those systems. ASTM Committee E17, Pavement Management Technologies, with assistance from Committee D4, Road and Paving Materials (symposium co-sponsor), recognized the need to further the knowledge of the pavement community and assist those who were trying to assess, design, and implement Pavement Management Systems.

The Symposium focused on both the basic premises of pavement management, and the experience of pavement management users. The aims of the symposium were to offer the engineering community an overview of pavement management structures and organizations, provide an opportunity for users of pavement management to review the state of the art and discuss their experiences, successes, failures, future innovations, and offer new users assistance in designing and using their systems.

This volume contains 31 papers and is divided into two sections. The first section presents papers of an overview dealing with such topics as the history of pavement management, requirements of pavement management systems, the problems of implementing a system, and how to evaluate pavement management systems. The second section presents papers detailing the experience of users.

Overview Section

The Overview section includes the keynote address of Louis Papet, Chief Pavement Division of the Federal Highway Administration. Papet reviewed the FHWA requirements for pavement management, and offered an overview of the present state of implementation. Papers by Nostrand, Carmichael et al., Amirkhanian et al., and Hudson et al. deal with an overview of Pavement Management addressing issues such as: the history of pavement management in the FHWA, minimum requirements for a pavement management system, the state of the art in pavement management, and standardization issues. Patterson offers a process to evaluate pavement management systems.

Additional papers deal with portions of pavement management systems that readers may want to include in their system, add to their existing systems, or use to evaluate the results of their systems. These include a discussion of data needs and priorities (Haas), pavement life (Baldi et al.), barriers that may affect implementation (Smith), engineering principles (Ullidtze et al.), and a look at timing and it's effect on network performance (Mohseni et al.).

Experience Section

The Experience section presents 21 papers detailing the experience of users, and offers the reader examples of systems from across the United States, Canada, and Europe. In total, 17 different federal and state agencies, as well as one foreign country, are represented in this section.

Pavement Management systems for roads, streets, highways, and airports are discussed. Various types of systems and system approaches are presented, including maintenance planning, statewide highway programming systems, airport pavement management systems, and military facility pavement management.

Advances in the state of the art addressed through papers on pavement life and feedback systems to evaluate the pavement management system.

For those organizations looking for assistance in implementing a pavement management system, the symposium and this STP offer an overview of the implementation process, and will, with the existing literature, assist the user in designing, implementing, and modifying their system to meet their agency needs.

As 1993 draws near, the requirement of the Federal Highway Administration to implement a pavement management system will cause agencies to review their present systems, and the papers presented in this publication will be of valuable assistance in that process. For those agencies looking to establish a pavement management system, this volume can assist in developing a system that not only meets the agencies needs, but can help preclude some of the pitfalls that other agencies have had to overcome, thus resulting in a more flexible and usable system.

Work remains to be done in reaching a consensus for the various elements making up a pavement management system. New standards, specifications, and guidelines will continue to be developed as experience is gained.

Agreement on the types, accuracy, and definitions of pavement information needed for use in a Pavement Management System will lead to standardization and automation, and enhance the ability of users to more easily exchange information and knowledge.

Committee E-17 will continue it's efforts to develop ASTM standards that address some of the issues presented in this volume. Standards dealing with network level pavement management, composite instrumentation, and priority of data needs for pavement management, are a few of the areas where standards are being formed to help users of pavement management systems.

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Key Note Address

Mr. Louis M. Papet, Chief, Pavement Division

FEDERAL HIGHWAY ADMINISTRATION - CURRENT PMS REQUIREMENTS

REFERENCE: Papet, L. M., "Federal Highway Administration Current PMS Requirements," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: On January 13, 1989, the Federal Highway Administration (FHWA) published its Pavement Policy. One of the most important parts of that policy is a mandate that every State develop and implement a Pavement Management System (PMS) within 4 years after that publishing date. All States have been attempting to meet that deadline and FHWA has been monitoring their progress. To provide guidance on the Policy, FHWA followed with an FHPM (6-2-4-1) in which the major elements that need to be included for a system to be judged acceptable were explained. The figures chosen depict the progress being made by number of States in each of the major elements of a PMS. The comments on each give one a feel for what FHWA thinks is needed in a PMS to meet minimum criteria for acceptability.

KEYWORDS: pavement policy, policy mandate, PMS in operation, 4-year deadline, inventory, condition survey, reference system

Current Pavement Management System (PMS) Requirements

On January 13, 1989, the FHWA published its Pavement Policy final rule in the Federal Register. In that policy there are three major mandates.

It should be pointed out at this point that the FHWA does not administratively issue many mandates. Unless a particular requirement is a specific part of the law, FHWA trys not to issue edicts of any kind. However, in the case of pavements, it is thought that the subject is so important that a deviation from the usual practice was necessary.

The first mandate requires the State highway agencies (SHA) to adopt a pavement design process and discard some of those old "rules of thumb" that have been used over

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the years to establish pavement thickness. The second requires that the SHA's develop a product selection process to justify the specific materials being used on Federal-aid projects.

The third mandate in the Pavement Policy, which is the most important one as far as the ASTM Symposium is concerned, requires that every SHA have a comprehensive PMS in operation, acceptable to FHWA, within 4 years from the date of issuance. The deadline date is January 13, 1993, so the mid-point in that time period has already passed.

When the 4-year period began, there were perhaps a handfull of States that had already progressed to the point where their PMS could be considered acceptable. There was another handfull which had no system at all; they had not even begun to collect data. The rest of the highway agencies were somewhere in between and were working toward the development of a PMS for their State.

Today the situation is considerably different. All of the States have begun developing a PMS and most of them have an operating system; although some SHA's have only a few of the basic elements working. There are still a few that will find it difficult to have a PMS "in operation" "acceptable to FHWA" before that 1993 goal.

The FHWA issued a reminder memorandum on December 28, 1990, to call everyone's attention to that impending deadline.

The title of this paper is "Current PMS Requirements" and those requirements will be covered quite thoroughly. However, because the information is available, a set of figures were chosen that shows the progress being made by the States towards meeting the aforementioned deadline.

About a year ago, a questionnaire was prepared for the States to complete indicating what progress each of them has made toward developing their PMS. This questionnaire was usually filled out during the presentation of the 1-Day Seminar on Pavement Management (PM) for mid/top level managers. Some of the other States were obtained through Regional Pavement Engineers and some updating was done by PM engineers that attended the Advanced Course in PMS given by FHWA.

Because of this, the information shown in the insuing figures is not completely up to date because it was gathered over a lengthy time period. However, it does give one a good indication of progress and of the trends that are taking place.

The figures do not label any State by name because their purpose is not to compare one State against another. The figures show various elements of PMS's and give the progress by number of States in each.

In the figures one will see a solid bar which represents the number of States that have progressed to that point at present. The hatched bar usually shown tacked on to the solid bar indicates the number of States anticipating that they will reach that point in the near future. The States are shown as 52 total because Puerto Rico and the District of Columbia are included.

As the status of each of these elements is shown, the text will indicate the importance of each element when considering the FHWA "acceptability" as stated in the Policy. It must be stated, however, that the responsibility for determining whether or not a system is acceptable rests with the FHWA Division Administrator in each State.

A PMS must be tailored to a particular State's needs if it is to be effective. The Division Administrator works with the State on a day-to-day basis and is in the best position to evaluate the State's needs and judge the acceptability of its PMS.

Although the Washington Office will not be making the determination of acceptability, the headquarters office will be asked for guidance.

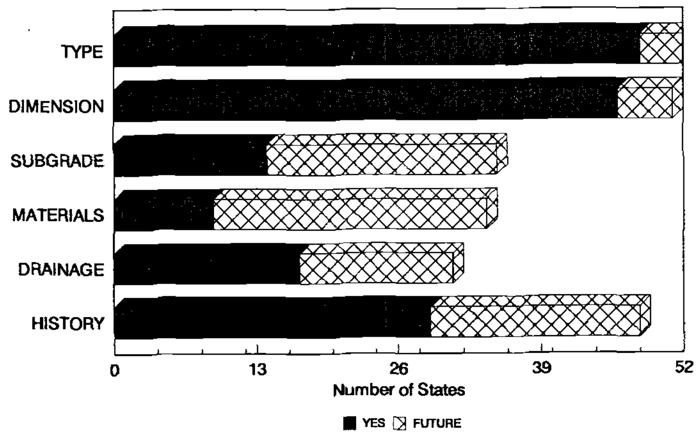

FIG. 1 - Elements included in inventory

One of the most important elements necessary for an acceptable PMS is an inventory. Figure 1 shows the number of States that have made and included a complete inventory of the network under their PMS's. The inventory should include as a minimum, the type of pavement and the dimensions, and as Figure 1 shows all of the States have or will have those included.

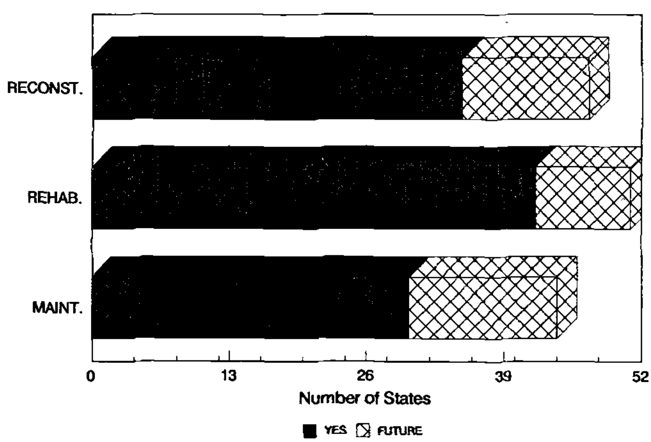

Fig. 2 - Type of work covered by PMS

Figure 2 depicts the coverage of the systems by type of work. It would seem that any PMS worth its salt would cover all projects in reconstruction and rehabilitation, so they probably all will. Maintenance may not be covered in all systems and although desirable, a division administration would probably not insist on it as a criteria for acceptability.

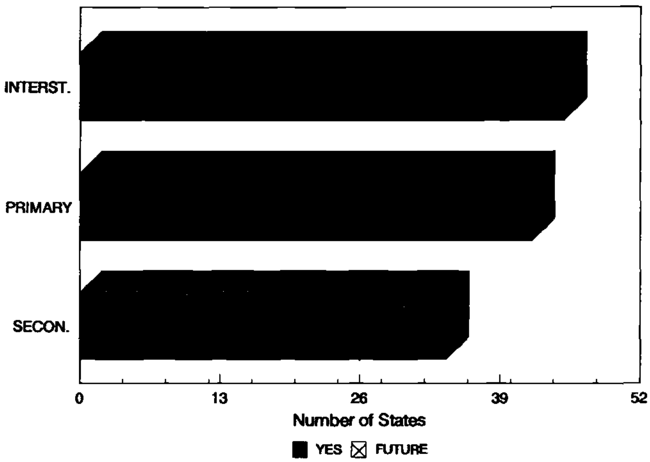

FIG. 3 - PMS Coverage by System

Figure 3 shows the PMS coverage by system. The Policy states that the PMS shall cover "all Rural Arterials (Interstate, Other Principal Arterial, and Minor Arterials) and Urban Principal Arterials (Interstate, Other Freeways and Expressways, and Other Principal Arterials) routes under its jurisdiction." It does not specify coverage by system.

If the proposed new legislation is passed, however, this may change because FHWA will probably apply the policy to the "System of National Significance."

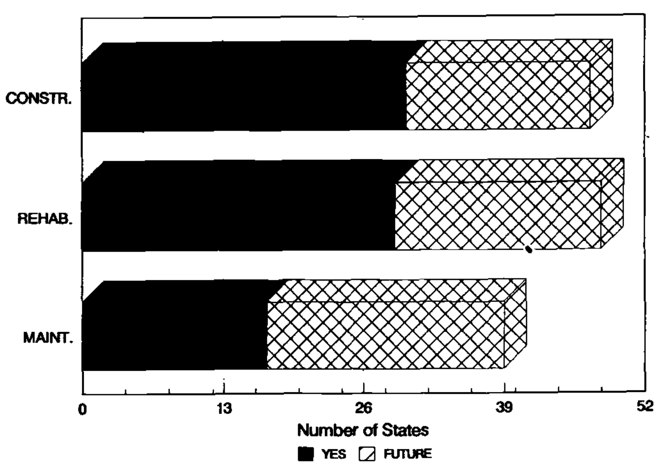

FIG. 4 - Type of work included in history

The bottom line product of a good PMS is to be able to predict performance. Performance prediction is based on the performance experience with a given set of materials and pavement design. Therefore, it would appear that a PMS needs to include a history of construction and rehabilitation and as one can see on Figure 4 almost all the States anticipate having a history of the type of work included.

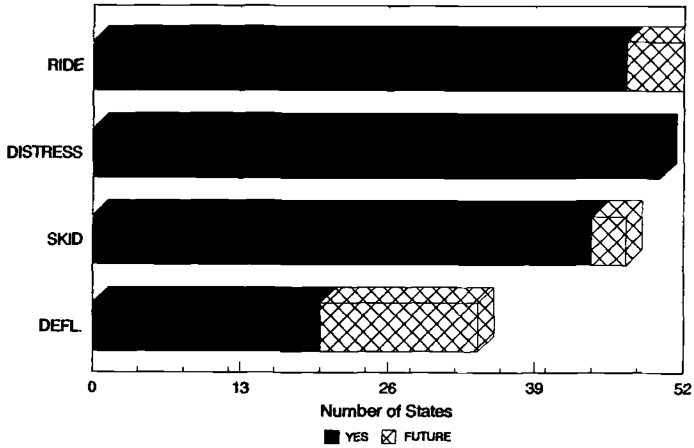

FIG. 5 - Condition Survey data included in PMS.

The FHWA advocates that the four major elements of deterioration be collected. Ride, Distress, Skid, and Deflection. The FHWA will not mandate that all States collect structural data, (deflection) though it is desirable. Most States will have all four as can be seen in Figure 5.

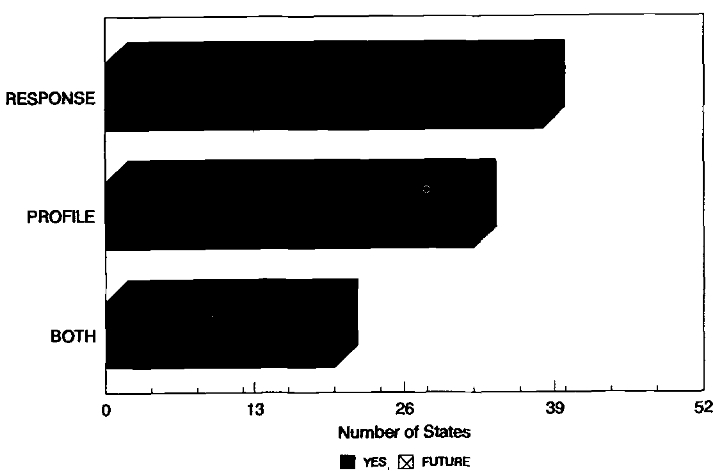

FIG. 6 - Type of ride measuring equipment used.

Figure 6 depicts what type of ride measuring equipment the States have. The FHWA does not require that any particular type of equipment be used. It is thought that collecting ride data is a must regardless of the way it is done. All States do collect ride for the Highway Performance Monitoring System data.

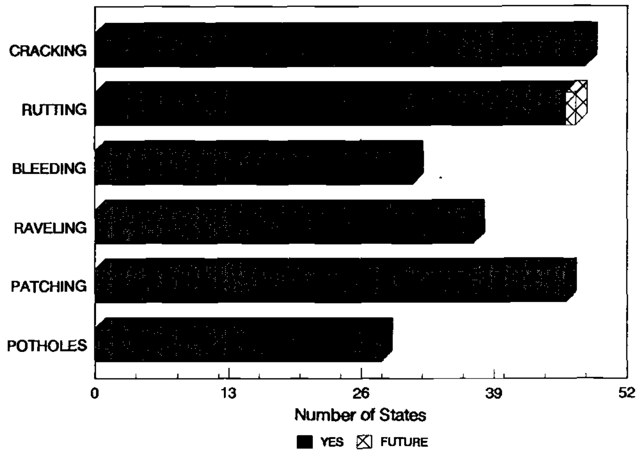

FIG. 7 - Types of AC pavement distress data collected

Figure 7 shows the number of States collecting data on each of the distresses normally connected with asphalt.

An acceptable PMS needs to have condition data. A good measure of condition is distress, therefore, distress data needs to be obtained. The FHWA does not and will not specify which individual items of distress should be collected.

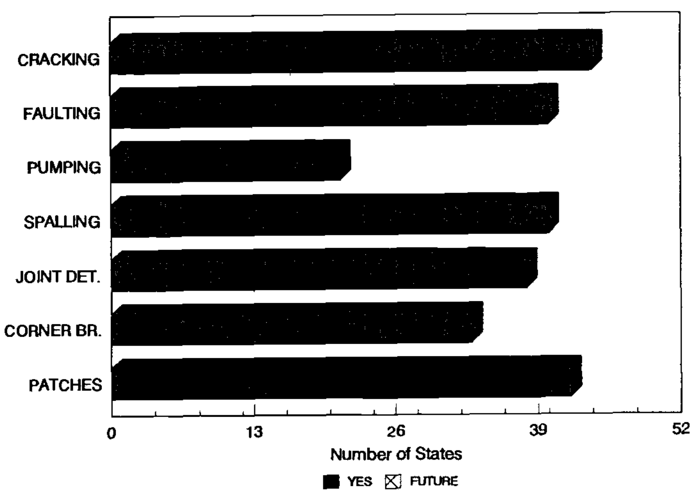

FIG. 8 - Types of PCC pavement distress data collected.

Figure 8 shows the distresses on Portland Cement Concrete pavement and it is also true here that FHWA will not make specific requirements. The FHWA does not mandate collection of specific distresses but does require that there be some measure of condition included in the PMS.

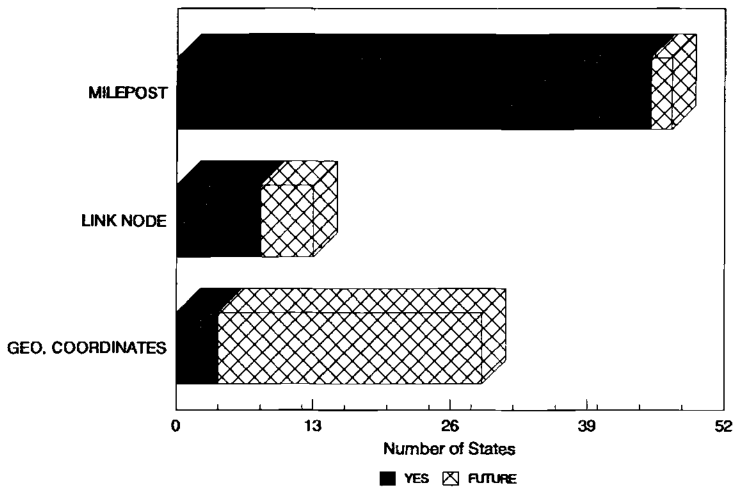

FIG. 9 - Types of reference systems used.

The State needs some kind of reference system so that control sections on their system can be identified both in the field and in the office. The specific method used is the States prerogative. Figure 9 shows the reference systems being used.

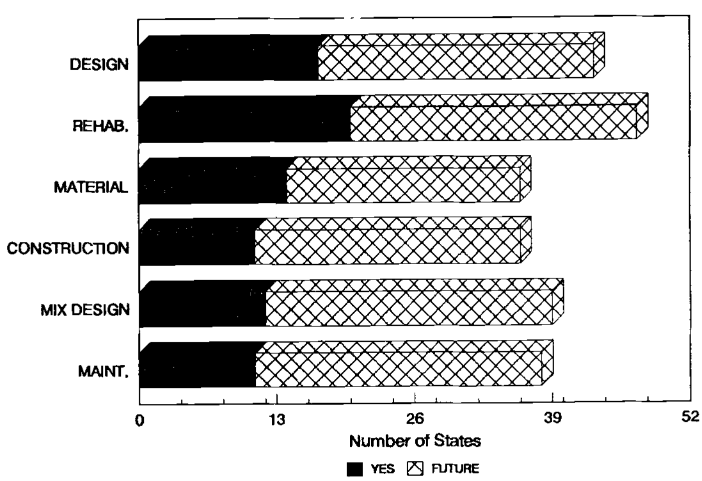

FIG. 10 - Evaluation of operations and elements.

While FHWA will have no specific requirements for using the PMS to evaluate design, construction, and materials, it would seem that the PMS is a perfect tool for performing such evaluations. If a State has an operating PMS they would be remiss if they didn't use it for such purpose. You can see in Figure 10 that most will be doing that.

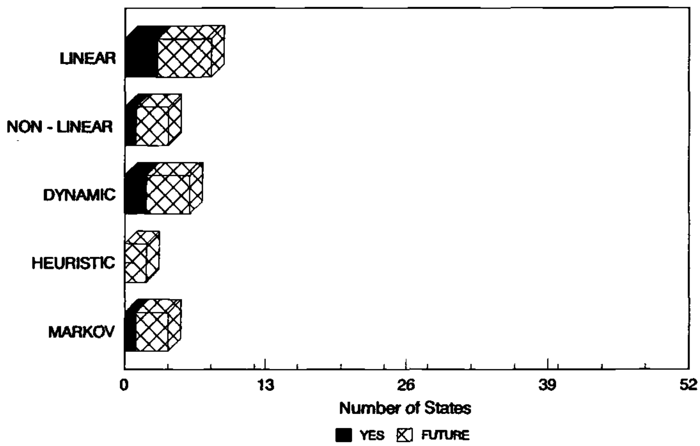

FIG. 11 - Optimization methods used.

An accomplished or truly sophisticated PMS would ultimately be able to optimize the selection of projects. There are only a few States, which have progressed to this point as Figure 11 shows. It is expected that 20% to 30% of the States' PMS's will be able to do this by the end of the 4-year period.

In summary, this paper attempts to identify the main elements needed in a PMS to make it effective, and to give an idea of how the States are progressing in developing their PMS. The PMS is not just a bureaucratic process to satisfy a Federal requirement. The PMS is an absolute necessity for any highway agency that is intent on providing top quality pavement service to the users in a cost efficient manner.

Overview Section

Mr. William A. Nostrand, Chief, Pavement Management Branch, FHWA

The History of Pavement Management in the Federal Highway Administration

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REFERENCE: Nostrand, W. A., "The History of Pavement Management in the Federal Highway Administration," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: The paper begins with the results of the authors research into the beginnings of pavement management (PM) and pavement management systems (PMS) in the Federal Highway Administration (FHWA). It continues on through its continued emphasis over the years culminating in the establishment of the Pavement Divisions issuance of a Pavement Policy in January 1989, which includes a mandate that all State highway agencies (SHA) must develop and put into operation a comprehensive PMS within 4 years of the date of issuance of that policy.

The discussion traces PM in the FHWA as it relates to FHWA's program manual (FHPM) and other directives that relate directly to the required activities in SHAs as a condition to receiving Federal-aid. While there have not been many specific mandates to SHAs until this recent one, the FHWA does develop emphasis areas and promote new innovations to the highway community from time-to-time, so it is interesting to relate those initiatives to see how the present requirement came about.

In 1986, the FHWA reorganized to create a Pavement Division. Prior to that there was a Pavement Design Branch consisting of seven people that was part of the Design Division. Today the Pavement Division has 22 people and includes a Pavement Management Branch, which is an indication of the emphasis being placed on pavements and in particularly PMSs.

The FHWA presented an introductory PM training course for State and Federal engineers a considerable number of years ago. There was also a training course for cities and counties labeled "Road Surface Management for local Governments," which was presented over 30 times and is the fore-runner of an updated course by the same name being offered today. There were several directives regarding the use of PMS which preceded the first FHPM on the subject. Now the FHWA, in

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cooperation with the Transportation Research Board (TRB) and the American Association of State Highway and Transportation Officials, (AASHTO) is offering an advanced course in PMSs for practitioners.

This paper traces the history, emphasis, pertaining directives, training, and organization with regard to PMS. It concludes with an insight to the future of PMS in FHWA and SHAs.

KEYWORDS: Pavement management systems (PMS), optimization, pavement management coordinating group (PMCG), and AASHTO Guidelines.

The bottom line goal of every highway engineer is to achieve the best possible design of the highway at the least possible cost. The engineer, in no matter what discipline he is, could probably achieve the best possible design without much trouble if funds were unlimited. The trick is to obtain the product which will have the maximum life at a minimum monetary outlay. These conditions (i.e., maximum life-minimum cost) can be labeled, "Optimum" and the objective of a polished sophisticated pavement management system (PMS) is to aid a transportation agency to achieve "optimization."

But going back to the original statement about engineers, one could say that FHWA and in fact, all the SHA's have been practicing pavement management ever since they began designing highways. Engineers have always practiced PM.

I like to draw a parallel between PM and Value Engineering (VE). If you have ever attended a VE session or you practice VE you have probably experienced the same surprise as I did. It is quite amazing how many projects can be improved by the VE process, even though we know that the original designer tried his best to achieve the best design at the lowest price. Engineers always try to pick the best design at the least cost but unless they actually do go through a formal VE process, they often do not achieve that original objective.

Similarly, the use of a PMS is a way one can insure that the projects selected are in fact the most appropriate from a cost effective point of view. It is very difficult to achieve the "optimum" list of projects unless its done through a functioning PMS.

I think that concept needs to be fully understood before any manager will accept PM. Moreover, that manager must also understand that the PMS is not a decisionmaker. The manager is the decisionmaker. The PMS merely provides him with the right information so that he can make the most appropriate decision.

These concepts were recognized by FHWA quite early in the game. However, when one considers how long the FHWA has been contributing the Federal-aid and the SHAs have been building highways, they should feel somewhat embarrassed that PM as we know it today, is only about 15 years old. After building all those highways all over the country, there really should be a wealth of data from which one could predict performance of all kinds of designs, all kinds of pavements, and all kinds of materials. But it is not so. Many States are just beginning to collect data in a comprehensive way and it will be some time before those States have an operational PMS.

In the 1970's, articles about a "Decaying Infrastructure" in publications like Newsweek and The Washington Post awakened a public awareness about our highways.

Our highway systems were deteriorating at an alarming rate, therefore, the thrust of our whole Federal-aid program needed change.

Instead of concentrating only on routes on new location, FHWA and the States had to shift emphasis to the repair of existing routes.

The Federal-aid Highway Act of 1976 initiated the 3R program; that is, resurfacing, restoration, and rehabilitation, were to be financed using Federal-aid Highway funds, with specific criteria as to how much money needed to be spent on that type of work.

Then in the 1981 Act, Congress added the fourth R, "reconstruction," to the program. Prior to that time, Interstate funds could not be used more than once on the Interstate System, whereas reconstruction was always allowed on the other systems. This change in law established a new class of funds, Interstate 4R, which allowed the financing of reconstruction on the Interstate System.

On May 21, 1980, FHWA issued a Federal Highway Program Manual addition called, "FHPM 6-1-1-12" entitled, "Pavement Management" encouraging all States to strengthen their system of selecting projects by developing a PMS. This directive was upgraded by FHPM 6-2-4-1 entitled, "Pavement Design Policy", dated March 15, 1984.

When one considers how a SHA should distribute its allotted funds to a 3R or 4R program, I think everyone recognizes now that one can not do it most effectively without a management system.

During these changes there was a continuing change to the definition of the word maintenance. It used to be that maintenance was a dirty word in Federal Highways and thin resurfacing or rehabilitation work was considered maintenance, therefore, ineligible for Federal-aid. Over the years, we tended more and more toward what in many States is still considered maintenance. Now about the only work that is absolutely ineligible for Federal-aid is snow removal, grass cutting, and drainage cleaning. In fact, our new Policy indicates that as long as the State can say that a certain overlay will last a specified length of time (8 years on major roads, 5 years on others) the work is eligible for Federal-aid. This trend is consistent with the nationwide change in emphasis toward making the existing system do the job instead of continuing to build new roads.

I think most people understand that FHWA is not directly involved with prioritizing or selecting projects. However, FHWA has a stewardship responsibility for the Federal-aid funds that go to the States, which perform those functions. The FHWA, therefore, is very concerned that the projects selected, designed, and built using Federal-aid are in fact the most appropriate and cost effective projects. For that reason FHWA is very much an advocate and promoter of PM.

One of the first major efforts toward promoting PM was in 1982 and 1983 when FHWA developed Demonstration Project No. 61. Two teams of FHWA people took Demo. 61 around the country and presented it to State and Federal people in 40 plus States. The demonstration explained the PMS examples from the States of Arizona, California, and New York. In later sessions, the New York System was dropped and Minnesota and Maine were added for another dozen sessions. The theme of the demonstration was in fact very much like a training course in which the recipients could receive ideas as to how a system was developed, what it consisted of, and what results were being obtained. This allowed interested people to take those ideas back to their respective organizations and attempt to implement a system of their own.

A rather extensively distributed and used document in the early development of PMS's throughout the States was a study FHWA did in 1983 under our Statewide Transportation Planning and Management Series which was called, "Pavement Management - Rehabilitation Programming: Eight State's Experiences."

This study described in considerable detail the PMS's of Arkansas, Florida, Idaho, Nevada, Ohio, Washington, Arizona, and California. A few of these are repeats of the ones used in Demonstration No. 61, but it was done at a later date, therefore, each of those States had made significant progress between the studies. This volume included some detailed information such as data collection forms and priority listings used in the various systems.

In 1979, the name of the American Society for Testing Materials (ASTM) Committee E-17 was changed from the committee on Skid Resistance to the Committee on Traveled Surface Characteristics because it was expanding its area beyond skid resistance. It was in 1988 that the committee's title became "Pavement Management Technologies." The FHWA has had representatives on the committee since the beginning and has always been a supporter of ASTM activities.

Probably the most significant development in the history of PM in FHWA was the formation of what is known as the Pavement Management Coordinating Group (PMCG). It was organized in 1980 to coordinate all pavement issues among the various FHWA offices.

The group is comprised of the eight Directors of the various Headquarters Offices plus one FHWA Regional Administrator, who serves a 2-year term. Most meetings are also attended by staff members under each of those directors.

The responsibilities of the PMCG are:

- Cooperatively Coordinate pavement activities.
- Identify problems and issues needing FHWA attention.
- Participate in field reviews.
- Serve as the RD&T Advisory Council.
- Recommend FHWA policies and programs to improve SHA and local government pavement-related activities.

The formation of this group and the issuance of an FHWA Notice in June 1981 precipitated the formation of satellite groups called "Regional PMCGs," many of whom meet as regularly as the National PMCG.

The PMCG meets regularly and reviews all efforts having to do with pavements including training courses, reports, and research efforts. The FHWA policies and directives regarding pavements and pavement related items must all be approved by the Group.

Because FHWA recognized the extreme importance of the whole pavement issue, it was reorganized to give it greater emphasis. There was a Pavement Design Branch in the old Design Division consisting of seven people. The reorganization allowed for a Pavement Division with two branches (one PM and the other Design and Rehabilitation) and 22 people are currently assigned. So, if manpower alone were used to measure, FHWA has increased its pavement emphasis three-fold.

In 1985, the AASHTO promulgated their "Guidelines on Pavement Management," which was prepared by the AASHTO Joint Task Force on Pavements. As is its practice, FHWA accepted those guidelines for use on Federal-aid highway programs. These first guidelines were minimal although they did enumerate the major basic elements of a PMS. As a rule the AASHTO publications are written by State people or written by a consultant with numerous reviews by FHWA and the AASHTO committee involved.

Those guidelines have just recently been superseded by a new set called, "AASHTO Guidelines for Pavement Management System," dated July 1990. These were done by Fred Finn, Engineer Consultant of Austin Research Engineering Inc., and went through the AASHTO process of committee review and full ballot approval. Of course, the FHWA made several reviews with comments on the drafts. These guidelines are considerably more comprehensive and give the organization attempting to implement a PMS a lot more detail as to what a PMS entails. The new guidelines are completely consistent with the FHWA's directives on the subject.

If a copy of these latest guidelines are needed you may obtain one by writing to the author.

The FHWA, in cooperation with the Ontario (Canada) Ministry of Transportation, jointly sponsored two North American Conferences on Managing Pavements. These conferences were attended by hundreds of the best PM minds in both countries and both produced papers that are still being used today by PM engineers.

The next major initiative by FHWA to promote and advertize PM was called, "Chief Administrative Officers (CAO) Training Course."

It was held in San Diego, and again in Clearwater, Florida (near Tampa). There was a rather illustrious faculty assembled to teach this course, including Byron Blasche from Texas, Dave Hensing of the AASHTO, and FHWA's Associate Administrator for Engineer and Operations, Ron Hienz. As a result of that faculty, a CAO from every State but one attended (and that person had a valid excuse). It was well received and developed a great deal of enthusiasm throughout the country for PMS's.

Since it was felt that the CAO Course had convinced the top-level management that PM was the greatest thing since the invention of the computer, FHWA then went after the mid to top-level managers, who are the most important decisionmakers in SHAs. The FHWA developed and taught a 1-day course for mid and top-level managers. It was given to 40 plus States and again it developed a great deal of interest. That course included a one-hour module on our Pavement Policy and the mandates included therein.

During the 1980's, the FHWA sponsored a course in Pavement Design and Rehabilitation, which included a very thorough module in PM. At Michigan State, where the last one given was in March of this year, the course was 4 weeks long. Graduates of these courses are much in demand for positions both in pavement design and in PM.

About 5 years ago, FHWA presented a 2 1/2 day course for city and county engineers called, "Road Surface Management for Local Governments." This course has been presented over 40 times using two different consultants and is currently being offered in a 1-day version for city and county administrative personnel.

The FHWA's latest and perhaps the most valuable initiative is the 1-Week Advanced Course in PM, which is currently being offered to State highway people and others. The course is being jointly sponsored by the AASHTO and TRB and has a teaching faculty of State PM Engineers, University Professors, and Consultant experts in the field. It was taught in Washington, D.C., last August and November, in Dallas in February, May in Denver, and will be offered in Boston this August and Atlanta this November. Brochures that include applications are available through the author.

Coming up at the end of September is a Pavement Management Symposium in the Chicago area jointly sponsored with the Illinois Department of Transportation. That conference will concentrate on what has been labeled, "Institutional Issues". The usual problems of "turf" between units in an organization, the problem of obtaining top-level management support, and the difficulty in selling PM within the organization and to legislatures are to be addressed.

Currently on the drawing board, for 1992 is an FHWA Seminar being designed for college professors to promote the teaching of PM and Bridge Management (BM) in universities. Right now, let alone in the immediate future years, the States, consultants, even local highway agencies are going to be looking for a great many people trained in PM. Unfortunately, there are only about three universities in the country that have a curriculum for PM. There are probably fewer teaching BM. The FHWA recognizes this void as does the American Society of Civil Engineers and AASHTO, and all three are considering some initiative to fill it.

This paper has been merely a relating of the various efforts, initiatives, and training that the FHWA has promulgated in order to promote the development and use of PMS. The paper may have triggered some questions in the readers mind about FHWA's position and goals. Feel free to contact the author for additional information.

On January 13, 1989, the Pavement Division published it's final rule on the Pavement Policy and an accompanying FHPM (6-2-4-1) on March 6, 1989, superseding the previously mentioned FHPM 6-1-1-12 of 1981 and FHPM 6-2-4-1 of 1984. This is the document that requires all SHAs to develop and implement a PMS. Refer to Division Chief, Louis Papets paper for complete information on that subject.

Stuart W. Hudson, W. Ronald Hudson, and R. Frank Carmichael III

MINIMUM REQUIREMENTS FOR STANDARD PAVEMENT MANAGEMENT SYSTEMS

REFERENCE: Hudson, S. W., Hudson, W. R., and Carmichael, R. F., "Minimum Requirements for Standard Pavement Management Systems," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: In 1965 a team of engineers from ARE Inc developed for the National Cooperative Highway Research Program the initial concept of pavement management. Subsequently, the authors have worked on a variety of pavement management applications worldwide at both the project and network level and at the city, county, state, and national level. This paper summarizes a series of findings from these extensive studies and outlines the institutional aspects of pavement management which have been found to be required for standard applications and for minimum success of a pavement management system. While the paper does not present quantitative mathematical relationships for pavement management, it does present standardization concepts and minimum requirements that have proven successful in a number of cases. Specific case studies and examples are also provided as a part of the paper.

KEYWORDS: pavement management systems, subsystem, decision tree, network level, project levels

Pavement management, in its broadest sense, encompasses all the activities involved in the planning, design, construction, maintenance, and rehabilitation of the pavement portion of a public works program. A pavement management system (PMS) can provide an organized methodology to assist decision makers in finding optimum strategies for providing and maintaining pavements in a serviceable condition over a given period of time. The function of a PMS is to improve the efficiency of decision making, expand its scope, provide feedback on the consequences of decisions, and insure the consistency of decisions made at different management levels within the same organization.

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The detailed structure of a PMS depends on the organization of the particular agency within which it is implemented. Nevertheless, an overall, generally applicable framework can be established without regard to detailed departmental organization. The following sections discuss some of the basic essential features of a pavement management system and key implementation considerations. These comprise a set of minimum requirements for any agency to undertake in the management of their pavement network.

SOME ESSENTIAL FEATURES OF A PAVEMENT MANAGEMENT SYSTEM

A pavement management system (PMS) must be capable of being used in whole or in part by various levels of management in making decisions regarding both individual projects and the entire pavement network. All types of decisions should be considered by the general PMS, including those related to information needs, projected deficiencies or improvement needs for the network as a whole, budgeting, programming, research, project design, construction and maintenance, resource requirements, monitoring, etc.

All functions involved in providing pavements are essential to a comprehensive PMS, but not all functions need be active at the same time or are required to perform the basic functions of a PMS.

Some of the essential requirements of a PMS include:

- Basic inventory data including traffic and structure information,
- Roadway condition information,
- The ability to consider alternative maintenance and rehabilitation strategies,
- The ability to identify a prioritized or optimized set of alternative strategies,
- A feedback process to update system models as better information becomes available.

Each of these characteristics of a PMS implies the need for certain secondary requirements. For example, in order to consider alternative rehabilitation strategies for sections within a highway network, the PMS must have a set of possible activities appropriate to the maintenance and rehabilitation program within the agency. Each alternative must be evaluated by the system. An optimum strategy can be chosen only if it is possible to compare the consequences of individual strategies. This leads to several requirements. First, it is necessary to identify important attributes, such as roughness, of the pavement or network of pavements under consideration. These attributes will form the value system by which the management system can rate the effects of any strategy. There are two additional requirements that are implied. Clearly, the PMS must be able to predict the effect of each activity on each attribute. This is necessary because it is not feasible to test alternative strategies in the field each time before making the optimum choice. In formulating this prediction, it is necessary, in most cases, to know the current values of these attributes. Also, the predictions will to some degree be based on past experience. Thus, the attributes must be measurable by some reproducible, reliable means, usually involving established engineering or economic techniques.

Another aspect of the decision-making process is that it must involve logical decisions based on justifiable criteria. The PMS must base recommendations on an analysis of quantifiable standards and constraints. Thus, actual numerical values must be supplied to the system. Exactly what information must be supplied is dependent on the scope and use of the individual PMS, but a general requirement is that the system should consider the entire range of factors that have an impact on the decision at hand. The optimization procedure must reflect as nearly as possible the needs, values and constraints that the users of the pavement management system are faced with.

It is convenient to describe pavement management in terms of two generalized levels: (1) the NETWORK MANAGEMENT LEVEL where key administrative decisions that affect programs for road networks are made, and (2) the PROJECT MANAGEMENT LEVEL where technical management decisions are made for specific projects [1-4].

A MINIMUM FRAMEWORK FOR PAVEMENT MANAGEMENT

Figure 1 provides a summary framework for pavement management. Various activity areas are identified at the network level [5]. This figure gives an overview of the interaction of the various activities, and points out that the basic functions of the PMS are to:

- Collect inventory, condition, and cost data
- Assign strategies, identify needs, and arrange priorities
- Project future needs and build long-range programs
- Provide management information
- Support budgets

Pavement management requires information input from all levels within an agency from upper management to the lower application and working levels. This information flow forms the basis for a general PMS framework as illustrated in Figure 2. Three basic subsystems are identified: "information," "analysis" and "implementation." In this concept of making a decision, pertinent information is gathered and the consequences of the available choices are analyzed in the light of this information. Based on this analysis of non-quantifiable considerations (perhaps political) or other constraints, a decision is made by the manager, not by the PMS. Once made, the decision is implemented, and the results of the decision are recorded in the data base and passed on to other management levels.

The interface of the pavement management system with higher level transportation system management occurs where "committed" projects come forward and where an optimized or prioritized program is submitted for review and approval. Any such prioritized program and its associated costs would likely go forward to the higher level of management as a recommendation, be evaluated with respect to the overall transportation program and objectives as well as the sector (i.e., highway, airport) budget allocation, and then be suitably modified if any program revisions were required.

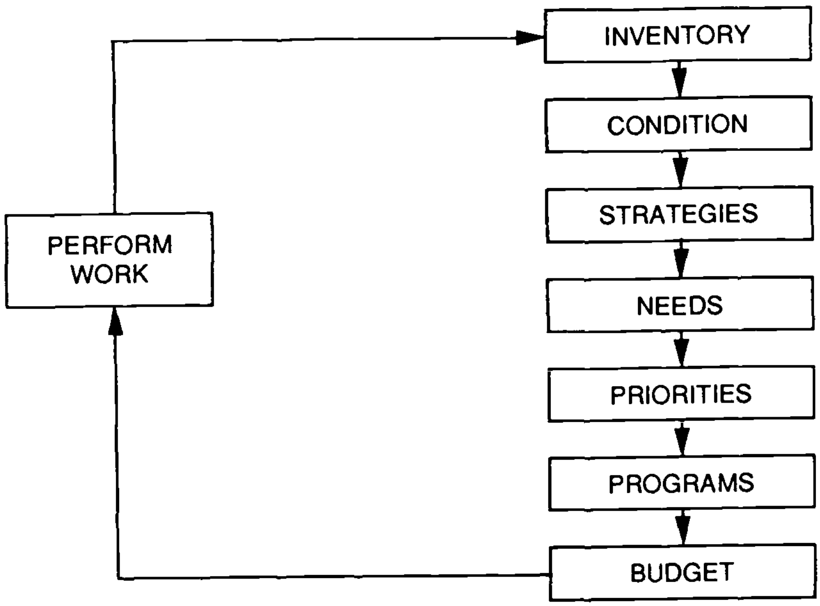

Figure 1. Basic structure of a pavement management system.

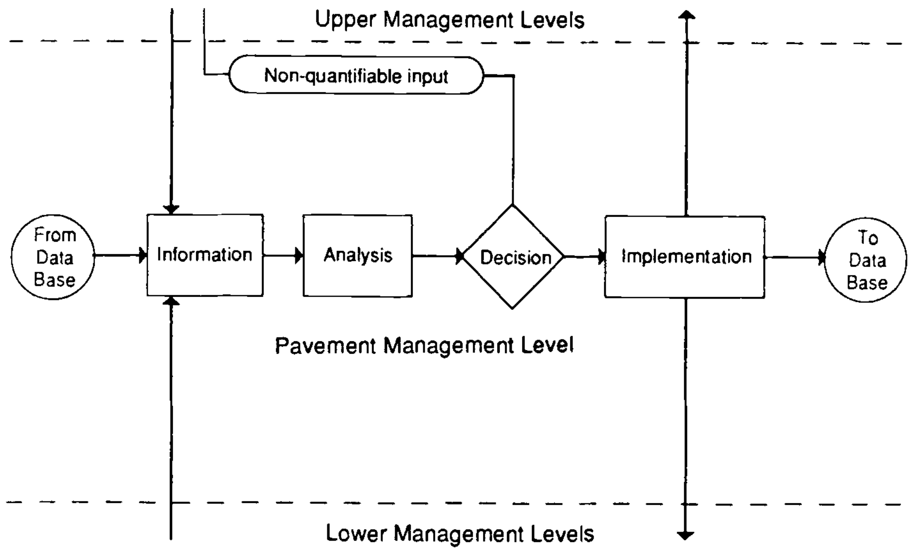

Figure 2. Information flow for a pavement management system.

Network Level Subsystems And Management Activities

The network management level subsystems and their components, plus the other key management activities at this level, are briefly described as follows:

Information subsystem: This subsystem involves pavement condition and inventory data as well as the data processing directed toward providing the basic foundation for conducting the network analysis. The essential activities and types of data collected for this subsystem include the following:

- Determination of pavement attributes to be measured and information to be acquired.
- Identification of homogeneous sections in the network.
- Geometric characteristics.
- Traffic, load and accident estimates.
- Field measurements for structural capacity, ride quality, surface distress, and skid resistance.
- Approximate unit costs for rehabilitation and maintenance.
- Inventory of available resources (materials, contractor "capacity," physical plant, etc.).
- Criteria on minimum desirable capacity, geometrics, ride quality levels, skid resistance, structural capacity, and distress.
- Data from as-built projects and maintenance.
- Data processing for input to network analysis subsystem.

Good condition survey data is a key to obtaining good results from a pavement management system [6]. The system must have valid information regarding the current condition of the pavement network in order to provide the best recommendations for maintenance and rehabilitation activities. Therefore, the condition survey data must be as concise and straight forward as possible. An agency should collect only as much data as they need to make decisions concerning the maintenance and repair of their road network. Excessive data is costly to collect and store.

Network level condition survey data does not need to be extremely precise. It is not necessary to know the exact lengths and widths of cracks for example. It is only necessary to know in general whether cracking on a section of pavement is slight, moderate, or severe. It is also useful to know whether it covers a small, medium or large portion or area of a section. A measure of pavement roughness on a 5 level PSI scale is adequate for network level screening of the pavement section conditions.

This is the level of detail that is necessary to make adequate network wide maintenance and repair decisions. More detail is only necessary when a project level rehabilitation design is being considered. This will warrant a second more detailed distress survey and possibly a structural evaluation such as a deflection analysis.

Network analysis subsystem: The essential function of the network analysis subsystem is to consider the pavement improvement and/or maintenance needs and to arrive at a program of rehabilitation, new construction and maintenance. This is accomplished through the following activities:

- o Identification of needs and "candidates" for improvement from the information subsystem.
- o Generation of alternatives for each candidate project or maintenance section (i.e., several alternative types, thicknesses and timings for new construction, several timings, types and thicknesses or recycling alternatives for rehabilitation, several levels of maintenance for each section).
- o Selection of analysis period, discount rate, minimum ride quality levels, etc., for technical and economic analysis; also, identification of what the basis will be for deciding on the final prioritized program (i.e., solely economic in terms of maximization of benefits or minimization of costs, or partially economic and partially non-quantitative, etc.).
- o Technical analysis of each alternative in terms of estimating performance, using models with acceptable computational time and input information requirements.
- o Economic analysis of each alternative in terms of calculating costs and benefits.
- o Development of initial program for new construction, rehabilitation, and maintenance, optimized with respect to some measure of benefit or ranked by priority.

<u>Selection of maintenance and rehabilitation strategies</u>: A prime function of any network level pavement management system is to recommend to the pavement manager specific maintenance and rehabilitation strategies for specific sections in the network [7]. A good pavement management system, therefore, will provide the manager with a valid plan and budget for performing all the maintenance and rehabilitation activities on his pavements. The detail and accuracy of this plan will be a function of the adequacy and sophistication of the pavement management system providing the recommendations.

The methodology used by the system to recommend and prioritize maintenance and rehabilitation alternatives depends on the needs of the agency and the system being employed. The important point is that the methodology provides reasonable recommendations and results in a feasible, workable, and cost effective maintenance and rehabilitation plan for the agency.

A straight forward method that works well, when properly installed, is the decision tree methodology. An example decision tree is shown in Figure 3. A decision tree examines key condition indicators of the pavement relative to agency needs and "decides" which alternative or set of alternatives is most appropriate for each set of condition levels.

A decision tree can provide multiple recommendations for each section. An economic analysis would then be required to determine which of the recommended alternatives is most cost effective for each section based on available budget and overall network conditions. This type of analysis can be performed using a life cycle cost and multi-year prioritization or optimization methodology. It is beyond the scope of this paper to go into details of the various optimization and prioritization procedures which are appropriate for pavement management systems. It is sufficient that there are a number of available methodologies, some of which are currently being successfully operated by agencies today.

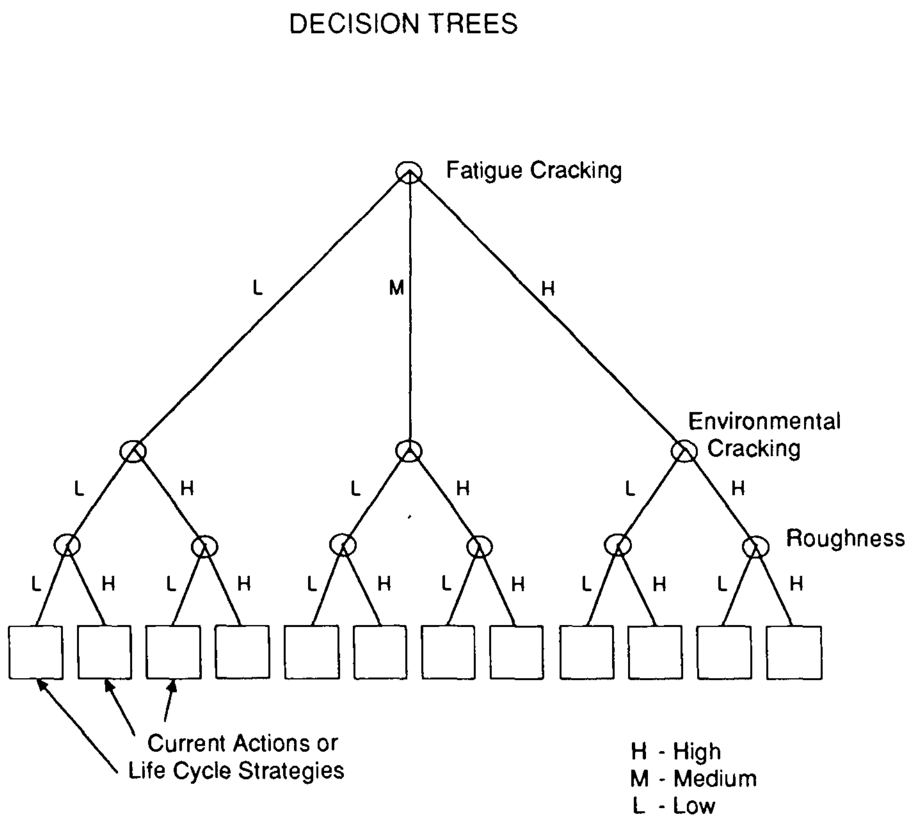

Figure 3. Example decision tree.

Decision Criteria And Budget Constraints Applied To Initial Program

The decision criteria and budget constraints applied to the initial program resulting from the network analysis subsystem may simply involve a rehabilitation and maintenance program which can be done within the available budget. This budget may have been fixed at the higher management level, or several alternative budget levels may be considered. The projects falling below the budget cutoff would then be put back on the candidate list for consideration of the following year.

Some agencies designate separate budgets for new construction, rehabilitation, and maintenance, while others have new construction projects "compete" with rehabilitation projects. As well, some transportation departments allocate budgets by region or district. The non-quantitative aspects of the decision criteria might involve engineering judgement to move a project in the priority list, or political decisions to include certain projects.

Implementation subsystem: The implementation subsystem of the network management level derives from the application of the decision criteria and budget constraints. It would list the final program and schedule for the new construction and rehabilitation projects within the analysis period plus the annual maintenance program. In some agencies, this program may be subject to final approval from the higher management level.

Project Level Subsystems And Management Activities

Project level subsystems and their components plus the other key management activities at the project level are briefly described as follows:

Information subsystem: This subsystem involves the collection of more detailed data, the amount appropriate to the size and type of project, so that the project analysis and subsequent implementation may proceed. The types of data and component activities may include the following:

- Identification of homogeneous subsections within the project or section length (this may in some situations follow field measurements),
- Field measurements for or estimates of
  - geometrics (lane widths, layer thicknesses, etc.)
  - traffic volumes and loads
  - structural capacity, ride quality, surface condition, skid resistance, etc., for existing pavements,
- Laboratory measurements to determine material properties,
- Acquisition or estimates of unit costs of materials, construction, etc.,
- Identification of criteria or standards for minimum ride quality, minimum skid resistance, etc.,
- Collection of climatic or environmental data,
- Collection of available data on construction and maintenance variability,
- Data processing for input to project analysis subsystem and for transmittal to data file.

Project analysis subsystem: The project analysis subsystem might equally be termed a design subsystem where new construction or rehabilitation projects are concerned. However, the terminology and concepts used in the project analysis subsystem are consistent with the network analysis subsystem; they also allow for such non-design activities as maintenance to be analyzed. A list of activities for this subsystem would include the following:

- o Generation of alternative material and layer thickness combinations, and future rehabilitation and maintenance alternatives,
- o Selection of analysis period, discount rate, etc., for technical and economic analysis,
- o Technical analysis of alternatives in terms of
  - predicting distress
  - predicting performance
- o Economic analysis of alternatives to determine costs and benefits.

Decision criteria and selection: The decision criteria applied to the various alternatives from the project analysis subsystem may involve both quantitative and non-quantitative factors. These factors should reflect the needs of the network as perceived by the decision maker. A least cost or maximum benefit alternative may be selected, or previous experience, judgement, etc., may be combined with an economic based criterion.

Implementation subsystem: This subsystem represents the achievement of a final physical reality from all preceding subsystems of both the network and project levels. Where new construction or rehabilitation is concerned it includes contract tenders and awards; the actual work activities; construction control; and documentation of as-built quantities, costs, and geometrics for updating the network information base and for transmittal to the database.

Where maintenance is concerned, this subsystem would include the actual work performed, quantities, schedules, costs, etc., comprising the application of what is usually termed maintenance management to individual section or project lengths. Maintenance management systems are usually, however, applied to regional or district networks.

KEY CONSIDERATIONS IN IMPLEMENTATION OF A PAVEMENT MANAGEMENT SYSTEM

One of the major failings of a pavement management system can be related to the amount of resources that an agency applies in implementing the system. Before undertaking a PMS implementation, an agency must understand that a significant capital investment is required to establish an effective PMS. The system, in turn, will save significant funds on a year by year operating basis. However, failure to recognize the early investment required to do this has resulted in failed systems for some agencies.

An agency must consider the following costs as necessary to any pavement management system implementation.

- Initial inquiry and background review costs
- Base system or methodology purchase
- Training to acquaint all necessary staff with PMS procedures
- Network partitioning and routing costs
- Gathering of the base network inventory data
- Initial condition survey of the entire network
- Data Entry and validation
- Costs to make numerous network analysis runs with the system over a factorial of significant parameters to understand the full sensitivities of the inputs to the program.

These are the minimum costs that will be associated with implementing a productive system which will begin to save the agency money on routine maintenance and rehabilitation costs. Any or all of these services can be contracted out or performed by the agency. Most failures occur when an agency undertakes its own PMS development and does not fully comprehend the costs described above. They do not allocate sufficient internal resources to accomplish effective implementation in a reasonable amount of time. If services are contracted out, all costs are normally included in a contract with an experienced firm, so it is less likely that they will be overlooked. Some agencies have attempted implementations in which some services are contracted out and some are performed within the agency, thus causing additional problems in timing and commitment of resources. If an agency is committed to investing adequate resources in a timely manner, such combined implementations can be very cost effective. The agency can obtain the specialized software setup and training from an experienced expert while fully integrating their personnel into the continuing operational activities such as data collection, data entry, and computer operation.

SUMMARY

Pavement management systems can provide several benefits for highway agencies at both the network and project levels. Foremost among these is the selection of cost-effective alternatives. Whether new construction, rehabilitation or maintenance is concerned, a PMS can help management achieve the best possible value for the public dollar. Although a PMS can exist at many levels of complexity within an agency, there are some minimum requirements necessary to effectively manage a pavement network.

At the network level, the PMS provides information pertinent to the development of an agency-wide program of new construction, maintenance, or rehabilitation which will optimize the use of available resources. Considering the needs of the network as a whole, a PMS provides a comparison of the benefits and costs for several alternative programs, making it possible to select the one which will have provide the necessary benefits over the selected analysis period.

At the project level, detailed consideration is given to alternative design, construction, maintenance or rehabilitation activities for a particular section or project within the overall program. Here again, by comparing the benefits and costs associated with several alternative activities, an optimum strategy is identified which all provide the desired benefits or service levels at the least total cost over the analysis period.

At both the network and project management levels, a cost-benefit comparison may by used for each strategy considered, providing evidence to support the value of proposed activities.

An operational pavement management system also provides an efficient means for continual evaluation of existing techniques and procedures. In the area of data collection, for example, significant savings may be achieved through the collection and storage of only that information which will be effectively used. In addition, systematic data collection and good prediction models within a pavement management system can provide the basis for special studies, such as an evaluation of the effects of increased vehicle load limits.

In order to realize the full benefits of a PMS, proper information for each management level must be collected and periodically updated; decision criteria and constraints must be established and quantified; alternative strategies must be identified; predictions of the performance and costs of alternative strategies must be estimated; and multi-year prioritization or optimization procedures that consider the entire pavement life cycle must be developed. Moreover, the proper implementation of all of these management activities, and the use of the strategies selected, is essential to the full realization of the possible benefits.

Implementation should proceed in several steps. The initial system should include some working models or procedures in each of the major subsystems of the total framework. This system may be initially applied to a single management area, such as rehabilitation programming, with additional areas to be added later. Successful implementation begins with a management decision to implement then continue with commitment of sufficient resources to complete a minimum implementation, followed by continuing management support of the activities. In all cases, qualified and interested personnel are the key to success and must include people from each pavement activity area (design, maintenance, etc.) plus personnel with expertise in such areas as computer programming, optimization, economics, and field measurements.

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Ralph Haas

GENERICALLY BASED DATA NEEDS AND PRIORITIES FOR PAVEMENT MANAGEMENT

REFERENCE: Haas, R., "Generically Based Data Needs and Priorities for Pavement Management," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: The foundation for pavement management is reliable and sufficient data. It is required to quantify present and future status, to identify needs and to provide the basis for priority programming of maintenance and rehabilitation. The role of data in a generically based pavement management framework is to provide the factual basis for activities models, methods and procedures, and for making decisions, at both the network and project levels. In order to develop a strategy and priorities for what data should be acquired and how often for any particular situation requires consideration of such factors as type and class of facility, characteristics of the agency, intended uses of the data, costs and the accuracy needed. Sets of priority guidelines for highway, airport and other area pavements, using these factors and for average or representative conditions, have been developed.

KEYWORDS: pavement management, data, priorities, framework, generic, decision, strategy, factors, guidelines, network, project, rehabilitation, maintenance

Highway and street pavements constitute an enormous public investment. In order to preserve this investment, timely and effective maintenance and rehabilitation are needed. This requires good data to identify deficient pavements, the availability of cost-effective alternatives, and sufficient financing to carry out the work and proper construction and maintenance.

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The major portion of pavement expenditures for many agencies now goes toward rehabilitation and maintenance, because their road systems are relatively mature. Such work is usually carried out for one or more of the following reasons:

1. Structural inadequacy, for the current or expected future traffic loading,
2. Unacceptable level of roughness,
3. Unacceptable level of surface distress,
4. Unacceptable level of safety, in terms of surface friction, and
5. Unacceptable costs to the road user.

The purpose of this paper is to address the problem of what data are required under what sets of conditions so that the foregoing reasons for rehabilitation can be adequately quantified, rehabilitation needs can be determined, and the best alternative can be selected for any given situation.

THE ROLE OF DATA IN PAVEMENT MANAGEMENT

The process of pavement management has evolved to the point where it can be described on a generic basis [1]. A framework for this generic structure is summarized in Figure 1. An actual operating pavement management system would have at each level a large number of specific activities, models, methods and procedures, appropriate to the agency involved, within the framework of Fig. 1 (see Ref. [1] for example). What makes it a system is the linkages and coordination between all these elements which, when combined and acted upon, result in various end products at either the network or project level.

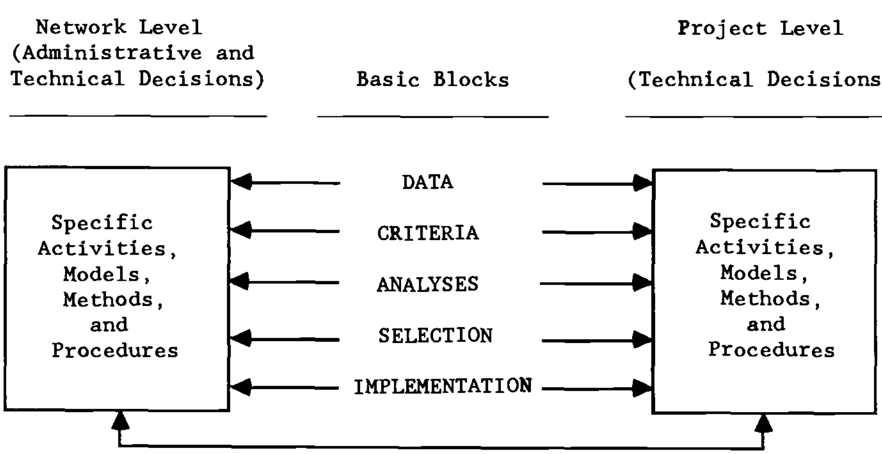

FIGURE 1 -- A generic framework for pavement management

Any pavement management system has as its foundation the first basic block of Fig. 1, which is data. It can include the following major elements:

1. Sectioning,
2. Data acquisition (field data and other such as costs),
3. Data processing and evaluation, and
4. Use of the data to portray present conditions or status.

Both field and other data must relate to defined sections or subsections, and they must be processed. Regarding data acquisition itself, a vast technology exists in the actual methods and equipment used. As well, there are many methods available for data processing.

Reliable and sufficient data provide the factual basis for making pavement management decisions. These include the determination of present and future rehabilitation needs, developing priority programs of rehabilitation and maintenance, determining the details of rehabilitation or maintenance treatments for specific projects, and doing the implementation.

In setting up and carrying out a plan for acquiring data, the following questions should be answered:

1. How shall sections be established?
2. What data should be collected and for what use?
3. How should the measurements be made, how often and at what spacing?
4. Are the data reliable? and
5. How should the data be evaluated and processed?

The first two questions are addressed in Figure 2 which lists the major classes and component of data that should be considered for both rehabilitation and maintenance. Which of these types might be acquired or used in a given situation, depends on local requirements, resources, class of road, etc. A noteworthy point is that nearly all of the data or information types are relevant to both maintenance and rehabilitation.

The remaining questions are addressed in detail in a variety of publications, including Ref.[2], the manuals of many highway agencies and various ASTM, AASHTO, RILEM and other standards.

TYPICAL USES OF PAVEMENT DATA

Data for pavement management are used at two levels, network and project, as shown in Figure 1. The network level data find their end use in the priority programs that are implemented, plus budgeting and financial planning. Project level data are used for the engineering associated with specific sections or projects.

Some of the typical network and project level uses for the types of pavement data identified in Figure 2 are listed in Table 1, which is based on Ref.[3].

Section Description	R + M		
Performance Related Data		Geometry Related Data	
•Roughness	R	•Section dimensions	R
•Surface distress	R + M	•Curvature	R
•Deflection	R	•Cross slope	R
•Friction	R + M	•Grade	R
•Layer material properties	R	•Shoulder/curb	R + M
		Environment Related Data	
Historic Related Data		•Drainage	R + M
•Maintenance history	R + M	•Climate (temp., rainfall, freezing)	R
•Construction history	R + M		
•Traffic	R + M		
•Accidents	R + M	Cost Related Data	
		•Construction costs	R
Policy Related Data		•Maintenance costs	R + M
•Budget	R + M	•Rehabilitation costs	R
•Available alternatives (maint. & rehab.	R + M	•User costs	R

R is data used primarily for rehabilitation
M is data used primarily for maintenance
R + M is data for both uses

FIGURE 2 -- Major classes and component types of pavement data

FACTORS IN DEVELOPING A STRATEGY AND PRIORITIES FOR PAVEMENT DATA NEEDS

A number of factors should be considered in developing a strategy and priorities for pavement data needs. These can include the following:

1. Type and class of facility (rural or urban highway, airfield, industrial or commercial area),
2. Functional classification (freeway, arterial, collector or local highway; runway, taxiway or apron for an airfield),
3. Levels of service required (maximum acceptable roughness, maximum severity and extent of surface distress, maximum shoulder dropoff, etc.),
4. Size of pavement network,
5. Type of agency (Federal, State, Local, Private),
6. Characteristics of the agency (size and resources, budget, policies, etc.),
7. Traffic characteristics (volumes, axle load repetitions, vehicles classes),
8. Intended use(s) and user(s) of the data (status reports, planning and programming, design, maintenance, public information, etc.)
9. Type and cost of data acquisition and processing (manual, semi-automated, automated, degree of sampling, etc.),

TABLE 1 -- Typical uses of pavement management data

Data Item	Network Level	Project Level
1. PERFORMANCE RELATED		
Roughness	a) Describe present status b) Predict future status (deterioration curves of roughness vs time or loads c) Basis for priority analysis and programming	a) Quality assurance (as-built quality of new surface) b) Create deterioration curves c) Estimate overlay quantities
Surface Distress	a) Describe present status b) Predict future status (deterioration curves) c) Identify current and future needs d) Maintenance priority programming e) Determine effectiveness of alternative treatments	a) Selection of maintenance treatment b) Identify needed spot improvements c) Develop maintenance quantity estimates d) Determine effectiveness of alternative treatments
Surface Friction	a) Describe present status b) Predict future status c) Priority programming d) Determine effectiveness of alternative treatments	a) Identify spot or section rehabilitation requirements b) Determine effectiveness of alternative treatments
Deflection	a) Describe present status b) Predict future status (deterioration curves) c) Identify structural inadequacies d) Priority programming of rehabilitation e) Determine seasonal load restrictions	a) Input to overlay design b) Determine as-built structural adequacy c) Estimate remaining service life d) Estimate remaining load restrictions
Layer Material Properties	a) Estimate section-to-section variability b) Develop basis for improved design standards	a) Input to overlay design b) Provide as-built records

TABLE 1 -- (Continued)

Data Item	Network Level	Project Level
2. HISTORIC RELATED		
Maintenance History	a) Maintenance programming b) Evaluate maintenance effectiveness c) Determine cost-effectiveness of alternative designs and treatments	a) Identify problem sections
Construction History	a) Evaluate construction effectiveness b) Determine cost-effectiveness of alternative designs and construction practices c) Determine need for improved quality assurance procedures	a) provide as-built records b) Provide feedback to design
Traffic History	a) Priority programming b) Input to estimate general performance/distress trends	a) Input for pavement design b) Identify traffic handling methods c) Estimate remaining service life
Accident History	a) Develop countermeasures b) Priority programming	a) Identify high-risk sites b) Develop counter-measures
3. POLICY RELATED		
Budget	a) Priority programming b) Selection of management strategies	a) Determine cost limitations
Available Alternatives	a) Selection of management strategies b) Priority programming	a) Economic evaluation c) Life cycle cost comparisons

TABLE 1 -- (Continued)

Data Items	Network Level	Project Level
4. GEOMETRY RELATED		
Section Dimensions	a) Develop general policy or standards	a) Determine section constraints
Curvature	a) Develop general policy or standards	a) Determine section constraints b) Assess safety
Cross Slope	a) Develop general policy or standards	a) Assess drainage b) Assess safety
Grade	a) Develop general policy or standards	a) Assess drainage b) Assess safety
Shoulders/Curbs	a) Develop general policy or standards	a) Assess safety b) Assess drainage
5. ENVIRONMENT RELATED		
DRAINAGE	a) Evaluate general network performance	a) Evaluate section performance
CLIMATE	a) Evaluate general network performance	a) Evaluate section performance
6. COST RELATED		
New Consctruction Costs	a) Priority programming b) Selection of network investment strategies	a) Economic evaluation b) Selection of strategy
Maintenance Costs	a) Priority programming b) Selection of network maintenance strategies	a) Evaluation of maint. effectiveness b) Selection of maintenance sections
Rehabiliation Costs	a) Priority programming b) Selection of network rehabilitation strategies	a) Economic evaluation b) Selection of rehabilitation strategies
User Costs	a) Priority programming b) Selection of management strategies	a) Economic evaluation b) Selection of mitigation strategies

10. Required accuracy of the data,
11. Predominant type(s), severity and extent of deterioration (roughness, surface distress, friction, structural adequacy), and
12. Required frequency of data collection (varies with type of facility, agency budget and resources, current state of pavement deterioration, etc.).

A schematic illustration of how the foregoing factors can be used in a decision process to arrive at a strategy and priorities is given in Figure 3. It traces (dark line) a path in the overall decision tree (not shown) to determine, in the example,that the surface distress data on the arterial network of the state agency should be collected annually.

USE OF FACTORS IN ESTABLISHING GUIDELINES FOR PRIORITIES OF DATA NEEDS

The factors listed in the preceding section and in Fig. 3 were used to arrive at a set of priority guidelines for highways, airfields and other paved areas [3]. Examples are shown in Tables 2, 3 and 4. It should be noted that these are guidelines only and apply to "average" conditions, most of which are represented by the heavy line in the decision process of Fig. 3. An individual agency might well assign different priorities, depending on its own circumstances and requirements.

Three levels of importance are assigned to the priorities of Tables 2, 3 and 4: high, medium and low.

The definition of major and minor highways in Table 2 is intended to cover most agency practices. Major would normally include, but not be limited to, freeways and arterials while minor would normally include collectors and locals. Some agencies use the terminology of primary, secondary and tertiary highways. In such cases, a decision would be required as to whether the secondary classification best suited the major or minor of Table 2.

Two traffic levels are given in Table 2: high and low. The high level is intended to represent, but not be restricted to, an annual average daily traffic volume (AADT) in excess of 10,000, while the low traffic level is intended for volumes less than 10,000 AADT.

Table 3 considers two basic types of airfields: general aviation and commercial aviation. High traffic would normally represent, but not be restricted to, facilities with more than 200 takeoffs and landings per day, while the low traffic level would normally be less than 200.

Two basic types of "Other Paved Areas" are considered in Table 4 and these are heavy and light traffic. The first would normally include industrial yards and the like with a high percentage of loaded trucks. The light traffic areas would normally be those used mainly by cars, such as shopping center parking lots.

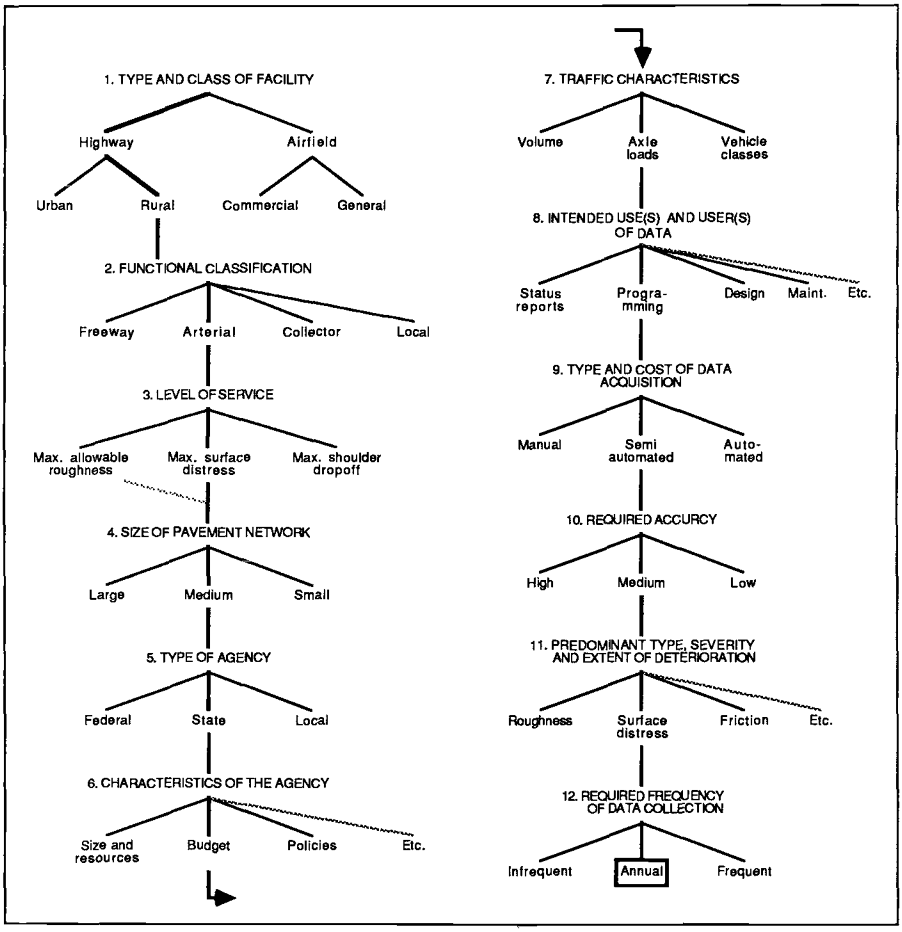

FIGURE 3 -- Schematic illustration of how a decision can be made to arrive at a strategy and priority for pavement data needs.

TABLF 2 -- Priority guidelines (level of importance) of data needs: roads

	Network Level				Project Level			
	Major		Minor		Major		Minor	
Data Items	High Traffic	Low Traffic	High Traffic	Low Traffic	High Traffic	Low Traffic	High Traffic	Low Traffic
1. PERFORMANCE RELATED								
Roughness	H	H	H	H	H	H	H	H
Surface distress	H	H	H	H	H	H	H	H
Surface friction	H	M	M	L	H	L	M	L
Deflection	L	L	L	L	H	H	H	H
Layer material properties	L	L	L	L	M	L	M	L
2. HISTORIC RELATED								
Construction history	H	H	M	L	H	H	M	L
Maintenance history	H	M	M	L	H	M	M	L
Traffic history	H	M	M	L	H	M	M	L
Accident history	H	M	H	M	H	H	H	M
3. POLICY RELATED								
Budget	H	H	H	H	H	H	H	H
Available alternatives	H	H	H	M	H	H	H	M
4. GEOMETRY RELATED								
Section dimensions	H	H	H	H	H	H	H	H
Curvature	H	M	M	M	H	M	M	L
Cross slope	M	L	M	L	H	M	M	M
Grade	M	L	L	L	M	L	L	L
Shoulder/curbs	H	M	H	M	H	H	H	M
5. ENVIRONMENTAL RELATED								
Drainage	H	M	H	M	H	M	M	L
Climate	H	M	M	L	H	M	M	L
6. COST RELATED								
New constr. costs	H	H	H	H	H	H	H	H
Maintenance costs	H	H	H	M	H	H	H	M
Rehab. costs	H	H	H	H	H	H	H	H
User costs	H	M	M	L	H	M	M	L

TABLE 3 -- Priority guidelines (level of importance) of data needs: airfields

	General Aviation		Commercial Aviation	
Data Items	High Traffic	Low Traffic	High Traffic	Low Traffic
1. PERFORMANCE RELATED				
Roughness	M	L	M	L
Surface distress	H	H	H	H
Surface friction	M	L	H	M
Deflection	H	M	H	M
Layer material properties	M	L	M	L
2. HISTORIC RELATED				
Construction history	H	H	H	H
Maintenance history	H	M	H	M
Traffic history	H	M	H	M
Accident history	L	L	L	L
3. POLICY RELATED				
Budget	H	H	H	H
Available alternatives	H	M	H	M
4. GEOMETRY RELATED				
Section dimensions	H	H	H	H
Curvature	N/A	N/A	N/A	N/A
Cross slope	H	H	H	L
Grade	L	L	L	L
Shoulder/curbs	N/A	N/A	N/A	N/A
5. ENVIRONMENTAL RELATED				
Drainage	H	M	H	M
Climate	M	L	H	M
6. COST RELATED				
New const. costs	H	H	H	H
Maintenance costs	H	M	H	M
Rehabilitation costs	H	H	H	H
User costs	N/A	N/A	N/A	N/A

TABLE 4 -- Priority guidelines (level of importance) of data needs: other paved areas (commercial areas, industrial yards, etc.)

Data Items	Heavy Traffic	Light Traffic
1. PERFORMANCE RELATED		
Roughness	L	L
Surface distress	H	H
Surface friction	L	L
Deflection	H	L
Layer material properties	M	L
2. HISTORIC RELATED		
Construction history	H	H
Maintenance history	M	L
Traffic history	H	L
Accident history	N/A	N/A
3. POLICY RELATED		
Budget	H	H
Available alternatives	H	M
4. GEOMETRY RELATED		
Section dimensions	H	H
Curvature	N/A	N/A
Cross slope	H	M
Grade	M	L
Shoulder/curbs	N/A	N/A
5. ENVIRONMENTAL RELATED		
Drainage	H	M
Climate	M	L
6. COST RELATED		
New construction costs	H	H
Maintenance costs	H	M
Rehabilitation costs	H	H
User costs	N/A	N/A

EXAMPLE FOR A HIGHWAY SITUATION

This example covers one part of the data base established by a State for its highway network, using the approach of Figure 3. While many data items (see Table 1) were collected, only one, that of surface distress, is used to illustrate the strategy adopted.

The State has an operational, computerized Pavement Management System (PMS). Two basic approaches were considered for the surface distress surveys. One was to conduct a detailed survey on a sample of the network, using a part of each road section. The other was to conduct a less detailed survey over the entire network.

The State was aware of studies showing that sampling could be misleading if not done properly. Proper sampling (i.e., to select a representative part on a section) could be very time consuming and thus defeat the purpose of achieving higher productivity levels.

One method considered of conducting the surveys manually over the entire mileage was to have a driver and a rater in a vehicle drive at a very low speed over the section, observing the distresses that exist, and then stopping and recording what they have observed. In this method the severity and density levels of each distress type can be observed and recorded with ease. However, the data then have to be manually entered into a data base for checking, conversion and index analysis.

Consequently, a semi-automated approach was chosen, where the surveyors sit in a slow moving vehicle (about 30 km/h, driving on the shoulder) and enter the same data as in the manual approach on specially designed keyboards, with magnetic tape recording for easy computer processing. They record the types, severities and densities of distress station by station (every 30 m). Figure 4 provides an example of detailed output for a section in the network. This is derived directly from a program which interfaces with the data recorded on tape. Also shown on Figure 4 is a weighted Surface Distress Index (SDI) on a scale of 0 to 10. It represents an aggregated or composite number for all the types, severities and densities of distresses observed.

The type of data shown in Figure 4 is collected annually on the arterial and collector portions of the network and on the local highways. This is based on the resources of the State plus several other factors previously identified in Fig. 3.

CONCLUSIONS

The major points of this paper can be summarized as follows:

1. The reasons for pavement rehabilitation include structural inadequacy, or unacceptable levels of roughness, surface distress, surface friction, maintenance costs or road user costs. Good data are needed to quantify these reasons so that maintenance and rehabilitation needs can be identified and cost-effective programs of work can be developed.

DATE: JUNE 2 1986 LANE: EAST BOUND #1
SECTION: 1802 LOCATION: HOG'S BACK RD FROM E END OF RIVER BRDG TO RIVERSIDE DR

STATION	PAVEMENT TYPE	RIP/ SHOV	RAV/ Strk	FLSH /BLD	DIS TORT	EXCS CRWN	EDGE CRAK	ALLG CRAK	POT HOLE	MAP CRAK	LONG CRAK	TRNS CRAK	RUT TING	PATC HING	SDI
0 + 000	OLD AC	NONE	S-1	S-3	S-1	NONE	NONE	NONE	NONE	M-5	NONE	NONE	NONE	M-3	8.9
0 + 030	OLD AC	NONE	S-1	S-3	S-1	NONE	M-1	NONE	NONE	M-1	M-1	M-4	S-2	M-3	5.9
0 + 060	OLD AC	NONE	S-1	S-3	S-1	NONE	M-1	X-1	NONE	M-1	M-1	M-5	S-2	M-3	4.5 ***
0 + 090	OLD AC	NONE	S-1	S-3	S-1	NONE	M-1	S-1	NONE	M-1	M-1	M-5	S-2	M-3	5.6
0 + 120	OLD AC	NONE	S-1	S-3	S-1	NONE	X-1	S-1	NONE	M-1	M-1	M-5	S-2	M-3	4.6 ***
0 + 150	OLD AC	NONE	M-1	S-3	S-1	NONE	NONE	M-3	NONE	M-3	M-1	M-5	S-2	M-3	4.5 ***
0 + 180	OLD AC	NONE	M-1	S-3	S-2	NONE	NONE	X-1	NONE	M-3	M-1	M-5	S-2	M-3	4.0 ***
0 + 210	OLD AC	NONE	M-1	S-3	S-2	NONE	NONE	M-1	NONE	M-1	M-1	M-4	S-2	M-3	5.5
0 + 240	OLD AC	NONE	M-1	S-3	S-2	NONE	NONE	X-1	NONE	M-1	M-1	M-4	S-2	M-3	4.3 ***
0 + 270	OLD AC	NONE	S-2	S-3	S-2	NONE	NONE	M-1	NONE	M-1	M-1	M-4	S-2	M-3	5.5
0 + 300	OLD AC	NONE	S-2	S-3	S-2	NONE	NONE	M-1	S-2	M-1	M-1	M-4	S-2	M-3	5.5
0 + 330	OLD AC	NONE	S-2	S-3	S-2	NONE	NONE	M-1	NONE	M-1	M-1	M-4	S-2	M-3	5.5
0 + 360	OLD AC	NONE	S-2	S-3	S-2	NONE	NONE	M-1	NONE	M-1	M-1	M-4	S-2	M-3	5.5
0 + 390	OLD AC	NONE	S-2	S-3	S-2	NONE	NONE	X-1	M-2	M-1	M-1	M-4	S-2	M-3	4.2 ***
0 + 420	OLD AC	NONE	S-2	S-3	S-2	NONE	NONE	NONE	NONE	M-1	M-1	M-4	S-2	M-3	8.2
0 + 450	OLD AC	NONE	S-2	S-3	S-2	NONE	X-1	X-1	NONE	S-1	M-2	M-4	S-2	M-3	4.3 ***
0 + 480	OLD AC	NONE	S-2	S-3	S-2	NONE	NONE	M-1	NONE	S-1	M-2	M-4	S-2	M-3	5.5
0 + 510	OLD AC	NONE	S-2	S-3	S-2	NONE	NONE	M-1	NONE	S-1	M-2	M-4	S-2	M-3	5.5
0 + 540	OLD AC	NONE	S-2	S-3	M-3	NONE	NONE	M-1	NONE	S-1	M-2	M-4	S-2	M-3	5.2
Means															5.4

S - slight
M - moderate
X - severe

Density (extent) codes ranging from
1 - lowest level of occurrence to
5 - highest level of occurrence

FIGURE 4 -- Example of a report from a surface distress survey (semi-automated) for a section of highway

2. Data therefore represent the foundation for pavement management at both the network and project levels. They provide the factual basis for making decisions.
3. A data collection plan must consider the questions of how to establish sections, what data to collect, how the measurements are to be made and how often at what spacing, reliability, evaluating and processing the data and setting the limits of acceptability.
4. The major classes of pavement data are as follows:

    a) performance related data
    b) historic related data
    c) policy related data
    d) geometry related data
    e) environment related data
    f) cost related data

    A number of typical uses of the components of these data classes are given in the paper.
5. Development of a strategy and priorities for pavement data needs should consider a number of factors, including type and class of facility, levels of service, size of the network, type and characteristics of the agency, intended uses of the data, type and cost of the data acquisition, required accuracy, state of deterioration of the network, and required frequency of data collection.
6. A set of priority guidelines for data needs, using these factors for average or representative conditions, is provided in the paper in tabular form. Also provided is an example application for a particular data item for a state highway network.

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ACKNOWLEDGEMENTS

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PAVEMENT MANAGEMENT SYSTEMS – STATE OF THE ART

REFERENCE: Saraswatula, S. R. and Amirkhanian, S. N., "Pavement Management Systems - State of the Art," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: The condition of the highway network in the United States is deteriorating rapidly. Maintenance and rehabilitation are becoming increasingly important. With an approximately 4 million mile highway network in place, and limited funds available for its maintenance, pavement management is assuming a significant role in the activities of America's highway agencies. This paper traces the history, development, and implementation of pavement management systems (PMS) through the past two decades. The results of a survey assessing the impact of the FHWA ruling requiring all state agencies to implement PMS by 1993 are presented. Applications for geographic information systems, knowledge based expert systems, and voice recognition systems in pavement management are discussed.

KEYWORDS: pavement management systems, geographic information systems, expert systems, voice recognition systems

HISTORY AND DEVELOPMENT OF PAVEMENT MANAGEMENT

The United States has approximately 3.9 million miles of roads. Although total road and street mileage has increased only 18.9 percent since 1925, asphalt and portland cement concrete (PCC) surfaced mileage has increased 2,000 percent (Figure 1) [1]. Approximately 50 percent of the primary, secondary and urban roads and 43 percent of the interstates are rated to be in only a "fair" condition [2]. Since 1956, over one trillion dollars have been invested in the U.S. highway system and about $400 billion will be spent repairing pavements before the end of the century [2]. In 1986, capital improvements represented

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47.9 percent of total expenditures for highways while maintenance activities accounted for 27.4 percent [3].

Need for Maintenance Management

With an approximately 3.9 million mile highway network in place and limited funds available to maintain it, pavement management becomes

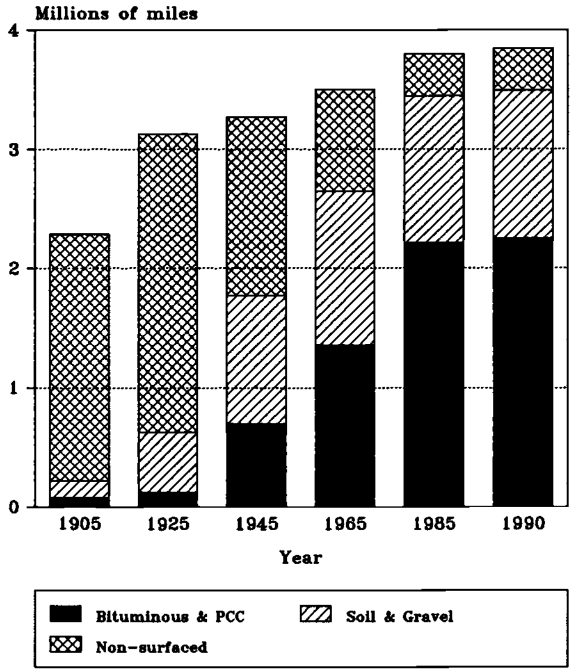

Figure 1. Total mileage by surface type

vital. As road systems become older and fewer new roads are constructed, maintenance of existing roads assumes new importance. Widely differing rates of deterioration make pavement management somewhat difficult to administer and finance. Maintenance will require greater engineering attention and increasingly larger proportions of the budgets of highway agencies [4]. This is supported by the results of a survey showing a relative increase in maintenance expenditures of highway agencies [5].

Maintenance budgeting problems are getting worse for many agencies. There are more deteriorated roads every year and maintenance costs are increasing. In general, during the first 75% of the pavement's life, it performs well and, to the untrained eye, looks good. After that, the pavement deteriorates rapidly. The number of years that a pavement stays in good condition depends upon how well it is maintained. Ideally, this plateau could be extended with proper timing of major rehabilitation and good interim maintenance [6].

Numerous studies indicate that if pavements are maintained in a perpetual 'good' to 'excellent' condition, the total annual maintenance investment is 4 to 5 times less than if the pavement is allowed to cycle through to the 'poor' and 'failed' conditions and then repaired [7]. Other studies have shown that by proper scheduling of maintenance, as much as 10 percent of the cost of the pavement can be saved over its lifetime [3]. Pavement maintenance costs three to five times less if repair is carried out before failure [6].

Current Problems

Every agency responsible for pavement maintenance must decide how to divide its resources most judiciously among various projects. Historically, most maintenance and rehabilitation decisions are based on the personal experience of the engineer rather than on documented procedures. This approach does not allow the evaluation of cost effectiveness of alternative strategies and can lead to inefficient use of funds.

This lack of standardized procedures for prioritization of projects is a major problem. Repairs carried out on a 'worst first' basis - functional in the past when there was not such a great disparity between the funds needed and those available - are not acceptable. Prioritization of projects based solely on political and other budgetary allocations do not take into consideration current serviceability ratings of pavements.

A maintenance decision is only as good as the supporting information. The absence of agency-wide databases which provide decision-makers with all pertinent information is resulting in decisions not consistent with long term requirements.

Pavement Management Systems

A pavement management system (PMS) is a decision support system to integrate pavement activities with roadways evaluation and computer simulation to achieve the best possible use of available funds by comparing investment alternatives and coordinating design, construction and maintenance. It is a tool that provides decision-makers at all management levels with strategies derived through clearly established rational procedures [8].

Pavement management, clearly, is not a new concept; management decisions are made as part of normal operations every day in highway agencies. A PMS incorporates in a systematic way all activities that go into providing and operating pavements, ranging from collection, processing, and analysis of data, identification of current and future needs, and development of rehabilitation and maintenance programs to implementation of the programs through design, construction and maintenance [9]. The idea behind PMS is to improve efficiency of decision making, expand its scope, provide feedback as to the consequences of decisions, and ensure consistency of decisions made at different levels within the same organization. A complete PMS has applications in virtually every division within a highway agency. The use of a well conceived PMS provides extensive short and long-term benefits to the implementing agency and highway users [10].

The current condition of a pavement is a result of decisions made in previous years and decisions made now will have an influence on the condition of the pavement in the future. Therefore, current decisions must be made in the light of both their immediate and anticipated future effects. When considering short/long term strategies, the most desirable trade-off can be selected if consequences of present actions can be reliably predicted. An estimation of future consequences of present actions may be made informally by the decision-maker ('engineering judgement') or through the use of scientific methods and procedures with the advantage of consistency.

The foundation of pavement management lies in proper management of data gathered from the periodic monitoring of pavements. For pavement management to be consistent, the information used should be accurate. Considerable data on the long term physical characteristics of a road and its current condition are required before corrective action can be decided upon.

Historical Background

Although significant contributions to the technological foundations of pavement management have occurred over a long period of time, it is the post World War II era which provided major impetus to development of the modern PMS. Three independent research ventures have resulted in the development of a PMS methodology. In 1966, the American Association of State Highway Officials (AASHO) through the National Cooperative Highway Research Program (NCHRP), initiated a study to make new breakthroughs in the field. The intent was to provide a theoretical basis for extending the results of the AASHO Road test [11,12]. Similar, independent efforts were being conducted at the same time in Canada to structure the overall pavement design and management problems [13]. A third keystone effort in this area was that of Scrivner and others at the Texas Transportation Institute of Texas A&M University as part of their work for the Texas Highway Department [14,15]. The work of these three groups provides an overall perspective for PMS.

The success or failure of a pavement depends partially on the design concepts used. Subsequent construction, and maintenance policies play a significant role in the success of the design. Historical studies by many agencies show that the concept of 20-year pavement design is fictitious. Most new pavements provide service for up to 10 or 12 years without major maintenance. After this period, maintenance is required more frequently. Consequently, the need to bring together planning, designing, constructing, and maintaining pavements was realized - to manage the technology of providing pavements on a comprehensive basis.

CURRENT PRACTICES

The Federal Highway Administration (FHWA) issued a policy ruling on January 13, 1989 which requires each state to establish a PMS. FHWA Docket 87-16 defines a PMS and related guidelines. According to FHWA, each state highway agency must have an operational PMS within four years of the date of policy issuance, or before January 13, 1993. A policy to select, design, and manage federal-aid highway pavements in a cost-effective as well as to identify pavement work eligible for federal-aid funding was set forth. FHWA is seeking uniform pavement quality on the federal-aid system through the PMS requirement, effectively utilizing a minimum of maintenance dollars.

In this study, a survey was conducted to estimate the impact of the ruling on the highway agencies. Questionnaires were sent to all the state and federal highway maintenance authorities in July of 1989. A detailed second questionnaire was sent in October of 1989 to agencies that had sufficient experience with PMS. A third questionnaire was sent in the month of March 1991 to all agencies that had indicated that they were contemplating the development of a system in 1989. The responses were analyzed and the results are presented in the following sections.

RESULTS OF THE QUESTIONNAIRE SURVEYS

Preliminary Questionnaire: Out of the total of 65 preliminary questionnaires that were sent, 42 were returned (i.e., a response rate of about 65 percent).The results of the survey showed that 34 states were using a PMS or were in the process of developing one. Eight states were contemplating the development of one. One of the earliest PMS was in use in 1975 while one of the latest had been implemented in 1990. Responses indicate that 42 states will be using a PMS in 1993. Figure 2 shows the trend in the use of PMS in the United States. Figure 3 shows the distribution of the states using PMS.

All agencies that are using PMS have computer based systems, with hardware ranging from personal computers to mainframes. Only two percent use commercial software packages, the remaining having developed their own. The approximate cost - an average of the tangible costs, mostly of the software - is $ 600,000. In-house development and the fact that they are being continuously improved prevent the accurate measurement of costs involved. The responses to some of the questions asked are presented in tabular form below.

1. *What are the primary functions of your system?*

Function	Number of Agencies
Inventory Maintenance	34
Calculation of condition indices	28
Project prioritization	28
Recommend correction treatment	8
Life cycle modeling	3

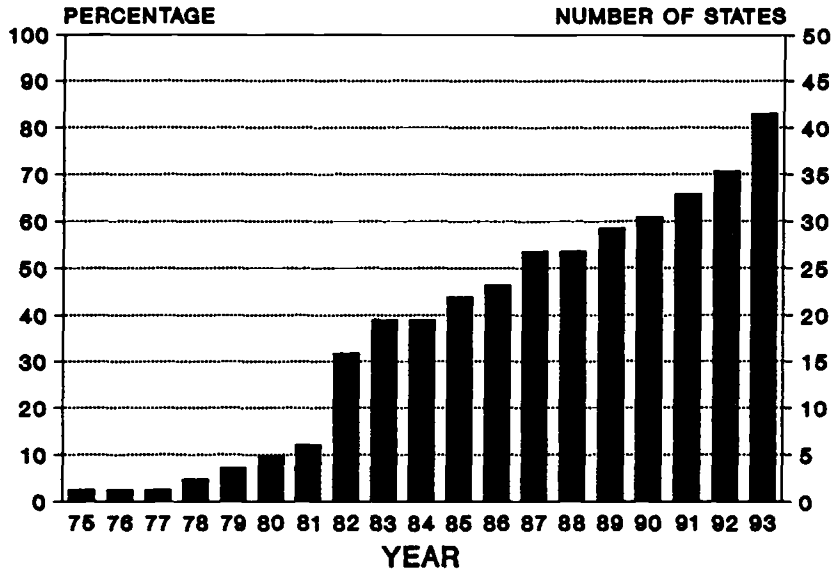

Figure 2. Trend in the use of PMS in the United States

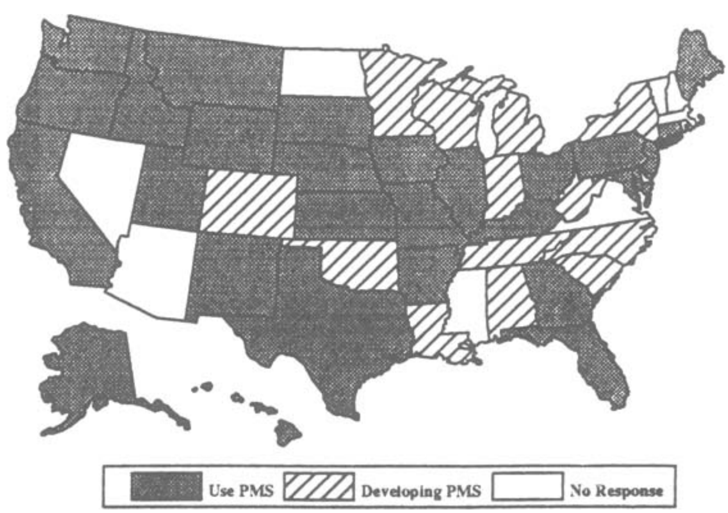

Figure 3. Geographic distribution of states using PMS - Survey Results

Other functions like generation of distress survey forms, maintenance budget and material quantity estimation were also performed.

2. What are the major advantages of using a PMS?

Advantage	Number of Responses
Get overall perspective	12
Consistent decisions	9
Documentation for allocation of funds for approval purposes	6

In addition, some agencies listed the following as advantages of using a PMS: ability to generate pavement performance curves, ability to optimize, ease of maintenance scheduling, the availability of an up to date record of maintenance, what-if analyses can be performed, and project or network level reports are easy to create.

3. What, if any, are disadvantages of your system?

Disadvantage	Number of Responses
Lack of user-friendly interface	6
No graphic output	4
Lack of detailed manuals/training	8

4. What additional features would enhance performance of your pavement management system?

Additional Feature	Number of Responses
Life cycling capability	10
Interface with a Geographical Information System (GIS)	11
Project/network level strategy development capability	4

<u>Detailed Questionnaires</u>: All of the second and third questionnaires were returned. It was found that all the state agencies surveyed maintained databases that contained information about pavement properties, pavement type, pavement width, number of lanes, layer thicknesses and construction and rehabilitation histories.

Skid resistance data was collected by all the agencies surveyed. Skid resistance measurements are made using pavement friction testers in compliance with ASTM E-274 - 85 (Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire). Pavement sections are tested based on past performance or if slippery conditions are suspected.

Ride quality data was collected by all agencies involved. This is a measurement of the roughness of the pavement surface. A majority of the respondents used Mays ride meters. This instrument measures the number and magnitude of vertical deviations on the surface of the pavement. The measurements are converted into rideability indices.

Collection of distress data is one of the most important aspects of pavement condition evaluation and the most subjective. There is not yet any completely rational and scientific method of accomplishing this objective. All agencies conducted manual condition evaluation surveys on an average of once a year. Selected pavement sections are examined and each type of distress is rated on a scale for severity and extent. These ratings are then quantified. Though visual survey was the most commonly used method, some agencies also used photographic devices to record pavement distress. Laser crack detection and video pattern recognition techniques are also being considered for use by at least one agency. Pavement surface deflection under load was measured most commonly with a Falling Weight Deflectometer (FWD).

For the calculation of the condition index, weights (signifying relative importance) are assigned to each of the distress types. In the survey, the respondents were asked to assign weights to distresses on a scale of 1 to 10 with 10 assigned to the most important and 1 to the least important distress for the calculation of a serviceability index. It was found that the agencies attached greatest importance to alligator cracking and least to bleeding. Table 1 shows the order of importance, based on the responses received. Stripping (the separation of asphalt from aggregate due to adverse conditions), a relatively common problem, was not measured by any of the agencies.

Table 1 — Weights assigned to different distress types

Distress Type	Weight Assigned
Alligator Cracking	10
Rutting	9
Pot holes	8
Patching	7
Block Cracking	6
Longitudinal cracking	5
Transverse cracking	4
Edge cracking	3
Raveling	2
Bleeding	1

MODERN PAVEMENT MANAGEMENT SYSTEMS

Knowledge in the field pavement management has largely been built through incremental improvements in the technology rather than spectacular breakthroughs. As more and more agencies implement PMS, the experience should in itself contribute to the advances in the technology.

Geographic Information Systems (GIS) and Expert systems are already finding several applications in the field of pavement management. Advances in computer hardware and programming techniques have promoted increased use of electronic data processing to support PMS. Computerization has led to a number of changes, both conceptual and technological in PMS. Modern methods and equipment offer very promising applications in the field.

GEOGRAPHIC INFORMATION SYSTEMS

Though the roots of geographic information systems (GIS) date back to the mid-eighteenth century, the three major factors for cartographic change: technology, theory and social awareness had each evolved into an advanced state only in the mid–twentieth century. The critical mix of digital computers, improved analytical techniques, and increased social awareness had set the stage for the first modern GIS [16]. The concept of GIS as a system for storing and organizing spatial information in a computer was conceived about 25 years ago, however, it has only been during the past 10 years that this technology has grown to its present state. GIS applications have grown from cartography to natural resource management, environmental assessment and planning, tax mapping, ecological research, emergency vehicle dispatch, demographic research and more.

An information system is a chain of operations that goes from collection, storage and analysis of the data, to the use of the derived information in some decision making process. A GIS is an information system that is designed to work with data referenced by spatial or geographic coordinates. It is a computerized database management system for the capture, storage, retrieval, analysis and display of spatial (i.e., locationally defined) data [17]. In other words, a database system with specific capabilities for manipulating spatially referenced data – a higher order map [18].

Elements of a GIS

There are five functional elements that a GIS must contain: data acquisition, preprocessing, data management, manipulation and analysis, and product generation. Data acquisition is the process of identifying and gathering the data required. Preprocessing involves the manipulation of the data so it may be entered into the GIS. Data management functions govern the creation of, and access to, the database itself, providing consistent methods of data entry, update, deletion, and retrieval. Manipulation and analysis are the focus of attention for a user of the system. This part of the system contains the analytic operators that work with database to derive new information. Product generation is the phase where final outputs, like statistical reports and maps are created [18].

Three features of GIS make it better than the reference systems currently in use. First, the ability to share a common database of spatial information, which leads to better interdepartmental cooperation and a vast reduction in data redundancy. Second, the ability to bring together otherwise unrelated data, using location as a method for building the relationships. And third, the ability to aggregate the very specific data commonly associated with operational functions, into larger spatial units which are more useful for the macro applications more commonly associated with management planning.

Applications in Pavement Management

A transportation system consists of nodes, lines, and entities distributed in space. Events happen within this system at a point (e.g., an accident, a signal location), along a segment (e.g., vehicle volumes, pavement deficiencies), or within a geographical area (e.g., the number of people living within two blocks of a bus stop or working in an industrial park) [17]. Spatial considerations are fundamental to transportation activities.

Identification of pavement segments is an essential function of PMS. Street or roadway segment identification is required for data collection, analysis, and reporting purposes. Present road classification systems are based on functional category, funding sources, traffic volumes, etc. Such systems have disadvantages like a lack of flexibility, and difficult to manage databases. A multifaceted, flexible reference system is required for pavement systems as extensive and complex as the present day networks.

A PMS is based on information accumulated over a period of time. Comprehensive models require a diverse collection of highway related information about the traffic volumes, construction and maintenance histories, pavement condition surveys, maintenance histories, etc. These data files within the same transportation agency are typically unrelated to each other, duplicative, and inconsistent even though they contain information about the same pavement segment. This can be mainly attributed to a lack of coordination between the various sub-divisions of the agencies which undertake the different activities. Typically, maintenance and rehabilitation are performed by departments which base their activities on entirely different regional and sub-regional demarcations.

The importance of consistent georeferencing systems is only now being recognized by highway agencies. GIS technology can provide the core of a framework for an integrated highway information system [19]. Variables like pavement condition, roadway geometrics, traffic volumes, etc., can be easily associated and correlated through the use of common georeferencing system. Typical PMS output consists of tabular data which needs to be transferred to a base map manually. A map based graphics interface and geocoded data would facilitate easy data input and output.

Comprehensive and easy to understand reports would be much simpler to produce [20].

A GIS can lead to new ways of thinking about the pavement management process. It can expand the decision making on repair strategies and project scheduling by incorporating diverse data. A GIS/PMS can be used to build projects through spatial selection, compute traffic impacts, incorporate life cycle forecasts into measurement of future mobility, etc. In addition, omissions in the data collection effort would be immediately apparent [21].

EXPERT SYSTEMS

The concept of the expert system (ES) arose in the 1970s when artificial intelligence (AI) researchers abandoned, or postponed, the quest for a generally intelligent machine and turned instead to the solution of narrowly focussed real-world problems.

An expert system is a program that manifests some combination of concepts, procedures, and techniques derived from recent AI research [22]. These techniques allow the design and development of computer systems that use knowledge and inference techniques. Conventional computing depends upon an analysis of all the elements and steps in a problem. AI programs rely on rules of thumb (heuristics) rather than on mathematical certainty; therefore, they allow managers to look at problems even when they have incomplete information.

The importance of ES is growing in all fields of science. Some of the reasons for this are: (1) the necessity for handling an overwhelming amount of knowledge; (2) the potential of ES to train new experts; (3) possible cost reductions provided by ES and (4) the desire to capture knowledge so it is not lost as personnel changes [23].

Organization of Expert Systems

The organization of ES differs from that of conventional computer programs. Ordinary programs organize knowledge into two levels - the data and the program. ES organize knowledge in three levels — facts, rules, and control. These three are analogous to : (1) the knowledge base, which contains general knowledge about the problem domain; (2) situation model or context, similar to the database of conventional programs; and (3) the inference engine, also called the rule interpreter, which controls the execution of the program. Another major difference is the ability to treat facts and rules as 'data'. In conventional programs rules are embedded in the procedural knowledge encoded as the program. Hence, it is difficult to separate the rules from the control mechanism. A knowledge based system separates domain specific rules from procedural language used for controlling the program. This organization makes it much easier to encode and maintain rules. Figure 4 shows graphically the structure of a typical ES.

Though there are many approaches to building knowledge based decision support systems, rule-based deduction is the most widely used and essentially the standard in AI today [24]. In this approach, domain specific problem solving knowledge is represented in rules which are basically of the form:

IF {antecedents} **THEN** {consequents},

although the exact syntax used may be quite different. If antecedents are determined to be true then it logically follows that the consequents are also true. The inference mechanism consists of a rule interpreter which, when given a specific set of problem features, determines applicable rules and applies them in some specified order to reach conclusions.

Applications in Pavement Management

Knowledge based ES technology can significantly benefit pavement management processes because it promotes systematic gathering, encoding, and consistent knowledge application. Knowledge associated with, for example, the selection of pavement preservation treatments, is not readily available in textbooks or reports. Much of this knowledge is heuristic, unpublished and dispersed among many experienced users. Capture and encoding of this knowledge within a rule-based ES structure would be very beneficial to highway agencies [25].

Implementation experience to date has already demonstrated that near-optimization techniques, incorporating an heuristic, marginal cost-effectiveness approach, are quite applicable to priority programming and can indeed be preferable to an approach that uses mathematical programming for optimization [26].

VOICE RECOGNITION SYSTEMS

In the last decade, there has been a dramatic simplification in the modes of communication between user and computer of late. Touch sensitive screens, lightpens, and enhanced keyboards have increased the effectiveness of information exchange but they still lack the directness of voice control. Speech is one of the most basic forms of human communication, so it stands to reason that if people are ever to interact freely with computers, the machines must be designed to recognize and understand the human voice.

Voice input to computers has a number of advantages. It provides a natural, fast, eyes/hands free, location free input medium. Extensive research in the field of computer speech recognition has led to the development of systems capable of accepting voice commands, although recognition of unrestricted, spontaneous speech appears unsolvable at present.

There are basically two types of speech recognition: Isolated Speech Recognition (ISR) and Continuous Speech Recognition (CSR). In ISR, the computer uses the pause between words to determine where words begin and end - the first step in recognition. Users of this kind of a system must re-train themselves to speak with a deliberate pause. This is clearly not a natural speech pattern, but it drastically reduces the

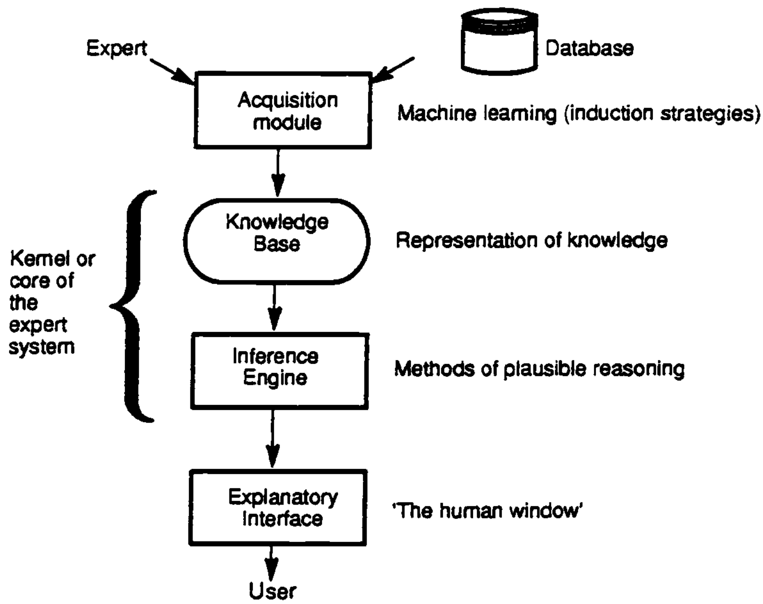

Figure 4. Typical Expert System Configuration

algorithm complexity necessary to decipher the spoken words. CSR allows the computer user to speak freely as he or she would to another person. No pause between words is necessary. This is more natural and the ultimate aim of all computer voice recognition systems.

Voice recognition technology as a whole can be divided into two categories: speaker independent recognition (SIR) and speaker dependent recognition (SDR). SIR systems can recognize a fixed number of words from a variety of speakers. Voice input is compared to generic templates for accepted words derived from a sampling of a large database of voices. Though SDR systems must be 'trained' by the individual using the machine, these systems may recognize as many as 1000 words or more. Consequently, SDR systems provide the largest vocabulary, highest accuracy (of recognition) and most implementation in industrial systems [27].

Limitations of Speech Recognition Systems

Although a few systems have demonstrated the feasibility of accurately recognizing human speech, it can be said that they performed well because they imposed one or more of the following constraints: (1) speaker dependence, (2) isolated word recognition, (3) severely limited vocabulary, and (4) constrained grammar [28]. Dependence on these constraints is caused by four major deficiencies: (1) lack of a sophisticated yet tractable model of speech; (2) inadequate use of human knowledge of acoustics, phonetics, and lexical access in the recognizer; (3) lack of consistent units of speech that are trainable and relatively insensitive to context; and (4) inability to account for between-speaker differences and speaker specific characteristics.

Speaker-independence is viewed as the most difficult constraint. This is because most parametric representations of speech are highly speaker dependent, and a set of reference patterns suitable for one speaker may perform poorly for another. SIR systems have been found to have three to five times the error rate of SDR systems. Because of these difficulties, most of the competent voice recognition systems are speaker dependent [28]. CSR, which is significantly more difficult than isolated word recognition, is another major limitation. Its complexity is a result of three properties of continuous speech:(1) unclear word boundaries, (2) co-articulatory effects (influence of previous and following sounds/phones) and, (3) emphasis placed on different kinds of words (verbs, adjectives etc.). While isolated word recognition systems have some applications, they are awkward for larger realistic tasks.

Applications in Pavement Management

Voice recognition systems are ideally suited for application in pavement management in the areas of distress and other field data collection operations. Present data collection procedures involve visual inspection, note—taking and subsequent transfer of the data to a computer database. Data collection is often accomplished while driving slowly down the pavement section. These operations involve considerable movement on the part of the user and simultaneous data gathering. It is in a such a hands/eyes busy situation that a voice recognition system can be used for direct data entry into a computer database. The primary advantage of automatic speech recognition is speed, since speech is the highest capacity human output channel. Conversational voice input/output provides many otherwise unobtainable benefits in these applications. Faster data capture and increased productivity due to the elimination of the need to stop and look at pads and computer screens. A voice recognition system connected to a portable data terminal would be ideal in such conditions. Data can be transferred from the portable terminal to any commercially available or custom developed database management software package. An additional advantage of such a system would be the complete elimination of the second data transfer operation (i.e., the transfer of data from the handwritten notes to the computer database).

CONCLUSIONS

1. Pavement management has emerged as a new field and has established its importance in helping achieve the objective of managing pavement systems most efficiently. PMS are being recognized as a very important part of pavement rehabilitation programs of the future. All state highway agencies are scheduled to have operational systems by 1993.

2. Each state agency has adopted different methods for all pavement management functions, from pavement condition evaluation to correction strategy implementation. It has been realized that standardization of pavement management practices is important, if the field is to progress.

3. Data collection procedures of some highway agencies are outdated and lead to inconsistent and redundant data. Crack detection equipment, laser profilometers, pattern recognition systems etc. will improve the quality of data and consequently, performance of PMS.

4. Implementation of expert pavement management systems (EPMS) will result in more efficient use of available data and consequently lead to better decisions. It was found that many of the agencies presently using PMS have been using these systems for training purposes. EPMS will perform this task of tutoring less experienced personnel better.

5. Flexible georeferencing systems have been recognized to be important parts of a modern PMS. Advanced computer graphics technologies are being incorporated into PMS. This will lead to faster identification of potentially troublesome pavement sections. Also overall system performance monitoring will become easier.

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PAVEMENT CONDITION INDEX - REMAINING SERVICE LIFE

REFERENCE: Baladi, G. Y., Novak, E. C., Jr., and Kuo, W. H., "Pavement Condition Index - Remaining Service Life," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: The issues and the setting of common engineering criteria to establish threshold values for a better calculation of the pavement distress indices and Remaining Service Life (RSL) are presented. Benefits derived from the use of RSL such as simplifying the Pavement Management System (PMS), computational procedures, improving communication between the various PMS users, and increasing the PMS capability are also included. Within the framework of a PMS, most State Highway Agencies (SHAs) collect pavement condition data to calculate pavement distress indices. Because pavement condition data is the basis for all PMS analysis, the values of the pavement indices are typically prioritized and the highest priority is placed on eliminating most deficiencies. Examination of this effort has indicated that the method is deficient and that the RSL is a better pavement condition index.

Common pavement distress indices deficiencies were found to be related to basing the indices on a single variable (pavement condition at the time of the survey). The rate of the pavement deterioration is not included in the calculation of the indices. In order to eliminate the common deficiencies, it was found that the pavement indices must be based on pavement performance which consists of two variables, surface condition and the rate of deterioration.

Keywords: Pavement Management System, Distress Index, Remaining Service Life.

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1.0 INTRODUCTION

The basic measurements of the condition of a pavement section are its existing distress. There are two classes (structural and functional (1 through 6) and several types of distress that are associated with each type of pavement. In general, pavements that exhibit structural distress and/or failure (e.g., severe alligator cracking) will also exhibit functional distress and/or failure. Inversely, functionally distressed and/or failed pavements (e.g., very rough) may be structurally sound. The pavement distress survey program should identify each distress type by a minimum of three factors: type, severity, and extent.

Furthermore, each type of distress is caused by one or more variables (e.g., moisture, drainage, environment, load) which, when known, provide great insight into the causes of pavement deterioration. Hence, for each pavement type, the proper pavement evaluation program and procedure should include the identification of the type, severity, and extent of the distress as well as any abnormal drainage problem (e.g., standing water in the drainage ditch). This information may assist the highway agency in determining the possible cause or causes of pavement deterioration and in selecting feasible rehabilitation alternatives.

Various data collection methods can be used in the pavement distress survey (monitoring) program such as manual, automated, high-speed lane pass, low-speed shoulder pass, photographic, etc. (2, 5, 7 through 12). The purpose of a distress survey is to periodically monitor the condition and other properties of the pavements.

2.0 USES OF PAVEMENT DISTRESS DATA

The use of the pavement distress data depends upon its detail, quality, and accuracy. For example, detailed data collected at short intervals (e.g., every 0.1 mile) along the pavements could be used at both the network and project design levels. Coarse data, on the other hand, that are made of the average pavement surface conditions along long sections (e.g., 1 mile or larger segments), may not be accurate enough to be used at the project design level. Hence, for project analysis and design, more detailed and accurate data needs to be collected. Nevertheless, detailed and/or course distress data can be used for the calculation of the pavement surface distress indices as explained in the next section.

3.0 CALCULATION OF PAVEMENT DISTRESS INDICES

Within the framework of a Pavement Management System (PMS), a SHA may choose to calculate:

1. Itemized pavement distress indices (e.g., rut index, roughness index).

2. A combined pavement distress index (e.g., surface distress index).

3. An overall pavement index (e.g., pavement quality index).

Regardless of the type of index (itemized, combined or overall) the methods for calculating the indices must be compatible with the policy and objectives established by the SHA and it must be based on sound engineering criteria. The policy and objectives and the engineering criteria must address several PMS issues including:

1. The types of the pavement distress data to be collected, frequency of data collection and the survey length, the type of pavement distress indices to be calculated and the various attributes to be included in the calculation.

2. A rating scale for each distress index. This scale could be bounded and based on values from 0 to 100, 0 to 10, or any other values; or it could be an open ended (unbounded) scale. Although some SHAs have established different rating scales for different distress indices, it is advantageous to establish one unique rating scale for all indices. This would facilitate a better communication between the various PMS users.

3. A threshold value at which the pavement condition is considered unacceptable. The threshold value could be any number between the upper and lower limits of the rating scale. Once again, different threshold values can be assigned to different distress indices. However, as for the rating scale, a unique threshold value would facilitate a better communication between the various PMS users. It should be noted that if the numerical value of the threshold is selected at this stage (prior to the calculation of any distress index), and if the value is based on a balanced engineering criteria, then it could be integrated into the calculation of the various distress indices. This will eliminate its impact on the number of pavement sections in need of repair. This issue is further demonstrated in the next steps and examples.

4. The severity levels (e.g., high medium and low) and their definitions.

5. For each distress type and for each severity level, the maximum extent of the distress at which the condition of the pavement section is considered unacceptable or at which the pavement score will be at a certain value. For example, the maximum acceptable extents for high, medium and low severity alligator cracks are, respectively, 10, 50, and 100 percent of the pavement section in question. The maximum acceptable extent for each severity level of each distress type must be established based on engineering criteria which must consider the economic analysis of the alternative repair actions that need to be taken when the maximum acceptable extent is reached. This can be illustrated by using the following examples.

Example 1 - Engineering Criteria - A SHA engineering criteria (policy) specifies that the maximum allowable extents for low, medium and high severity alligator cracking are, respectively, 100, 50 and 10 percent of the survey section under consideration. The SHA uses a rating scale from 0 to 100 (100 = perfect pavement) and a threshold value of 60 to indicate that the pavement is in need of repair. Based on the above criteria, rating scale, and threshold value, establish an equation for the calculation of the Alligator Cracking Index (ACI).

Solution 1

1. The criteria specifies that when the maximum acceptable extent of the High Severity Alligator Cracking (HSAC) of 10 percent of the survey section is reached, then that section will be rated 60 (the threshold value). Hence, the deduct value for the HSAC = 4*HSAC. When HSAC = 10%, then the deduct value = 4*10 = 40 points.

2. For Medium Severity Alligator Cracks (MSAC), the deduct value is equal to 40 * MSAC / 50 = 0.8*MSAC. That is, if the MSAC = 50%, then the deduct value = 0.8*50 = 40 and the pavement rating is 100 - 40 = 60 (the threshold value).

3. Similarly, the deduct value for Low Severity Alligator Crack (LSAC) = 0.4*LSAC.

4. The combined equation for the calculation of the Alligator Cracking Index (ACI) is: ACI = 100 - (4*HSAC + 0.8*MSAC + 0.4* LSAC). Note that the factors 4, 0.8, and 0.4 of the above equation represent the weight factors between the three severity levels.

Example 2 - Based on the ACI equation of example 1, calculate the ACI for a pavement section with 20, 10, and 5 percent low, medium, and high severity alligator cracking respectively.

Solution 2

ACI = 100 - (4*HSAC + 0.8*MSAC + 0.4*LSAC).
ACI = 100 - (4*5 + 0.8*10 + 0.4*20) = 64 (acceptable).

Now note that the same pavement section with the same extent of low, medium, and high severity alligator cracking (5, 10, and 15 percent, respectively) can be numerically represented by a different threshold value by simply recomputing the weight factors.

Alternatively, The engineering criteria for the maximum acceptable extent of certain severity level may assign only some deduct points, that is the threshold value is not reached as illustrated below:

Some SHAs combine various types of pavement distress for the calculation of Combined Pavement Indices (CPI) such as structural index. In this case, each distress attribute must be assigned a relative weight factor and severity and extent factors.

It should be noted that any distress index represents only one pavement distress category. The total number of categories or indices (e.g., roughness index, structural index) used in the PMS depends upon the criteria and the practices of the SHA.

Some other SHAs calculate an overall or combined condition or priority index using various attributes. Table 1 summarizes some of the various pavement indices calculated by some SHAs.

4.0 PAVEMENT SERVICEABILITY AND THE INTERNATIONAL ROUGHNESS INDEX

Pavement Serviceability Rating (PSR) is the numerical average rating determined by a panel of individuals who ride the pavement in question and independently rate it. The PSR is a subjective concept first developed by Carey and Irick at the AASHO road test (8). In the U.S.A., the PSR is based on a rating scale from 0.0 to 5.0. At the AASHO road test, the PSR was correlated to objective measurements made on the pavement surface, which included a measure of roughness, extent of cracking and patching, and (for flexible pavement the average rut depth in the wheel tracks (1, 5, 7, 13, 14).

Road roughness is a measure of the ride quality and the economic benefits (user benefits) derived from rehabilitation actions. Hence, it is an important measure of the condition of the network. Road roughness is typically measured by using either a response-type measuring system or a profilometer. Roughness is usually measured in terms of mm/km, inches/mile, counts/unit length, etc.

The International Roughness Index (IRI) provides a common quantitative basis to reference the different measures of roughness for the purpose of calibration and comparison of results. The IRI was developed at the International Road Roughness Experiment, which was held in Brazil in 1982 (15 to 16).

Recently, an increasing number of SHAs have acquired roughness data using the IRI. Due to this trend, efforts were expanded to correlate the existing PSI data to IRI measurements. Equations 1 and 2 express two such correlations that were obtained by the highway agencies in Maine and South Carolina, respectively.

Table 1. Overall pavement distress indices used by various SHAs.

STATE	DISTRESS INDEX
ARKANSAS	COMBINED INDEX (RIGID) = 0.6(DISTRESS) + 0.4(RIDE) COMBINED INDEX (FLEX.) = 0.5(DISTRESS) + 0.5(RIDE)
DELAWARE	PSI = 0.25(RIDE) + 0.75(SURFACE DISTRESS)
FLORIDA	COMBINED INDEX = THE SQUARE ROOT OF RIDE AND DISTRESS.
IDAHO	COMBINED INDEX = 0.5(PSI + CRACKING INDEX).
KANSAS	RIDE, PRIMARY AND SECONDARY DISTRESSES, AND INFLUENCE VARIABLES ARE COMBINED TO GIVE 1 OF 216 POSSIBLE CONDITION STATES WHICH ARE GROUPED INTO THREE PERFORMANCE LEVELS: NO ACTION, MAINTENANCE ACTION AND REHABILITATION ACTION.
MARYLAND	ITEMIZED INDICES DETERMINED BY EACH CONDITION INDEX COMPONENT SUCH AS RIDE, DISTRESS AND TRAFFIC.
MASSACHUSETTS	PSI = 2(PSR) + (D1 + D2 + D3 + ...DN)/(N + 2) PSR = PAVEMENT SERVICEABILITY RATING (0 - 5).
MICHIGAN	DISTRESS POINT ACCUMULATION (0 = EXCELLENT, 50 = THRESHOLD VALUE OR REMAINING SERVICE LIFE OF ZERO).
MINNESOTA	PQI = FUNCTION OF SURFACE RATING, RIDE RATING AND STRUCTURAL ADEQUACY RATING.
MISSISSIPPI	COMBINED INDEX = RIDE + DISTRESS
MISSOURI	COMBINED INDEX = 2(RIDE) + 5 POINTS FOR EACH OF THE FOLLOWING DISTRESSES: CRACKING, PATCHING, JOINTS, RAVELING AND RUTTING ON AC).
NEW HAMPSHIRE	COMBINED INDEX = 0.5(ROUGHNESS) + 0.5(DISTRESS)
NEW MEXICO	COMBINED RATING = 100 - [0.6(ROUGHNESS - 25) + 0.4 (DISTRESS DEDUCT)]/1.6
PENNSYLVANIA	OVERALL PAVEMENT INDEX = COMBINATION OF 13 INDICES.
TEXAS	FIVE COMPOSITE INDICES BASED ON UTILITY THEORY ARE USED WITH MULTIPLICATION FACTORS BETWEEN 0 AND 1.
VERMONT	COMBINED INDEX = 0.6(ROUGHNESS) + 0.25(CRACKING) + 0.15(RUTTING).
MONTANA	COMBINED INDEX BASED ON ROUGHNESS AND RUTTING.
NORTH DAKOTA	COMBINED INDEX BASED ON RIDE, DISTRESS AND AGE.
NEVADA	PROJECT LEVEL: DEDUCT SYSTEM, CONSIDER ALL POINTS. NETWORK LEVEL: DISTRESS POINT ACCUMULATION (0 - 49 = PREVENTIVE MAINTENANCE, 50 - 399 = CORRECTIVE MAINTENANCE, 400 - 699 = OVERLAY, AND OVER 700 = RECONSTRUCT).

Figure 1 provides a comparison between the two equations.

$$PSI = 9.577 - 4.394[LOG(IRI/5.9597)] \quad \text{for } 5>PSI>0 \tag{1}$$

$$PSI = 5\{EXP[-0.00286(IRI)]\} \tag{2}$$

where LOG = base 10 logarithm;
IRI = International Roughness Index (inch/mile); and
EXP = exponential function.

The ride index of a pavement section can be calculated by using roughness data, the PSI equation, the PSR, the international roughness index (IRI), or any other correlation developed by the SHA. The method for calculating the ride index is basically the same as that presented earlier.

5.0 USES AND LIMITATIONS OF PAVEMENT DISTRESS INDICES

It should be repeated herein that the number and types of distress to be included in the calculation of a combined pavement index (CPI) or an overall pavement index (OPI) is dependent on the engineering determination of the SHA. One important point to be noted is that, balanced engineering criteria, experience, and understanding are essential elements for establishing the equation(s) for the calculation of the OPI or CPI. The assigned weight factors must be based on a balanced engineering criteria which must address real life problems as well as the economics of alternative actions. The PMS users/practitioners must know how, when, and why to use the various types of pavement distress indices. For that reason, the following paragraphs provide guidance in the use and limitations of pavement distress indices.

5.1 Uses of Pavement Distress Indices

The CPI and/or the OPI can be used to help the SHA to:

1. Check the accuracy and modify existing pavement performance models that are based on the CPI or OPI.
2. Determine the combined rate of deterioration of the various pavement sections.
3. Produce strip maps and pie or bar charts concerning the distribution of the pavement condition for the network.
4. Facilitate communication between the various PMS users and the top management of the SHA. The highway agency can use the values and the trend of the OPI or CPI to support budget request or

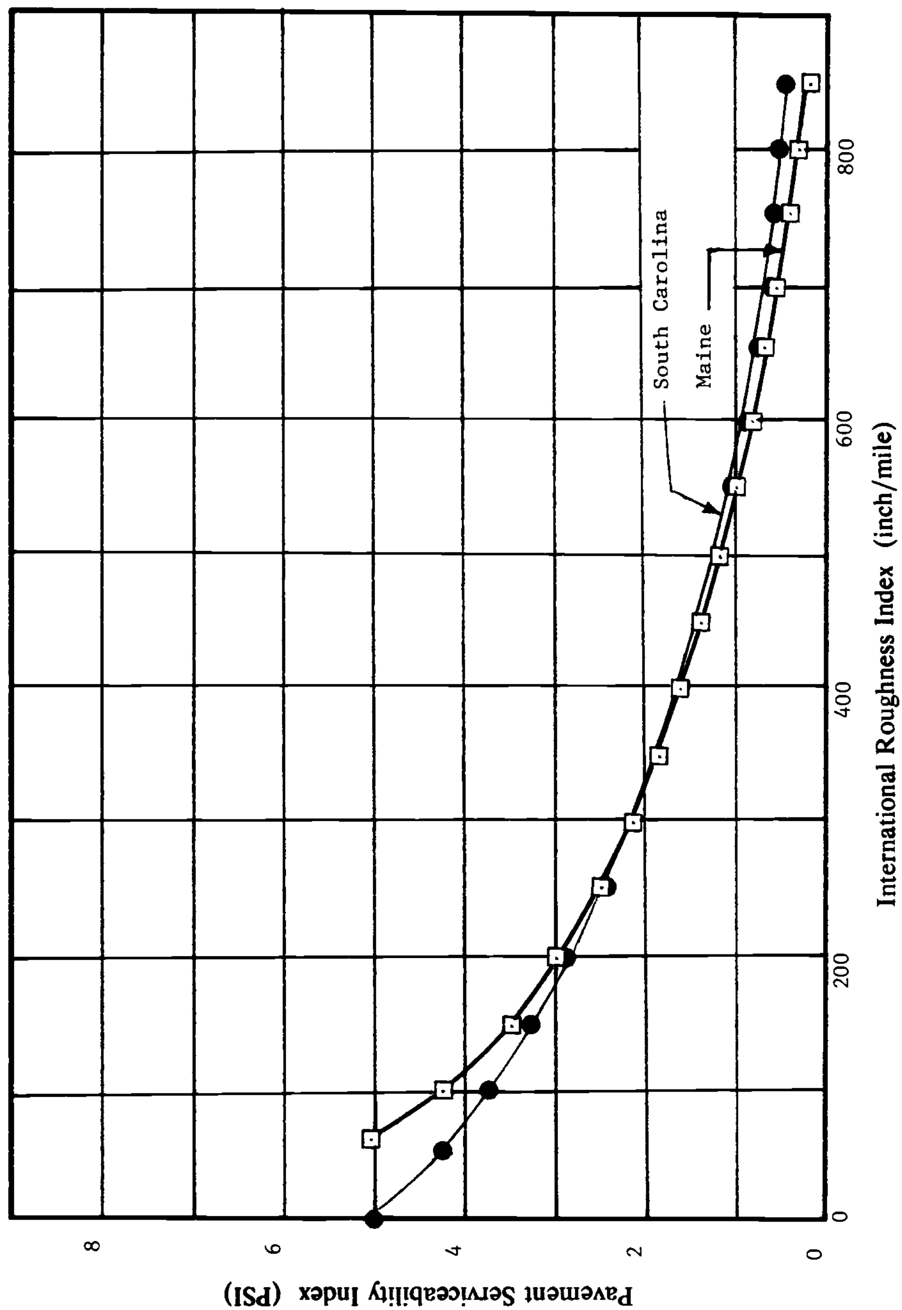

Figure 1. Pavement Serviceability Index versus the International Roughness Index.

to show the impact of various budget levels on the health of the network.
5. Assess and understand the impact of rehabilitation strategy on the health of the pavement network.
6. Examine the pavement design methods and the impact of the various design and construction variables on pavement performance.
7. Produce prioritization lists of the various uniform sections of the pavement network.

5.2 Limitations of the Pavement Distress Indices

The concepts for calculating and using pavement distress indices in the framework of a pavement management system were introduced in the early 1970. Since then, most SHAs have directed their efforts to take advantage of this new technology and to use it in the development of a PMS. Today, most agencies calculate one form or another of itemized pavement distress indices, combined pavement indices, and/or an overall pavement index. SHAs should analyze and scrutinize the applicability of distress indices to real life problems and to the various decision making processes. In this subsection, limitations of using pavement distress indices (itemized, combined or overall) for engineering purposes (e.g., prioritization of the various pavement sections and the selection of an optimum rehabilitation strategy) or for other decision making processes are presented and discussed. These limitations include:

1. The value of any pavement distress index reflects the pavement condition observed during the survey. The value of the index alone does not reflect the rate of pavement deterioration.
2. Any prioritized list generated on the basis of the values of the distress indices without considering their rate of change can be misleading. It is possible that two or more pavement sections with the same value of the distress index have drastically different rates of deterioration (see Figure 2). Hence, this affects their future priority ranking because one section may fall below the threshold value in one year while the other may have an acceptable condition for five additional years.
3. For newly rehabilitated or constructed pavement sections that show no distress, the values of the various distress indices are the same. Yet, one section may be designed to last for eight years while the other is designed to last for fifteen years.
4. The distress indices alone cannot be used to assess the benefits of rehabilitation activities. For example, the improvement in the distress index (short-term benefits) for one or five-inch overlay

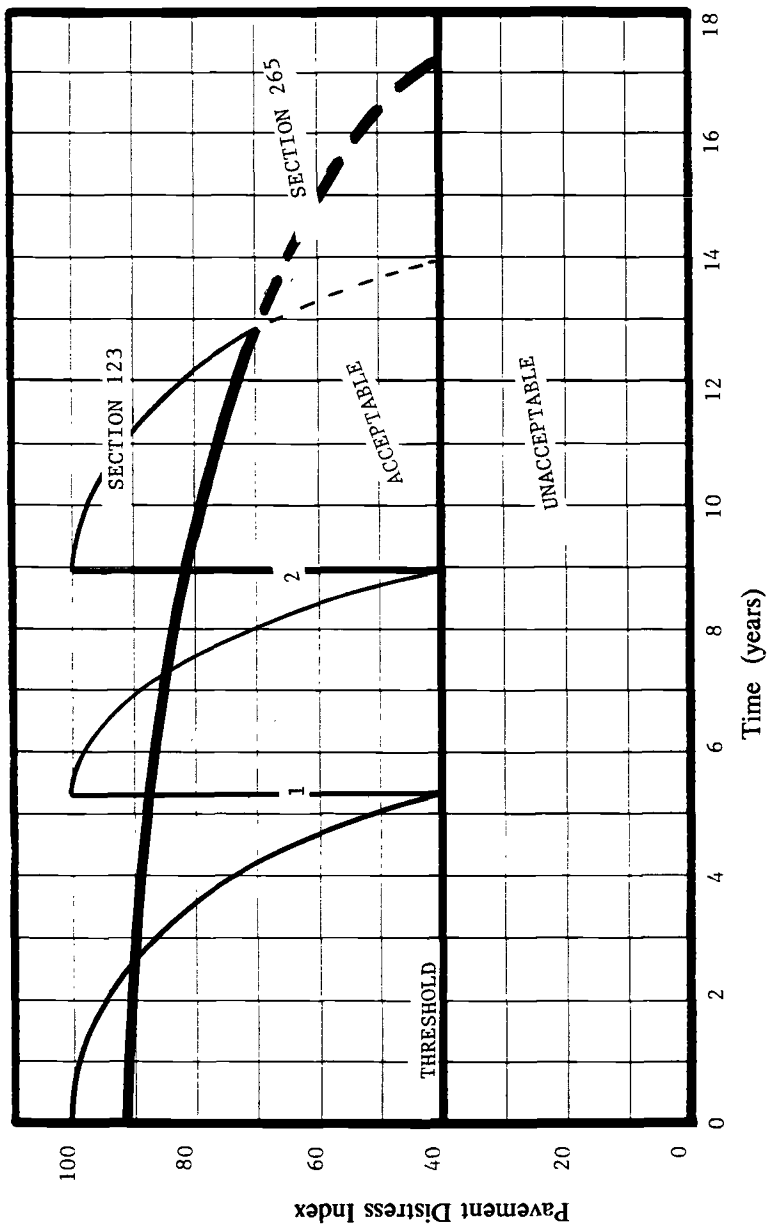

Figure 2. Pavement distress index versus time for various rehabilitation activities.

may be the same (no distress after overlay). The long-term benefits, however, are likely different. Hence, rehabilitation benefits cannot be related to the improvement in the value of the distress index alone. The design life of the rehabilitation alternative needs to be considered.

5. If rehabilitation benefits are measured only by the improvement in the value of the distress index, then rehabilitation decisions tend to favor a cheap repair (e.g., thin overlays). Because the expected service life of thin overlays is relatively shorter than thick overlays and because the rest of the network is continuously deteriorating, the backlog of pavement sections in need of repair will continuously grow if only short design life rehabilitation options are used.
6. Rehabilitation decisions based on distress indices alone would not help the SHA to control future distribution of the pavement network conditions.
7. The value of any CPI or OPI is typically obtained by averaging the various distress attributes with proper weight factors. Hence, the value alone does not allow the examination of the various distress types nor does it reflect the true condition of the pavement. That is, it is possible for a pavement section to have a relatively good combined index value and an unacceptable value of one of the distress indices (see case studies of sections 8 and 9 below).
8. The value of a CPI or an OPI may be used to estimate network-level needs. However, the values of the various distress indices or the raw distress data have to be examined prior to making any decision or recommendation regarding possible rehabilitation techniques and their estimated costs.
9. The OPI and/or the CPI are not intended to be used to identify the percent of damage contributed by each distress attribute. That is, the values of the OPI and/or the CPI indicate the average amount of damage delivered to a pavement section by the various distress attributes. The relative amount of damage delivered by each attribute can only be obtained by examining the raw distress data.

6.0 REMAINING SERVICE LIFE

For a better understanding of Remaining Service Life, the following definitions are introduced:

6.1 Definitions

1. Design Service Life (DSL) - An estimate of the number of years of service (after construction or rehabilitation) for the pavement to accumulate the

predetermined threshold value of distress points. This estimate is typically a function of the design procedure and the distress prediction models used by the SHA.

2. Pavement Service Life (PSL) - The actual number of service years, starting from the year of construction or rehabilitation, provided by a pavement section before it accumulates the predetermined threshold value of distress points. For a newly constructed or rehabilitated pavement section, the PSL is assumed to be equal to the DSL. The actual PSL could be shorter or longer than the estimated DSL.

3. Remaining Service Life (RSL) - The remaining service life is the estimated number of years, from any given date (usually from the last survey date), for a pavement section to accumulate distress points equal to the threshold value. For the network, it is the weighted average of the RSLs of all the pavement sections within the network. The RSL of any pavement section is zero if its condition falls below the acceptable standard (threshold value). For a newly constructed or rehabilitated pavement section, the RSL is equal to the estimated DSL.

4. Pavement DSL or RSL Category - For ease of calculation and data presentation, the DSL and/or RSL may be divided into several categories as follows:

	Remaining service life category						
	I	II	III	IV	V	VI	VII
Design life or remaining service life (years)	0-2	3-7	8-12	13-17	18-22	23-27	28-32

5. Network Condition - The RSL of the network can be tabulated in various formats. The following is an example of a simple format that shows the percent of the total mileage of the network in the various network RSL categories.

Pavement Category	Remaining Service Life (years)	Percent of Network
I	0- 2	20
II	3- 7	10
III	8-12	25
IV	13-17	10
V	18-22	15
VI	23-27	13
VII	28-32	7

6.2 General

A pavement distress index (e.g., rut index, alligator cracking index) provides a measure of severity and extent of the particular distress in question. However, the index does not express the rate of deterioration of the pavement section nor does it reflect the type of pavement rehabilitation used. For example, after an overlay, the value of most distress indices are the same (they indicate a good pavement) regardless of the thickness of the overlay. Similarly, a value of a distress index of a pavement section of 75 does not express the rate of deterioration of that section. The values of the index over a period of time (several years) need to be examined to determine the rate of deterioration. Hence, pavement sections having the same value of a distress index may or may not require rehabilitation at the same time. Therefore, it is not accurate nor is it possible to produce an ultimate multi-year rehabilitation program based solely on the distress index.

The RSL of a pavement section combines the severity and extent of the distress and its rate of change. In general, a pavement section will experience more than one type of distress (e.g., rut, alligator cracks, transverse cracks, longitudinal cracks, corner break, etc.) during its service life. The rate of change of each distress type is usually not the same. Based on the established threshold value for each type of distress (see section 3 above) and distress survey data, a pavement section may receive different condition ratings for each distress type such that each section may have a different RSL (different time periods are required for each distress type to reach its threshold value). Among all distress types, the one that reaches its threshold value first (i.e., the shortest RSL) should trigger the need for repair actions. Thus, the RSL of a pavement section is analogous to that of a human being. If a person is diagnosed to have heart, clogged arteries, and kidney problems that would cause death in 2, 5, and 10 years, respectively, then the remaining life of that person is likely to be 2 years and not the weighted average of the three time periods. This concept assumes that the interaction between the various problems has been accounted for. For pavements, the interaction between the various distress types is included in the survey data. That is if the survey data of one distress type indicates that the distress has increased by 20% since the last survey, then that increase is most likely the result of the interaction of the various distress types and the various factors (i.e., environmental, load, etc.) affecting that distress.

6.3 Calculation of RSL

The calculation of the RSL of any pavement section must be based on its current condition, the rate of condition change and the threshold value that relates to unacceptable condition. The method of calculation depends on the available distress data. This can be illustrated using several examples.

Example 3 - For flexible pavements, assume that the SHA engineering criteria calls for: a) the collection of five distress types: rut, alligator cracking, transverse cracking, roughness, and edge cracking; and b) the calculation of five respective distress indices as presented in section 3 above. Each index is based on a rating scale from 0 to 100 (100 = perfect pavement) and a threshold value of 50 below which the pavement is rated unacceptable. Further, assume that the PMS databank of that agency contains only last year's survey data (no historical distress data). Based on survey data; the rut, alligator cracking, transverse cracking, roughness, and edge cracking indices of a pavement section were calculated at 60, 95, 90, 80, and 90, respectively. Estimate the RSL of that pavement section which has been in service for 8 years and was designed for 7 years.

Solution 3 - In this example, one can assume that, when the pavement was constructed 8 years ago, the value of each distress index was 100. Since distress data (indices) are available for only one year, a straight line deterioration curve can be assumed (see figure 3) and the following RSLs can be calculated:

Distress type	Equation for RSL	RSL (years)
Rut	(8)(60-50)/(100-60)	2
Alligator Cracking	(8)(95-50)/(100-95)	72
Transverse Cracking	(8)(90-50)/(100-90)	32
Roughness	(8)(80-50)/(100-80)	12
Edge Cracking	(8)(90-50)/(100-90)	32

Overall RSL = 2 years.

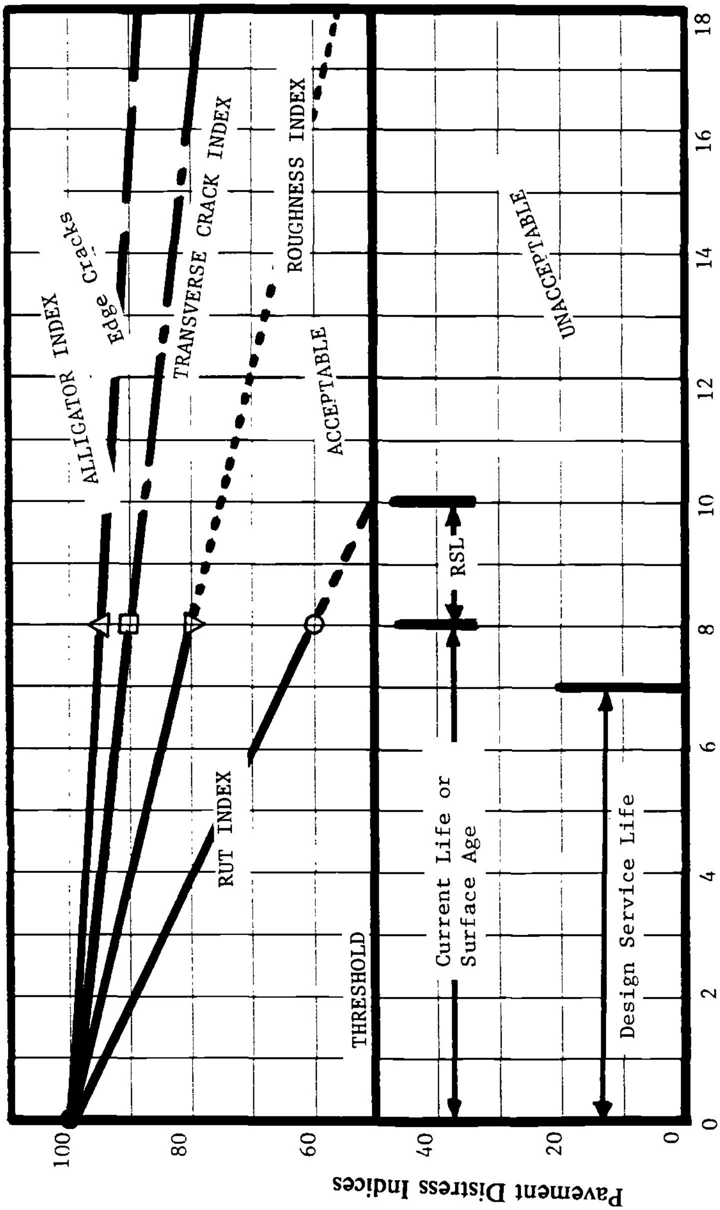

Figure 3. Straight line performance curves for various distress indices.

That is, according to the SHA engineering criteria and the straight line deterioration assumption, it is predicted that this pavement section needs to be rehabilitated for rut failure in 2 years. This information alone can be used to place that section as a candidate project on the 2-year work plan. For the recommendation of feasible rehabilitation alternatives or for cost estimate purposes, the engineer must examine the severity and extent of the other distress indices. It should be noted that it is not intended to recommend a straight line deterioration curve. However, if a SHA does not have historical distress data, then a straight performance line could be used as surrogate. The straight line can be modified as historical data become available.

Example 4 - For another pavement section (same SHA engineering criteria as in example 3), the PMS databank contains the following data:

Distress Type	Historical Distress Index				
	1983	1985	1987	1989	1991
Rut	100	85	72	65	60
Alligator cracks	100	100	99	98	95
Transverse cracks	100	100	98	95	90
Roughness	100	95	90	80	65
Edge cracks	100	100	100	94	90

Estimate the RSL of that pavement section which has been in service for 8 years and was designed for 10 years.

Solution 4 - In this example (for each type of distress) a computerized curve fitting technique can be employed whereby a performance curve can be obtained based on the historical distress data. Figure 4 shows the best fit curves for the given values of the distress indices. Extending each curve to intersect the threshold value of 50, one can obtain the following RSLs:

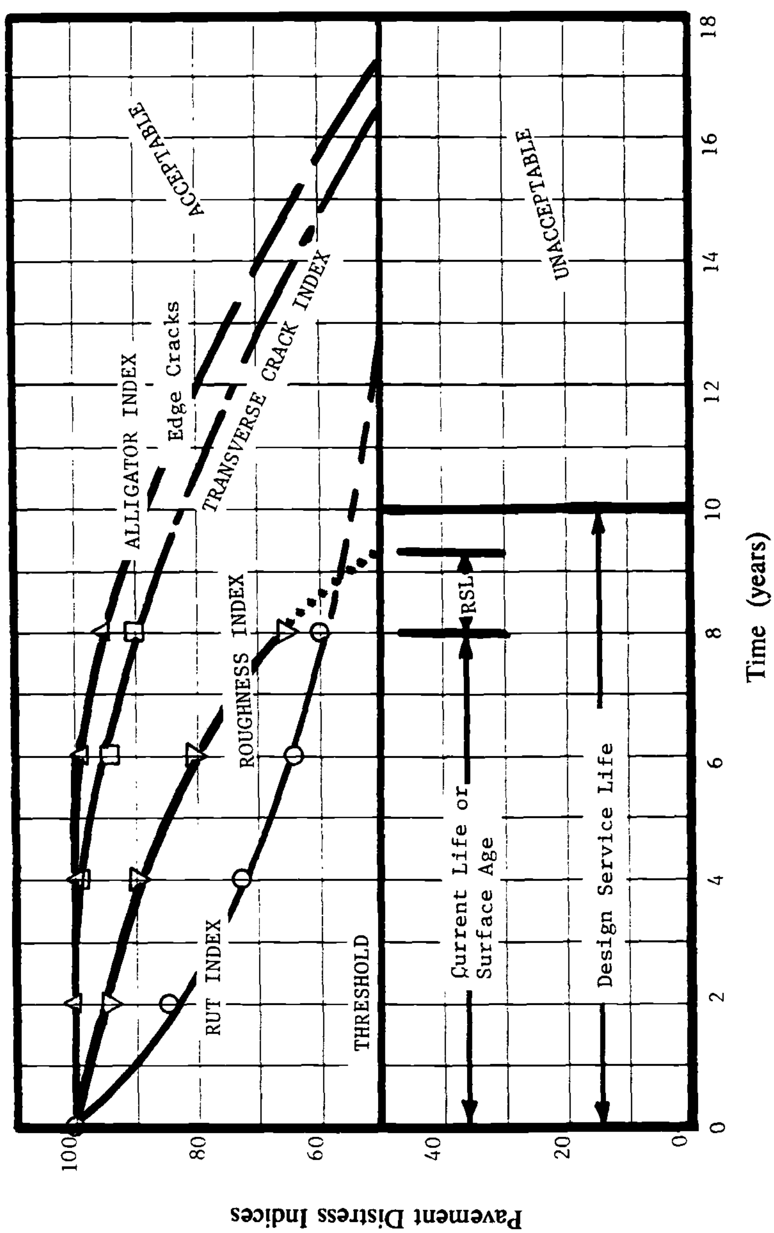

Figure 4. Performance curves based on historical distress data.

Distress Type	RSL (years)
Rut	5
Alligator Cracking	9
Transverse Cracking	8.5
Roughness	1.3
Edge Cracking	8.5

Overall RSL = 1.3 years.

Again, in accordance with the SHA engineering criteria, the pavement section needs to be rehabilitated for roughness in 1.3 years. This information alone can be used to place that section as a candidate on the one- or two-year work plan. For the recommendation of feasible rehabilitation alternatives or for cost estimate purposes, the engineer must examine the values of the other distress indices. For this example, examination of the other RSLs or the values of the other distress indices suggests that a rehabilitation alternative can be recommended which will alleviate both the roughness and rut problems and extend the service life of the pavement by another 8 years (the RSL for transverse cracking). It should be noted that the predictive equation generated from each curve fitting technique must be updated on a yearly basis as more distress data become available. Hence, the value of the RSL for any pavement section is revised on the basis of the most recent condition data.

6.4 Uses of Remaining Service Life

As stated previously, for each distress type, the RSL concept combines the severity and extent of the distress and its rate of change. the RSL can be used to:

1. Estimate the RSL of the various pavement sections within the network, the weighted average of which is the RSL of the network.

2. Calculate the percent of the network in each RSL category to provide the distribution of the RSL of the network.

3. Detect at an early stage any unwanted (e.g., uneven) distribution in the RSL of the pavement network. For example, if the RSL of a large percent of the network is 5 years, then the SHA should expect the work load to increase within 5 years unless something is done to even-up the distribution.

4. Assist the SHA in determining the type of distress that controls pavement performance. That is, if the RSL of the various pavement sections is mainly controlled by one distress type (for example, alligator) then the pavement design and the asphalt mix design processes need to be examined.

5. Estimate the average short- and long-term benefits of rehabilitation actions that are required to keep the health of the network at, or to improve it above, a certain level. For example, a 13,000 lane-miles network will lose 13 000 lane-mile-years of RSL for each year of service. If the rehabilitation program causes the network to gain only 12,000 lane-mile-year RSLs, then the network will experience a net loss of 1 000 lane-mile-year. Hence, the RSL of the network can be used as an objective function in determining network needs

6. Select an optimum rehabilitation strategy based on maximizing the average RSL of the network or on adjusting the distribution of the percent of the network in the various RSL categories to a desired one.

7. Generate one-year and multi-year rehabilitation programs based on network performance and available funds and assess the impact of each program on future work loads and future pavement condition, and the impact of various budget levels on network performance.

8. Enhance communication with legislators concerning network needs.

9. Control future conditions and funding requirements of the pavement network.

10. Estimate what percent or the number of lane-miles of the network that will be substandard in the future for the given and projected revenues and for any given rehabilitation program.

11. Provide the SHA with a link between their annual rehabilitation program's strategy, its cost, and the network's performance (17, 18).

12. Develop optimum rehabilitation strategies to control future network condition by using the average RSL of the network and its condition (17 through 21). The strategy can be developed in terms of lane-miles of pavement to receive certain improvement in its RSL without the need to deal with specific projects. This allows the agency to: a) exercise maximum flexibility in selecting specific projects that meet the optimum strategy; and b) keep its existing practices regarding rehabilitation program development yet, meet the requirements of the new FHWA policy.

6.5 Discussion and Limitations of RSL

The concept of RSL is based on the policy, objectives, and engineering criteria of the SHA. The engineering criteria must address in a balanced way the various distress types. As is the case with any calculation routine, inaccurate, incomplete, or erroneous inputs or criteria will lead to erroneous RSL estimates. In this regard, the RSL concept does not apply to all distress types. For example, reactive maintenance items (e.g., pothole filling and blowup of rigid pavements) should not be included in the calculation of RSL because they require immediate repair. These distress occurances should be treated in the agency's reactive maintenance program.

To illustrate the limitations of distress indices and the uses of RSL, two case studies are presented in the next sections.

7.0 CASE STUDY NO. 1

The highway agency in this case study calculates four pavement indices: roughness index (ROI), cracking index (CRI), rut index (RI) and a combined pavement index (CPI). Each index is based on a scale from 0 to 100 (100 = excellent). The threshold value for all indices is 40. The rating scale implies that any pavement section with an index value of less than 40 is rendered unacceptable. The calculation of the combined pavement distress index (CPI) is based on the following equation:

$$CPI = 0.6(ROI) + 0.25(CRI) + 0.15(RI).$$

The surveying data collected on a ten year old Interstate pavement section are:

1. Roughness = 98 in/mile.
2. Cracking = 30% of the section at low severity; 15% at medium severity; and 2% at high severity.
3. Rut = 0.75 inches.

Based on equation 2, the Present Serviceability Index (PSI) and the roughness index (ROI) are calculated as: PSI = 3.8.; ROI = 76.

Based on the agency formula, the cracking index (CRI) and the rut index (RI) were calculated as: CRI = 75. RI = 25.

Using the combined index equation yields:

$$CPI = 0.6(76) + 0.25(75) + 0.15(25) = 68.1.$$

The first important observation that can be made is that the CPI value indicates a good rating while the RI indicates a poor rating. That is, although the pavement section has failed as far as rut is concerned, the combined index shows the section to be in a good condition. Because the Agency uses the CPI for prioritizing and selecting those pavement sections in need of repair, the priority of this section will be low, and it will not be selected.

The second observation that can be made is that even if the CPI value is low and the pavement section is selected for rehabilitation, then it is highly likely that the cheapest rehabilitation alternative which will maximize the value of the CPI would be selected. Such an alternative is a rut depth patching and a thin overlay. Although the short-term benefits of a thin overlay is high, the long-term benefits based on the rate of deterioration is low. Hence, the selection of feasible rehabilitation alternatives based on the value of the CPI alone does not allow the highway engineer to assess the long term benefits and/or cost. The value of the CPI and the rate of deterioration need to be examined prior to the selection of rehabilitation alternatives.

Using the RSL concept relative to each distress type and assuming a straight line deterioration curve (no historical distress data is available) yields:

$$RSL_{roughness} = (10)(96 - 40)/(100 - 76) = 15 \text{ years.}$$
$$RSL_{cracking} = (10)(75 - 40)/(100 - 76) = 14 \text{ years.}$$
$$RSL_{rut} = (10)(25 - 40)/(100 - 25) = -2 \text{ years} = 0.0 \text{ year.}$$

The overall RSL = 0.0 year.

Hence, the RSL of the pavement section is 0.0 year (i.e., in need of immediate repair). In addition, if the selected rehabilitation alternative includes rut depth patching and a thick overlay is designed to last for 2 years, then the RSL of the section after rehabilitation is 14 years. That is, the short-term (improved distress index) and long-term (14 years of additional life) benefits of the rehabilitation activity can be properly assessed and designed to be compatible with the performance characteristics of the pavement section.

8.0 CASE STUDY NO. 2

In this case study, the highway agency calculates 13 itemized pavement distress indices, 3 combined pavement distress indices and one overall pavement index (OPI). Each index is based on a rating scale from 0 to 100 (100 is best). Table 2 provides a list, definitions, and equations for the calculation of the roughness index, the combined pavement indices, and the overall index. Further, the agency has established three levels of pavement repairs based on three predetermined values of the distress indices as follows:

1. When the values of all indices satisfy the values listed under "R.M. ALL" column heading in table 2, then routine maintenance (R.M.) activities should be taken.

2. When the values of all indices satisfy the values listed under "PRES. ALL" column heading in the table, then preservation activities need to be taken.

3. When the value of one or two indices satisfy any one or two values listed under "4R 1/2" column heading in the table, then rehabilitation activities need to be taken.

Table 3 provides a list of distress data collected for 3 flexible pavement sections. For each section and for each type of distress, the deduct value is listed in the table. The values of the various itemized distress indices (each value is equal to 100 - deduct value) were also calculated for all the sections and are listed in the table. In addition, for each pavement section, the values of the combined pavement distress indices and the overall index are listed in the bottom half of the table.

The agency uses the value of the overall pavement distress index to recommend those pavement sections in need of repair. The other indices are then used to establish the type of repair. The agency's procedure is summarized below.
used to establish the type of repair. The agency's procedure is summarized below.

1. All pavement sections are first prioritized relative to their OPI rating. A pavement section with the lowest OPI is given a top priority.

2. After prioritization, a few pavement sections with the highest priority are selected for repair actions. The number of selected sections depend on the available budget. All other sections are deferred until the next year's analysis. That is, no further analysis is conducted on any of the remaining pavement sections.

3. The values of the combined indices of only those selected pavement sections are then examined to determine the type of repair actions (routine maintenance, preservation or rehabilitation) that need to be taken.

4. After determining the repair action for each selected pavement section, the values of the itemized distress indices are then examined, and specific repair action or actions are then recommended.

Based on the agency's procedure, the three sections of table 3 will have low priority (high OPI ratings) and they will not be selected for any action. Examination of the distress data indicates that section 1 (not recommended for

Table 2. Distress indices and threshold values for case study number 2.

SYMBOL	INDEX	INDEX LEVEL FOR		
		R.M. ALL	PRES. ALL	4R 1/2
	ITEMIZED DISTRESS INDICES			
IRI	INTERNAT. ROUGHNESS INDEX (IN/MILE)			
RI	RIDE INDEX	>70	>60	0<RI<60
ACI	ALLIGATOR CRACKING INDEX	>85	>60	<60/ -
EDI	EDGE DETERIORATION INDEX	>80	>45	- /<45
EPI	BITUMINOUS PATCHING INDEX	>75	>30	<30/ -
PI	POTHOLE INDEX	>80	>40	- /<40
TLCI	TRANSVERSE/LONGITUDINAL CRACKING INDEX	>80	>25	<25/ -
BCI	BLOCK CRACKING INDEX	>70	>45	<45/ -
RUTI	RUT INDEX	=100	=25	=0 / -
WDI	WIDENING DROPOFF INDEX	>70	>55	<50/=55
EAI	EXCESS ASPHALT INDEX	>75	<75	- / -
RWI	RAVELLING AND WEATHERING INDEX	>75	>40	<40/>40
PDI	PROFILE DISTORTION INDEX	=100	=50	- /=0
SDROPI	SHOULDER DROPOFF INDEX	-	-	-

COMBINED PAVEMENT DISTRESS (case study number 2)

STRUCTURAL INDEX = SI = 0.3(ACI) + 0.2(EDI) + 0.25(BPI) + 0.2(PI) + 0.05(PDI)

SURFACE DISTRESS INDEX = SDI = 0.1(EAI) + 0.13(RWI) + 0.2(BCI) + 0.25(TLCI) + 0.05(EDI) + 0.12(WDI) + 0.15(RUTI)

SAFETY INDEX = SFI = 0.15(EAI) + 0.1(EDI) + 0.15(PI) + 0.1(WDI) + 0.1(PDI) + 0.2(RUTI) + 0.2(SDROPI)

OVERALL PAVEMENT INDEX (OPI) (case study number 2)

OPI = 0.45(RI) + 0.09(ACI) + 0.075(BPI) + 0.0675(PI) + 0.05(TLCI) + 0.04(BCI) + 0.04(RUTI) + 0.029(WDI) + 0.0275(EAI + 0.026(RWI) + 0.02(PDI) + 0.01(SDROPI)

WHERE RI = ROUGHNESS INDEX = 20{11.16 - 4.06LOG[(IRI+80.19)/2.3734]}

Table 3. Distress indices for three pavement sections calculated using case study number 2.

EXAMPLE
CASE STUDY NUMBER 2

DISTRESS DATA, FLEXIBLE PAVEMENTS

DISTRESS	SYMBOL	DEDUCT VALUES			DISTRESS INDEX		
		1	2	3	1	2	3
EXCESS ASPHALT	EAI	5	5	0	95	95	100
RAVELLING AND WEATHERING	RWI	2	2	0	98	98	100
BLOCK CRACKING	BCI	10	10	0	90	90	100
TRANS./LONG. CRACK	TLCI	10	10	0	90	90	100
ALLIGATOR CRACKING	ACI	5	5	0	95	95	100
EDGE DETERMINATION	EDI	10	10	0	90	90	100
BITUMINOUS PATCHING	BPI	0	0	0	100	100	100
POTHOLES	PI	5	5	0	95	95	100
WIDENING DROPOFF	WDI	10	10	0	90	90	100
PROFILE DISTORTION	PDI	0	30	0	100	70	100
RUTTING	RUTI	100	0	0	0	100	100
SHOULDER DROPOFF	SDROPI	30	30	0	70	70	100
IRI (in/mile)	IRI	80	150	60	N/A	N/A	N/A
ROUGHNESS = 20{11.6 - 4.06LOG[IRI +80.19)/2.374]}	RI	-	-	-	75	62	79
STRUCTURAL = 0.3ACI+0.2EDI+0.25BPI +0.2PI+0.05PDI	SI	-	-	-	96	92	100
SURFACE DISTRESS = 0.1EAI+ 0.13RWI +0.2BCI+0.25TLCI+0.05EDI +0.12WDI+0.15RUTI	SDI	-	-	-	78	93	100
SAFETY = 0.15EAI+0.1EDI+0.15PI +0.1WDI+0.1PDI+0.2RUTI +0.2SDROPI	SFI	-	-	-	71	83	100
OVERALL INDEX = 0.45(RI)+0.3(SI)+ 0.2(SDI)+0.05(SFI)	OPI	-	-	-	81	78	91

any action) has failed due to 1 inch of rut depth. Yet, no corrective action will be taken unless the analysis procedure is designed to flag each distress type that falls below the threshold criteria. Indeed, relative to the given 3 sections, section 1 will be given the second priority (OPI = 81), while section 2 will be given the highest priority (OPI = 78).

Furthermore, the distress data for section 3 of table 3 indicates that an action (2-inches overlay) has been taken that caused the values of all distress indices to be 100. Yet, none of the indices indicate the design life of that action or the type of action that has been taken. That is, if the rehabilitation action was a 1-inch or 5-inches of overlay, the values of all the indices would still be 100. This illustrates the continuous need for PMS engineers to examine all the data and put it into its proper perspective.

For the pavement sections in table 3, if the concept of RSL is used, then the RSL of section 1 is zero because of the severe rutting distress. The RSL of section 2 would be based on the lowest value of the distress indices (shoulder dropoff and profile distortion), and the RSL of section 3 would be the design life of the 2-inch overlay that was undertaken. Hence, section 1 will be recommended for repair. That is, using the RSL concept, some of the limitations of using the distress indices are eliminated. In addition, the benefits of each repair action of each pavement section can be evaluated based on the number of years of RSL that are gained by the repair action.

Note that, if the RSL of each pavement section is known, then the percent of the pavement network in each RSL category can be determined. This information allows the highway agency to examine the work load of future rehabilitation programs and to control future network conditions so that the annual work load does not vary drastically from year to year. This important information cannot be obtained unless distress data and their rate of change are used.

9.0 SUMMARY

The calculation of pavement distress indices must be based on the policy, objectives, and engineering criteria of the SHA. For each pavement section, if historical distress data are available, then they can be used to determine the rate of pavement deterioration and predict future pavement performance.

The use of the pavement indices for prioritization purposes, estimation of the benefits of the various rehabilitation alternatives, or for strategy selection may be misleading and should be conducted with care and full knowledge of their limitations.

The RSL concept can be used to estimate the performance of the pavement network and its constituent sections. The RSL can be used to determine the short- and long-term benefits of the rehabilitation program, to estimate the trends of the network condition, to produce balanced one-year and multi-year programs, to estimate future network conditions, to control future distribution of the pavement condition, to enhance communication at the engineering, management, and legislative levels, to evaluate the strategies of the SHA, and to recommend the optimum rehabilitation strategy.

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ADDRESSING INSTITUTIONAL BARRIERS TO IMPLEMENTING A PMS

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ABSTRACT: Pavement management systems (PMS) are not being adopted and implemented at the rate expected. Many factors reducing the implementation can be attributed to barriers related to institutional issues. Diffusion of innovation studies help describe these barriers. They can also be used to help develop methods to remove or bypass the barriers.

KEYWORDS: pavement management, barriers to implementation, diffusion of innovations, infrastructure management

Pavement management systems (PMS) have been available for several years. Although several agencies have adopted a PMS, there are many more agencies that should be using a structured PMS. Several agencies that have adopted a PMS use only part of the capabilities available to them. Some agencies that implemented a PMS discontinued use after some period of time.

In the San Francisco Bay Area, the Metropolitan Transportation Commission (MTC) has supported the development and implementation of a PMS for Bay Area agencies since 1984 [1]. The support has included training in implementation, on-call assistance during implementation, on site assistance during implementation to address special problems, assistance with preparing budget needs and requests, and assistance in presenting budget information to the funding authority. This has provided an opportunity to be a part of the implementation process, to observe the use of the PMS by the agencies, to determine what barriers have prevented partial or full implementation, and to develop approaches to address these issues.

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Diffusion of innovation concepts in organizations were investigated to find available guidance to assist with the problems of developing and implementing new management techniques within existing organizations. MTC used these approaches to structure the training and support system provided by MTC to agencies in the Bay Area. Although this has not eliminated all institutional related problems, it has helped to provide an approach that should minimize the effect of the existing barriers and prevent development of others.

BARRIERS

A barrier can generally be described as a barricade, obstruction or anything that prevents advance. Barriers can limit, obstruct or prevent PMS implementation. Full PMS implementation occurs when the PMS process becomes the standard method of managing the pavement system in the agency. There are many different types of barriers that can affect PMS implementation. In the early years of PMS implementation and development, some of the most important barriers were technical; the PMS concept was not well developed and the analysis techniques required considerable research to find those that were most helpful. Most automation of analysis techniques was completed on mainframe computers that were both cumbersome to use and often difficult to access. Software development was time consuming and expensive. However, over the last several years, the microcomputer revolution has changed access to computers and created a more friendly computational environment. The state-of-the-art in PMS analysis techniques has advanced to such a level that many of the technical problems have been solved, or the approaches to solving them have been identified. Many of the most troublesome barriers to implementation are now people related. Some of these people related barriers are built into the organizations into which the PMS must be integrated.

The following describes several problems that have been encountered by the author in work with MTC or other pavement management implementation efforts. Each defines a category into which the barriers have been neatly fit. Any one of these can prevent implementation or limit use; however, more than one of these barriers may be encountered simultaneously. These categories are only helpful in understanding the reasons behind the barriers so that methods to remove or bypass the barriers can be developed.

Fear of Exposure: Pavement management systems provide structured information that often is not widely available prior to the implementation. Those who have been making decisions with less than complete data may resist implementation of a PMS because they fear that the PMS will show that their decisions were incorrect or less accurate than they have previously stated. In the Bay Area, one public works director, who had supported implementation of PMS, stopped the agency from using the PMS when the results indicated that the agency needed considerably more funding than he had been requesting over the previous several years. He made a statement similar to, "I am not going to tell my board that I have been a poor manager over the last several years. I am retiring in two years, and I won't change my requests during that period."

Turf Protection: A PMS provides information and analysis procedures that often cross several formal and informal lines of authority and communication within an organization. It provides information on planning for funding needs, programming sections of pavement for both maintenance and rehabilitation, selecting sections of pavement for maintenance and rehabilitation, and determining the impact of funding decisions on the future condition of the network and future funding needs. Information is power in an organization, and access to information may influence who has the formal, or informal, power to make decisions. This often affects the decisions currently being made by planning, maintenance, design, operations, and administrative groups within a single organization. When a PMS is implemented in a unit of the organization, or in a newly formed unit, the remaining units within the organization often feel threatened by the new power of the PMS operating unit. They may resist implementation of a PMS to prevent a perceived loss of power. There have been several instances where the engineering group within a public works department adopted a PMS without the concurrence of the maintenance group that generally made the selection of projects which would be programmed for maintenance and rehabilitation. The maintenance group then refused to use the results of the PMS, and the PMS was either used at an inefficient level or was discontinued. In one agency, the maintenance personnel threatened to go on strike when the agency head tried to adopt a PMS, because they thought the PMS program would make all of the decisions for which were responsible.

Organizational Level: Since a PMS provides new information affecting many major operating units within the organization, new communication channels, both formal and informal, must be established. When the PMS operating unit is buried deep within the organizational structure, it is difficult for the PMS engineer to communicate and have access to all of those affected by the implementation of the system. Many times, the PMS engineer is relegated to communicating with those on the same pay scale due to protocol and tradition within the organization. Those at the same pay scale as the PMS engineer in other operating units are far enough down the organizational hierarchy that they have little impact on the actual decision making process. This may result in the development of new informal communication channels; however, it may also hinder the full implementation and use of the PMS because the real decision makers are not getting or not using the information prepared by the lower operator in another unit. In at least one case, the PMS engineer was placed low in the public works structure. Another operating group within the organization controlled most of the construction and maintenance history for the pavement network. That group set up restrictions that only their personnel could access those records. When the PMS engineer asked that this information be retrieved and placed in the PMS data base, the other group stated that they had other priorities and would not be able to retrieve the data or move it to the data base.

Black Box PMS: The "black box" approach to PMS tries to get the user to place his trust in some magic system or program. The PMS software is considered a "black box" when it provides recommendations but the rationale behind the recommendations is not known. In some cases, proprietary systems were developed in which the developer purposely refused to describe the programmed analysis procedures. In PMS, many early systems described the computer software as a PMS when in fact PMS is a concept that must be adopted by the entire organization and the software is a decision support tool. Some public works engineers selected a computerized PMS software with the understanding that it would provide all of the decisions needed for maintaining their pavement network. They could proudly point to the output of the program and state, "The computer told me to do it" when questioned about their decisions. However, they often did not know the reasoning behind the computer generated programs. When the programs could not be carried out as the computer instructed, the systems were often discontinued.

Complexity: In some cases, the PMS decision support software has been so complex, or poorly documented, that the user could not understand the concepts used in the system and could not explain them to others. When the public works department took the recommendations to the council, they could not explain the basis for programming specific streets for rehabilitation or the justification for selecting sections for preventive maintenance. The council would not accept the public works department's recommendations, and the PMS was discontinued.

Matched to Agency Needs: PMS decision support software can provide recommended programs for maintenance and rehabilitation. It can also assist in providing support for funding requests. Some agencies have implemented a PMS on the assumption that they could use the results to assist in justifying their budget requests only to find that the software only provided assistance in selecting sections needing maintenance and rehabilitation. They then discontinued the use of the PMS or used it at a lower level than could have been provided by the PMS. In other cases, when the agency tried to evaluate the PMS software generated recommendations to prepare a final program, they found that the pavement sections, cost units, and treatments used in the PMS decision support software did not match their management process. The manual effort to make the PMS software generated recommendations match their normal management process was so massive that the system was abandoned. In other cases, the cost to maintain the system was so large that it could not be justified, and the agency discontinued use.

Competing Funding Needs: Almost every agency has more funding needs than resources, and there are always many competing funding needs. Funds are needed for pavements, bridges, airfields, transit, and many non-transportation related needs. Often, funds are diverted to the element that has the highest visibility. In the Bay Area, when a sewage treatment plant overflowed into a well known river, the public works director of the responsible agency was fired and PMS implementation efforts were effectively abandoned. Those who have spent considerable energies to adopt, develop, and implement a PMS only to see the results ignored because other more visible needs are the current hot item, often become discouraged and discontinue use. When reactive management controls decision making, even in the presence of engineering management systems such as PMS, the PMS users come to feel that planning in the agency is an "exercise in futility." It is then difficult to get any management approach adopted in the organization.

One Person Show: Several agencies have invested their PMS experience in one or two people in the organization. Often, PMS is only one of several responsibilities of the PMS engineer. The PMS engineer positions often are at a relatively low pay level so the individual will only stay for a limited time. When a transfer within, or job change outside, the organization or a promotion then moves that person from the responsibility for PMS, it may take several weeks to several months to replace the person. In one agency, the position was vacant for over eighteen months. By the time the position is filled, the PMS experience from the preceding PMS manager is often lost. The new person must start over on much of the system. In some cases, the new person did not like the old system and started PMS implementation again from scratch. In other cases, the new individual did not place the same emphasis on PMS as the predecessor, and the system became dormant or was lost. This problem is one of the most troublesome found. In one agency over period of three years, one PMS engineer died and two left for positions outside the agency.

If It Wasn't Developed Here, It Can't Be Any Good: A few agencies refuse to use anything that was not thought of or developed within the agency. Because of the, "if it wasn't developed here, it can't be any good" approach, they invest excessive amounts of money in developing a PMS when they could have used an existing system with a few relatively inexpensive modifications. It is true that almost every public works or highway agency is somewhat differently organized than the others; however, they all have similar requirements to provide the using, and funding, public with the best return on the funds provided the agency. Some customization will be necessary in almost any implementation. However, the basic elements in a PMS are similar. The components from one agency can often be modified to allow use in another agency.

CURES FOR BARRIERS

There are no magic solutions to remove or bypass all barriers. Some can be removed or replaced by improved communications and education. Others can only be removed by moving or replacing the individual who is creating the barrier. However, there are several general guidelines that can be used to minimize the development of barriers and remove, or at least reduce the impact, of others. One of the most important steps is to develop the innovation, in our case the PMS, to minimize the uncertainty with which it is viewed by the adopter. Another important factor is to understand the reasons behind the barriers and to develop an approach that will minimize the development of factors which create barriers. One place to start is with diffusion of innovation concepts.

There is a wide gap between what is known and what is actually used in many fields [2]. Engineers tend to be optimists and assume that when a better mouse trap is available, it will be adopted. However, getting a new idea, method, or approach adopted and used is often very difficult, even when the advantages are obvious. Diffusion of innovations is the study of how new ideas are developed and implemented. Most of the diffusion of innovation research has been conducted by anthropologists, geographers, and sociologists [2]. More recently, people in economics, marketing, political science, communications, education, and engineering have conducted research in the area [2, 3, 4, 5] or in the related field of technology transfer [6, 7, 8, 9, 10, 11, 12]. These studies help explain not only why many new, good ideas are not used but also how to increase the likelihood of adoption of an innovation [2].

Innovations

An innovation is an idea, practice, object, or product which is perceived as new by the potential adopters. It not the actual newness of the innovation but rather the perception of newness to the potential adopter that influences adoption and use. The PMS concept may have been available for years, but if it has not been used in the particular agency, it is new to that group of potential adopters. All innovations are dichotomies; (1) they are adopted to resolve an uncertainty by providing a solution to a perceived problem; however, (2) they create uncertainty because of their newness and the unknowns of the expected outcome from using the new technique or procedure. In the pavement arena, managers are asked questions such as: what can be cut from the pavement budget; how will the condition of the pavement network be affected by the proposed budget cut; how much money should be allocated to preventive maintenance of pavements; how much money should be allocated to maintenance and rehabilitation over the next five years; and how will the proposed funding level affect the future network funding needs? These questions create a problem because it has been very difficult to answer most of them with any level of accuracy. PMS is an innovation developed to help quickly answer these questions with improved accuracy. However, some road, street, and highway managers fear that the PMS will either diminish their authority or completely replace their position with a computer. Others have heard of the problems another agency encountered in adopting a PMS, and are afraid that if the implementation fails, their professional standing will be diminished. These situations create considerable uncertainty concerning adopting a PMS.

The Diffusion Process

Diffusion is the process by which an innovation is communicated over time and space. Uncertainty is associated with newness, and information is used to reduce uncertainty through communication. During communication the participants in the process create and share information to reach a mutual understanding concerning the innovation. The understanding can lead to acceptance or rejection at any point in this process. The communication is carried out by members of a social system (or organization) through communication channels. The channels can be formal channels established to communicate information concerning the innovation, or they can be informal channels [2]. In an organization, especially a bureaucratic organization, the informal channels are often more important than the formal channels. Information flow through these informal channels can often determine the success or failure of an innovation implementation.

Social System

The social system is the domain that sets the "norms" of the arena into which the innovation is being introduced. These norms define the range of tolerable behavior and serve as a standard against which ideas are judged. Diffusion of an innovation is a type of social change, and the existing "norms" are sometimes barriers to change. Innovators are often perceived as deviants because they adopt new ideas that do not match the norm. The set of interrelated units engaged in joint problem solving forms the social system in innovation diffusion. For PMS implementation, the social system is the highway, road and street arena. The arena includes the organizations within which the actual implementation occurs and those that communicate information about the area of interest. These include the actual highway, road and street agencies, the Federal Highway Administration, Transportation Research Board, ASTM, AASHTO, APWA, and ASCE among others. Each agency within that system has a more defined structure, and it is within these agency structures that the "norms" which become barriers are most important to define. The structure of the social system is the arrangement of the units in the system or organization, and this structure influences the communication channels that must be used or established. The more bureaucratic organizations often have significant informal lines of authority in addition to the formal lines. These set up the power base that defines the "turf" which tend to resist changes that might actually, or appear to, change the lines of authority.

Opinion leaders are members of the social system who have become informal leaders based on perceived technical competence, social accessibility, and conformity to the system norms. They are generally the center of the informal interpersonal communication network in the organization, and they have a major impact on the adoption of innovations. If the opinion leader of an agency decides that PMS is something that should be adopted, it often will occur. However, if the opinion leader is opposed to PMS, it generally will not be adopted. If the PMS is forced on the agency from a top-down decision against the wishes of the opinion leader, it will probably not be fully used, or it will be discontinued shortly after the top-down pressure is removed.

Diffusion agencies such as government agencies or marketing firms are sometimes established or used to encourage adoption of new ideas considered beneficial to the agency [2]. They try to increase communication and influence the opinion leaders, often using a change agent. A change agent tries to influence the agency to adopt the innovation. The FHWA, APWA and MTC have been acting as change agents for PMS.

The innovation-decision process is an information seeking and information-processing activity in which the potential adopter seeks to reduce uncertainties about the innovation until the advantages of the innovation outweigh the disadvantages. If this is not achieved, the innovation is rejected. The PMS should be structured to maximize the advantages and minimize the disadvantages reducing the uncertainties.

Characteristics of Innovations That Affect Adoption

Several characteristics of innovations have been identified that influence the potential for adoption [2]. During the development and customization of a PMS, careful attention to these characteristics can reduce the resistance to the PMS. This can be considered proactive development. The development and implementation are organized to provide the greatest potential for adoption, implementation, and full use while minimizing barrier development.

Relative Advantage: Relative advantage is the degree to which the innovation is perceived to be better than the process it is to supersede. The greater the perceived advantage, the more likely adoption is to occur. The advantage can be in terms of monetary benefit, such as the ability to repair more pavements with available funds, or it can be in terms of non-monetary benefits such as the ability to more objectively answer the city council or county board questions. The goals in PMS should be both monetary and non-monetary. The pavement managers are constantly being asked to "do more with less." By structuring the PMS to better allocate funds for pavement maintenance and rehabilitation, saving the department money with little or no increase in engineering effort, it provides a monetary advantage over the existing approach. However, cost savings must be carefully described. In general, an agency will not see cost savings in terms of reduced funding requirements. When the funds are spent more effectively, reducing the funding needed to keep the pavement system in the desired condition level, those "saved funds" are then diverted to some other unmet need. In one agency, the maintenance forces are now able to mow more right-of-way because of reduced pavement maintenance; however, the overall funding of the agency has not been reduced. Savings in user costs may be a better method to document savings than agency costs. By structuring the PMS to provide quick and accurate answers to the "what if" questions that are common at budget time, it provides an advantage to the manager by making him appear more responsive and knowledgeable. The problems associated with innovations being rejected or not fully matched to the agency needs can be eliminated or reduced if the developers carefully determine the needs of the agency and develop the PMS to match the needs at all levels and in all operating divisions.

In the San Francisco Bay Area, a thorough study of the agency needs was conducted to determine the PMS needs of potential users. In some cases, the agencies did not always understand their needs; however, as they used the PMS, they developed an understanding of what the PMS concept could provide and requested additional assistance from the PMS decision support software. All development was completed under the guidance of a select group of public works personnel. This insured that the decision support software was directed at their needs.

Compatibility: Compatibility is the degree to which the innovation is perceived to be consistent with the current process, existing values, experience, and adopter needs. The more compatible, the more likely adoption will occur. In terms of PMS, the system that fits into the current structure of the managing organization and complements the current style of management by providing a tool for the managers to use in making decisions and answering questions is more likely to be adopted. The system that requires restructuring the organization will likely be very difficult to get adopted. If the current decision making is decentralized, it will be much easier to get the PMS implemented if it supports the decentralized decision making process. By providing each user with the support needed within the current organizational framework, the turf problem is minimized. When the PMS decision support system matches the agency structure, the system will more likely match the agency needs and will appear to be less complex to the potential adopter. When system analysts and programmers start trying to force the structure to fit their decision support programs rather than making the programs fit the organization, it is time to find new system analysts and programmers. The system that provides the answers in terms familiar to the decision makers will be perceived as more compatible. The decision support software should produce reports and graphics which match those currently effectively used by the agency. The system that collects and uses mostly data that the agency is already collecting will be considered more compatible. All of these will reduce the uncertainty associated with the PMS and help minimize barriers. It requires PMS development, work, and implementation committees or work groups. They should be formed to include all of those who will be users and affected in any way by the PMS. They should meet regularly and have a say in the actual development and implementation process. It requires a commitment of time, effort and patience to work with the committee and work groups, but it is necessary to get the "buy in" of those who are will be the users. It reduces the resistance to later implementation and use.

In the San Francisco Bay Area, the entire development was conducted under the guidance of a group of PMS users. As each component was developed it was reviewed by the task group, and the concept was approved, modified, or rejected. After it was programmed into the decision support software, they pilot tested the software. As the Bay Area PMS became more accepted, MTC started holding quarterly user meetings. All users are encouraged to attend these meetings. This allows interaction with other users, information on the latest changes to be disseminated, and provides a forum for potential changes to be identified and approved. However, when major changes are to be made to the decision support software, or when new procedures are being developed, a small task group is formed from the users to guide this development.

In the San Francisco Bay Area, MTC has tried from the start to inform users and potential users that the Bay Area PMS is a "tool" that will assist them in decision making. They try to point out that the agencies are currently managing their pavements and that the PMS concept includes all of the personnel involved in pavement decision making. By developing the Bay Area PMS decision support software to match the current public works structure and showing how use of the system will improve efficiency rather than replace the existing system, the PMS is seen as less of a threat and more as an aid. This reduces problems of turf protection.

Complexity: Complexity is the degree to which the system is perceived to be difficult to understand and use. Ideas which are easier to understand are more likely to be adopted. The system that uses concepts and techniques that are familiar to the managers will be perceived as being less complex. With the availability of inexpensive microcomputers, concepts that can be completed by agency personnel on a hand-held calculator but would require computations too numerous for even a small agency are possible and will be perceived to be less complex. This provides the appearance of simplicity; although, the computer programs may be quite complex. Minimizing the amount of data that the system uses and the number of steps required to complete a task by the user causes the system to be perceived as less complex. Complexity is relative to the sophistication of the users and can be decreased by communication and training. Comprehensive documentation of the software and the operating concepts help reduce the appearance of complexity.

MTC established on-call assistance for users of the Bay Area PMS. An excellent set of users manuals was prepared that could be used at the executive level, the inspector level, the computer user level, and at a technical level. The decision support software was programmed with simple menu operating screens. However, many of the calls received are simple problems that are addressed in those manuals. The fact that the PMS operators can reach a human voice that can direct them to an answer, even if it is in the manual makes the innovation appear much less complex and more likely to be fully used.

MTC originally believed that the PMS could be developed and turned over to the cities and counties of the Bay Area. It soon became apparent that PMS decision support software is never really finished, because there are always improvements that the users would like. However, even more important is the training. An initial set of training was completed, but almost immediately, new users needed the same training, and before that was complete, new personnel in the original using agencies needed retraining. Of the six original using agencies, none have the original personnel as the primary PMS operators. In a few agencies, several different primary operators have been trained and replaced in a period of less than seven years. Support from a central agency appears to be a key method to overcome the problem of investing most of an agency's experience in a single person. To be effective the training must be sequential and repeated at intervals. It must be provided to each level and each component that is affected by the PMS to insure they understand the system as it affects them. This requires a commitment to long-term training and can be assisted by implementing an on-call support system from the operating unit to decrease the perceived complexity.

Trialability: Trialability is the degree to which an innovation can be experimented with or adopted in stages. New ideas that can be tried on a limited basis are more likely to be adopted. Implementation of a PMS requires considerable effort, time, and funds. The innovation champion who pushes for the implementation of a PMS invests much credibility in the process. If the system does not provide the desired results at the end of the implementation process, the champion may loose his credibility or even his position. The PMS that can be tried in a pilot program will be more acceptable because it can be tested without investment of the full set of effort or credibility. This can be accommodated by allowing a small portion of the network to be implemented. In addition, a system that is developed incrementally over time, making use of mostly existing procedures, will be considered more trialable as well as more compatible and less complex. The system that costs less and can be implemented primarily by in-house staff will be perceived as more trialable because it requires less investment of resources, especially those that are most easy to track.

In the San Francisco Bay Area, MTC development of the PMS was incremental. Existing systems were carefully evaluated, and the best available components were selected whenever feasible. Each participating agency was encouraged to start with only a portion of their network. This incremental development and implementation also reduces the perceived complexity of the PMS. The trial implementation also serves as a training vehicle. When full implementation commences, the PMS operators were already familiar with the system. The trial implementation allows the agency to determine the resources required to implement the system and permits reasonable implementation goals to be established. By fully using the PMS decision support software, the full impact of the PMS process can be assessed and all potential users can be identified. They can be brought into the evaluation and adoption decision making process that facilitates their "buy in" and reduces their turf protection potential. Those who have been making decisions in the past can start assessing the effect of the PMS on their past decisions and minimize the fear of exposure.

Observability: Observability is the degree to which results of the innovations are visible to others. The PMS decision support system that provides reports in a form that allows the user to show the results of his efforts to both his superiors and outsiders is both more compatible and more observable making it more likely to be adopted. The more visible the positive results, the more quickly the adoption will spread to other adopters.

In the Bay Area, MTC used trial implementation to get six agencies using the PMS decision support software quickly. An older maintenance supervisor in one county who had previously not used computers and originally felt that decision making belonged in the field with those "who knew their pavements" became involved with the PMS and was soon one of the best sellers of PMS concepts in the Bay Area. As agencies that implemented the Bay Area system were able to increase their funding through their agency general funds and increased gas tax at the county level, the visibility of the PMS helped entice other agencies to adopt and implement the system. MTC does as much as possible to help make the results of PMS success visible to the pavement arena.

Adaptability: Recently, especially for organizations adopting innovations, adaptability, which is the degree to which an innovation can be modified to meet individual differences in needs, has been identified as a positive influencing factor on adoption of innovations. Decision support needs can change over time, and the ability to modify the PMS decision support system to meet these changes is desirable from the point of view of the potential adopter. Many pavement agencies perceive that their organization is so different from all other agencies that they must have a different system. This difference is often less than the perceived difference; however, all agencies are slightly different and those differences should be accommodated by the PMS. The PMS must be flexible to allow changes without making the system unduly complex. This can be helped by using a standard data base manager as the base for much of the programming. Standard reports and analysis programs are provided as part of the PMS package; however, it provides the using agency with the flexibility of formatting and generating a customized report using the data base manager.

During the development of the PMS decision support software, MTC originally thought that they could release it to the users and get out of the PMS business. After a period of time it became apparent that the PMS decision support software would have to continue to evolve as the sophistication of the users increased and the needs changed. A process was instituted through the quarterly user meetings that allowed the users to define their needs and desired changes to the decision support software. New and improved reports, graphics, and map display capabilities were added. MTC provides continuing training to the users to insure that their level of sophistication matches the level of the PMS decision support software.

The Bay Area PMS decision support software has continued to increase in sophistication and capabilities. However, the user always has access to the data through a commercial microcomputer based data base manager. Several agencies use information from the PMS as the basis for related inventories such as sign inventories. MTC includes information on how to access the data in the data base as a part of their ongoing training activities for using agencies.

Overcoming Other Barriers

There are several steps that can be taken to overcome other barriers beyond those related to structuring the components of the PMS. One of the most difficult barriers is the organizational inertia that resists change and is allied with the fear of exposure. In several instances, PMS has been misunderstood or misrepresented. Several agencies have come to believe that a PMS will manage their pavements. This is very closely related to the problems of turf protection. In fact, the PMS software is nothing more than a decision support tool. The personnel in the organization are the real management system. They make decisions, the software only provides organized information that is used in the decision making process.

MTC has stressed this again and again. Proper communication concerning what should be expected from PMS software decision support systems is used to help resolve this problem. It is extremely important to show that the software packages are prepared to provide assistance to an experienced pavement engineer and that they provide support. In the hands of someone unfamiliar with pavements who follows the recommendations blindly, they can provide erroneous results. PMS software cannot replace a manager, it supports him in making more accurate, better supported decisions. MTC has decreased the resistance to PMS implementation by providing training for several levels of PMS efforts in an agency. This includes training and seminars on proper use of maintenance treatments, quality assurance, and specifications for maintenance and rehabilitation treatments. This approach creates an atmosphere in which PMS can be discussed in the context of how it helps make decisions about treatment selection and timing making it appear much less threatening to those who have made these decisions in the past.

Many turf protection and fear of exposure barriers can only be overcome with support from upper level management and a long-term commitment to using the PMS. The informal communication channels and may have to be altered, and this generally takes a long time. Structuring the PMS to address each operating component's needs will help minimize the development of barrier, but it cannot prevent some barriers from personnel in the organization who feel that new information and communication channels will undermine their real, or imagined, power. Upper management may be able to force the formal communication channels to function, but sometimes new informal channels which bypass the impediment may have to be developed. This is the same process that must be used to address those who intentionally block communication channels.

MTC has addressed this type of problem in the Bay Area by providing long-term support. When turf and fear of exposure barriers are encountered in a given agency, the MTC staff tries to work with the public works department personnel to provide training and on site briefings to introduce the PMS concepts to those who are creating the barriers reducing their fear of the concept. They work through the upper echelon management and through a network of similar level users in other agencies to help overcome the reluctance to using the system. In some cases, the only remedy to overcome a problem created by an individual high in the organization is to wait until that person is transferred or retired. MTC tries to monitor the situation and come back to provide assistance when it is appropriate.

The organizational level of the PMS section head can only be addressed by demonstrating the importance of PMS to the heads of the highway, road and street organizations. MTC has helped address this by having short, half day seminars, for public works directors and by developing a video tape addressed to the public works directors and elected officials. However, this will be a long standing problem that can only be corrected with considerable time and effort.

To address the problem of competition for funds, the PMS decision support software should be developed to justify funding needs in a manner similar to that used by other fund requesting groups. If the police department uses the number of patrols and crime level to justify their funding request, then the pavement needs should be justified based on the amount of streets that can be repaired and the impact on the condition of the street system. If the social services justify their funding request based on the impact on the economic health of city or county, then the pavement needs should be justified based its impact on the economic health of the agency. MTC provides assistance in the Bay Area by helping agencies develop their needs estimates and the impact of different funding scenarios on the condition of the pavement network, the backlog of funding needs, and the impact on future funding needs.

There is a constant personnel turn-over, especially in local agencies but also at the district level in state agencies. In the Bay Area, it is routine to have one or two new personnel show up at each quarterly user meeting who has just been assigned to the PMS position in their agency. When an agency's PMS system is a one person operation, the PMS is operator or champion dependent. If that person leaves the position, the PMS often is discontinued, or is at least less fully utilized. In the Bay Area, MTC addresses this problem with its continuous cyclic training programs. In addition, MTC provides on-call assistance to the users and provides on site assistance when it is needed.

SUMMARY AND CONCLUSIONS

Several barriers have been identified that are often related to the structure of a bureaucracy or an organization. These include: fear of exposure; turf protection; low organizational level; black box PMS; excessive complexity; not matched to agency needs; competing funding needs; one person show; and if it wasn't developed here, it can't be any good. Any one of these can prevent adoption of a PMS, prevent full utilization, or cause discontinuance. Understanding their impact and the causes will help determine methods to overcome them.

There are a number of concepts from diffusion of innovation studies that can be applied to the development and implementation steps of a PMS that will make it more likely to be adopted and implemented. These include relative advantage gained by the adopter, compatibility with the current processes, complexity of the process, trialability of the PMS, observability of the results, and adaptability of the PMS to the specialized needs of the agency.

Especially for local agencies, but also for the various elements in a state agency, training and a support structure are essential to the successful adoption and full use of a PMS. There are some barriers that can only be removed or bypassed with continuous training and effort over time. The constant personnel turn-over often leads to discontinuance of a PMS when the PMS is a one person show in the agency. This is a very common problem, and is thought to be one of the most common causes of discontinuance. Training and a support structure are necessary to identify the agencies with problems, get the replacements interested in continuing the operation of the PMS from the point left by the preceding operator, and bring the new person up to a training level to continue use of the PMS. Comprehensive documentation of the software, the operating concepts, and formal communication channels are essential. Without this support, many agencies discontinue use of the PMS.

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Per Ullidtz and Richard N. Stubstad

STANDARD ENGINEERING PRINCIPLES IN PMS APPLICATIONS

REFERENCE: Ullidtz, P. and Stubstad, R. N., "Standard Engineering Principles in PMS Applications," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: An essential element of any Pavement Management System (PMS) is its ability to correctly predict the future "condition" of pavements. When a new PMS is introduced to a highway agency, the likelihood of successful implementation and acceptance is strongly dependent upon how well future pavement condition, as predicted by the system, agrees with local engineering knowledge of those pavements. Highway engineers still play an important role in the implementation of a PMS. Modeling pavement performance is extremely complicated, and no PMS can consider more than a few of the parameters involved, and then only in a highly simplified manner, whether they be analytical or "expert" system techniques. In order to improve the objective engineering performance and avoid rejection of the system, it is suggested that the following capabilities should be included in any PMS:

- A PMS must be capable of predicting structural as well as functional deterioration. Materials in the pavement layers, and their degradation under the effects of time and loading, are of primary concern to those highway engineers responsible for the maintenance and performance of the pavement network. A system that empirically predicts "only" the future ride quality or user costs ignores one of the main engineering considerations, and may be rejected as being too subjective or "political". Currently accepted performance prediction techniques are usually applied at the project level for design purposes. At the network level, their application becomes somewhat more difficult, but now these difficulties can be dealt with.

- A method must be provided which uses predictive models tied to historical data as it becomes available in the specific PMS database, and for modifying these models so that the engineers' knowledge of local materials, environmental effects, construction and maintenance practices, etc., can easily be incorporated in the modeling procedure. In other words, predictive models based on sound engineering principles can be calibrated for a specific PMS application using historical data from the system itself. "Modeling" pavement performance by extrapolating future condition from historical data is a technically unacceptable simplification, however, because the effects of material degradation, maintenance, or rehabilitation measures cannot be considered. The engineering techniques for dealing with this new approach already exist and are applicable to a system-wide analysis. Statistical use of historical data (often of dubious quality) appears to be a poor substitute for engineering skill and the use of presently available analytical tools.

KEYWORDS: pavement management, standardization, mechanistic design methods, pavement evaluation techniques, pavement performance models

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INTRODUCTION

Planning is an important aspect of Pavement Management, both short tern planning or programming of activities and long term policy or strategic planning. To plan, predictions need to be made and goals need to be set. An important element of the planning process is the future pavement maintenance and rehabilitation of the existing roadway network. These activities often account for 20-30% of the total spending for a highway agency.

This paper deals with the problems associated with forecasting future pavement condition using fundamental, standard engineering principles. It is the belief of the authors that, when a new PMS is introducėd to a Highway Agency, the likelihood of successful implementation of this PMS is strongly dependent upon how well the future pavement condition, as predicted by the PMS, agree with the local engineers' and technicians' knowledge of their own pavements and materials. If the PMS is not in harmony with local engineering experience, it will not be accepted.

A large number of different pavement performance (or design) models are already available but — perhaps not surprisingly — given the same input (data) they tend to produce different output (predictions). One way to overcome this confusion is to "standardize" through the use of "threshold" values, but this must be done with great care. The attitude, "if we cannot do it correctly anyway, couldn't we agree to all do it wrongly in the same way?", can be rather harmful in the long run.

Only by basing pavement performance models on fundamentally correct and standard engineering principles, can reliable and acceptable models eventually be developed. It is equally important that these models are easily adjustable in accordance with available historical data and the engineers' knowledge of local materials, environmental effects, construction and maintenance practices, etc.

Reliable predictions of future pavement condition are important, but it is no less important how these predictions are used in the decision-making process. Enormous amounts of time and effort have been used by highway engineers on defining threshold values for skid resistance, rutting, and roughness, etc. One of the main objectives of Pavement Management is to reduce the overall costs to society of roadway transportation. Achieving this goal may very well be *prevented*, however, by using these threshold values. Here again, standardization must be handled with extreme care and must be based on general and sound principles rather than on specific elements.

This paper discusses both modeling of pavement performance and evaluation of the usefulness or utility of a pavement, with reference to the Performance and Economic Rating System (PERS), presently being developed. At the current stage of development, the model is essentially limited to flexible pavements, although cement stabilized materials may also be included.

DEGRADATION OF PAVEMENT MATERIALS AND STRUCTURE

Under the influence of time, loads and climatic effects, pavement materials will deteriorate and the pavement structure will deform. The stresses caused by heavy loads may result in microcracking in asphalt- or cement-bound materials, and may also cause permanent deformation in the pavement layers. Aggregate in the pavement surface is polished through tire wear, and surface texture may be changed so that skid resistance is reduced by depression of aggregate into the pavement surface, or by bleeding. Frost heave may cause cracking and deformation, while "spring thaw" can considerably reduce the permissible stresses in the unbound materials. Aging of the bitumen may have a similar effect on the asphalt-bound materials. With time, microcracking can develop into macrocracking, allowing water to penetrate into the pavement, and so on. Maintenance and/or rehabilitation may then restore some of the original and desirable pavement characteristics.

This process of material deterioration and permanent deformation is, unfortunately, quite complex and difficult to model using analytical tools. From an analytical point of view, it is probably true to say that pavements are among the most complicated of all civil engineering structures.

Before computers became an everyday tool for pavement engineers, models had to be simplified in the extreme. Some empirical models, like those developed by AASHTO based on the AASHO test road results in the 1950s, do not even attempt to predict the deterioration of pavement materials (ie., changes in layer coefficients), while the classical analytical-empirical design criteria, like those developed by Shell [1], Nottingham University [2] or the Asphalt Institute [3], are limited to a prediction of the number of loads to cause a certain amount of cracking or permanent deformation (roughness or rutting). The effects of cracking on bearing capacity, or the interaction between cracking and permanent deformation, are not considered.

The Highway Design & Maintenance Standards Model (HDM) developed by the World Bank [4] establishes the "causality of events: a pavement starts to crack and to ravel (in a random fashion, after a few years of service); the cracking then increases in extent and intensity; this leads to potholing and other surface disfigurement, which together with rutting, leads to increased roughness — the principal parameter affecting vehicle operating costs". This is achieved using an incremental-recursive procedure, where the effects of loads, time, and maintenance or rehabilitation is determined from empirical relationships for an increment of time (one year), and the results are used (recursively) as input for the next increment of time.

The same procedure is used in the Mathematical Model Of Pavement Performance (MMOPP) developed at the Technical University of Denmark [5&6], but in this model the calculation of material and structural deterioration is based on the actual stresses and strains in the pavement materials as a result of traffic loads. Another model based on fundamental engineering principles is the VESYS system developed by the Federal Highway Administration [7].

The basic engineering techniques are thus available but, until recently, they have hardly been in a form usable for pavement management purposes. This situation is rapidly changing as a number of agencies and consultants are working on more complete and fundamental models of pavement performance. To illustrate the workings of such a model, "PERS" is described below. This description can hopefully contribute to the need for better pavement evaluation, performance prediction, and the definition and determination of pavement "utility".

PERFORMANCE AND ECONOMIC RATING SYSTEM (PERS)

Figure 1 shows a section of a typical PERS working PC video display.

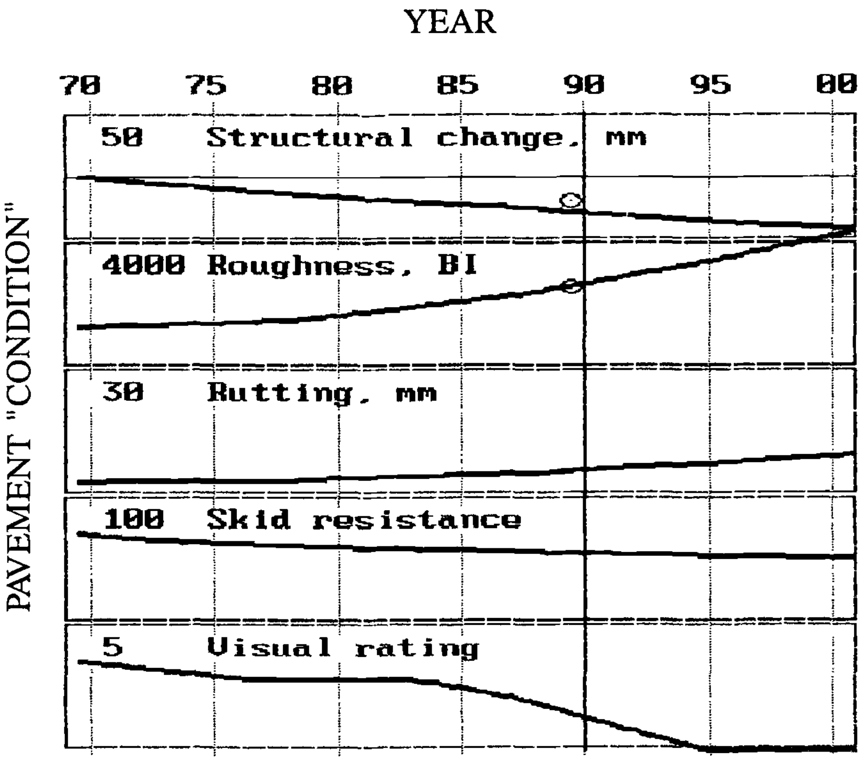

FIGURE 1 — Five Measures of Pavement Condition vs Year (1969 - 2001)

In Figure 1, five different performance parameters are shown on the vertical Y-axis, as a function of time on the horizontal X-axis from the year 1969 to 2001, with the year of evaluation, 1990, shown by an enhanced vertical line. These deterioration curves, from top to bottom, are a result of the following:

1) Structural change, shown in Figure 1 in (eg.) mm, is the structural deterioration expressed as an effective loss in thickness of a standard asphaltic material. Microcracking of the asphalt causes a reduction in the effective cross sectional area, thus resulting in a proportional decrease in modulus. Moisture penetrating into the unbound layers may also reduce the stiffness of the materials, and surface wear caused by studded tires may reduce the thickness of the wearing course. The thickness of a standard material needed to restore the overall pavement stiffness is used as an indicator of structural deterioration.

2) Roughness, expressed as the Bump Integrator number (BI) in mm/km, may also be expressed as the International Roughness Index (IRI), Slope Variance (SV), Present Serviceability Index (PSI), or any other quantifiable indication of surface roughness as experienced by a moving vehicle.

3) Rutting, shown in mm, is the sum of the permanent deformation in the pavement layers, plus surface wear, in a wheel path.

4) Skid resistance is shown on a scale from 0 to 100, but may be any other measure of the tire/pavement friction.

5) Visual rating can be a user-defined function of other pavement distresses and age of the wearing course. In Figure 1 it is shown as a deterioration in surface condition on a scale from 0 = poor to 5 = excellent (new).

The model simulates pavement deterioration by using the incremental-recursive method described above. Each increment is one season, during each of which the elastic modulus of each material may be considered as being reasonably constant. In addition to being a function of season, the modulus of a material also depends on environmental conditions (eg. drainage), previous deterioration, permeability of the surfacing, and age of the material.

For each season the critical stresses and/or strains are calculated, in each layer and for all of the different traffic loads considered. The decrease in modulus is then determined from the maximum horizontal tensile stress or strain, while maximum vertical compressive stress or strain determines the increase in rutting and surface roughness. The decrease in skid resistance and increase in surface wear is considered a function of tire pressure. For each parameter, the total damaged is then summed for expected traffic loads during the season considered, etc.

Use of Historical Data

Any historical data available is shown as an encircled point. In Figure 1, structural condition and roughness were measured in 1989. The structural condition was determined using the Dynatest Model 8000 Falling Weight Deflectometer (FWD), from which the moduli of the pavement layers were derived, while roughness was measured using the Bump Integrator. The initial pavement conditions, after the last rehabilitation was carried out in 1969 (a new leveling course), was assumed based on local conditions and experience.

In the example shown in Figure 1, PERS correctly "predicts" the roughness actually measured in 1989, based on the 1969 data, but somewhat overestimates the structural change. However, the empirical relationships between tensile strain in the asphalt and decrease in asphalt modulus are user controlled, as are initial conditions, environmental effects, or other parameters influencing structural performance. Thus the effects of changes to these parameters can immediately be seen on the PC video display, whether for calibration or other purposes.

PERS may be set up to be read data from a database gathered for pavement management purposes. The user can evaluate various pavement sections in the database, making use of local knowledge of materials, environmental effects, construction and maintenance practices, etc., to calibrate the model for a specific roadway network.

Effects of Maintenance or Rehabilitation

Once each model has been calibrated to give a satisfactory description of historical performance for the network as a whole, it can then be used with relatively good degree of confidence for prediction of future performance. As the historical base grows, the models used can be further updated to increase this level of confidence.

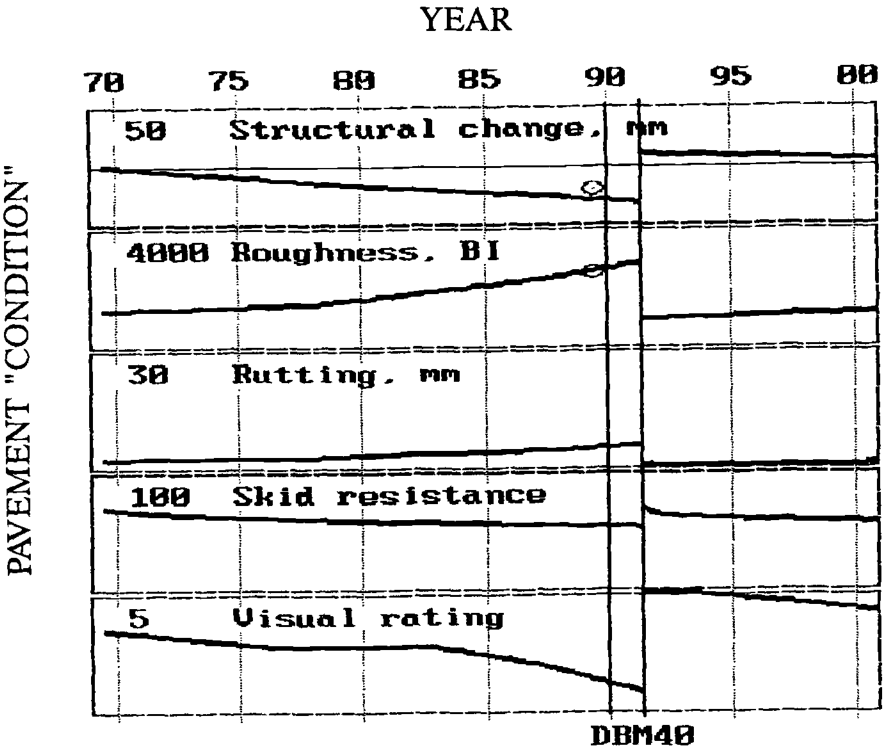

FIGURE 2 — Five Measures of Pavement Condition vs Year (1969 - 2001), with Assumed DBM Overlay in 1992

Figure 1 shows the expected development of pavement condition (for a single, example roadway) until the year 2001, assuming nothing but routine maintenance is performed. In Figure 2, it is assumed that 40 mm (1½ in.) of Dense Bitumen Macadam (DBM) has been placed in 1992. This restores the structural condition of the pavement, and also ensures a high functional (ride quality) standard for the rest of this century.

The user may define any number of maintenance or rehabilitation alternatives, including recycling and reconstruction. The effects of past maintenance and rehabilitation may be used in estimating the influence of a specific alternative on the structural and functional condition. The program may also be used in an automatic mode, where all of the feasible maintenance strategies, combining the alternatives specified by the user, are tried out over the analysis period (eg. in Figures 1 & 2 from the year 1990 through 2001.

QUANTIFICATION OF PAVEMENT "UTILITY"

Accurate prediction of future pavement performance is extremely important to the planning process. If planning is based on incorrect predictive models, actual conditions encountered will be different than expected, and planned procedures or actions may be inapplicable which, essentially, invalidates the planning process.

It is difficult, however, to use performance parameters directly for decision-making. What is important to decision-making is the *utility* of the pavement to the users (or to society in general), as well as the costs to the highway agency. However, if "utility" is translated into "user costs", it more often than not becomes quite a controversial subject.

Some pavement engineers claim that they do not consider user costs. But in practice such considerations are made implicitly, if not explicitly. Nobody maintains a farm-to-market road to the same standards as an expressway or freeway. When a decision is to be made whether Alternative "X" is necessary on Section A, rather than Alternative "Y" on Section B (at identical costs), the usefulness of the two alternatives must be considered. It is the authors' opinion that an explicit, quantifiable consideration of usefulness is preferable to an implicit or intuitive one.

To consider usefulness explicitly, the effects of different performance parameters on the users, or on other sectors of society, must be quantified. For inter-urban traffic, the direct user costs (fuel consumption, vehicle wear, etc.) have been studied extensively by the World Bank [8] and others. A number of studies have also been carried out on the relationship between skid resistance and accident frequency. Though these relationships are certainly not perfect, they do indicate the order of magnitude these "user" costs amount to, and can thus be used with a reasonable degree of confidence pending further studies and fine-tuning of these relationships.

It is not possible to establish objectively correct relationships between performance parameters and user costs. The "real" value of time savings (or waste) as well as the "costs" of traffic accidents are highly political issues. But such quantifications are already assessed for other purposes, and it can be argued that by quantifying such costs (or "benefits"), it then becomes possible to discuss the relationships involved and evaluate their effects in a more scientific and objective manner.

When using PERS, the engineer can specify vehicle operating costs as functions of roughness and skid resistance, for each vehicle category. Costs of skid related accidents may be specified as a function of skid resistance and/or rut depth. In addition, a monetary value may be assigned to the visual condition of the pavement. Deteriorated pavements can have economical repercussions in both industrial and residential areas.

Figure 3 shows another portion of the PERS working PC video display, where the economic consequences of certain actions to the roadway segment shown in Figures 1 and 2 are displayed.

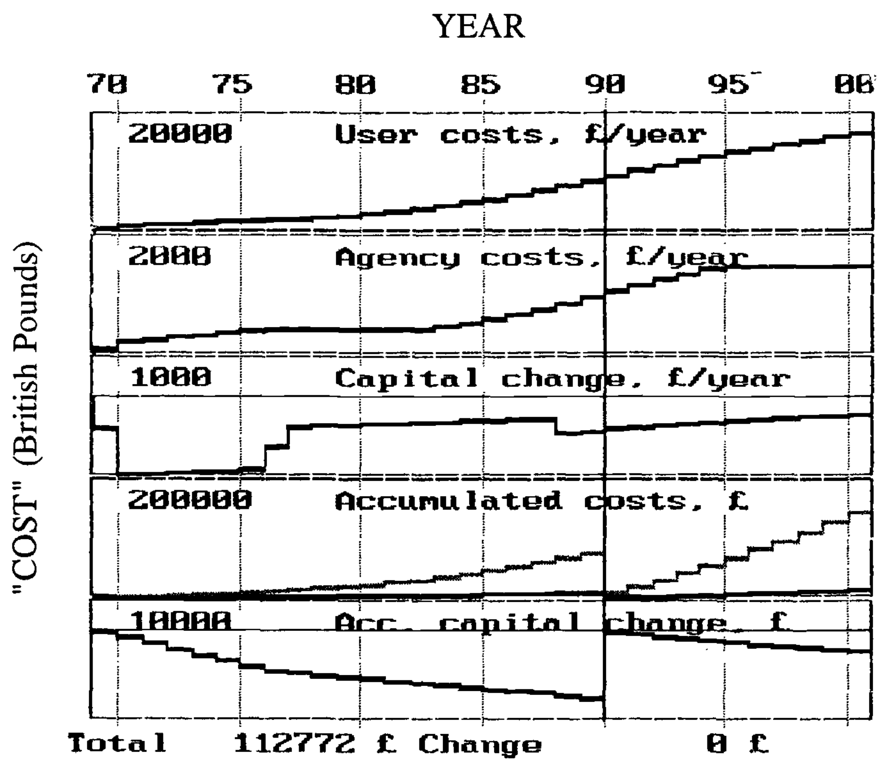

FIGURE 3 — Five Economic Indicators (in British Pounds) vs Year (1969 - 2001)

In Figure 3, five different economic parameters are shown on the vertical Y-axis in units of British Pounds, as a function of time on the horizontal X-axis from the year 1969 to 2001, with the 1990 year of evaluation shown by an enhanced vertical line. These economic curves, from top to bottom, represent the following:

1) In the upper graph in Figure 3, the sum of vehicle operating costs, accident costs, and "costs" of visual condition as described previously is depicted. The total for these costs is designated "user costs", even if this includes other elements.

2) Agency costs are defined as the sum of routine maintenance costs and any maintenance or rehabilitation measures carried out by the roadway agency itself.

3) The change in the "value" of the pavement structure, called "capital change", is then shown. This change in value consists of structural loss (as indicated at the top of Figure 1) plus the deterioration of the wearing course material, which is depreciated over the estimated residual life of the wearing course.

4) "Accumulated costs" is shown, with this economic indicator set at zero (pounds) in the year the analysis is carried out, since future costs only are considered for planning purposes.

5) The bottom graph in Figure 3 shows "accumulated capital change". Again, since future costs are most interesting for planning purposes, this economic parameter is set to zero in the year the analysis is carried out.

The total costs in British pounds over the analysis period (here, from 1990 to 2001), discounted back to the evaluation year, is shown in numerical form at the bottom of Figure 3 user's PC video display. These costs comprise the user costs, agency costs, and the change in capital value (which may be negative or positive). The change with respect to the previous pavement and economic evaluation is also given (in this case zero, since this was the first evaluation for the pavement section shown in this example).

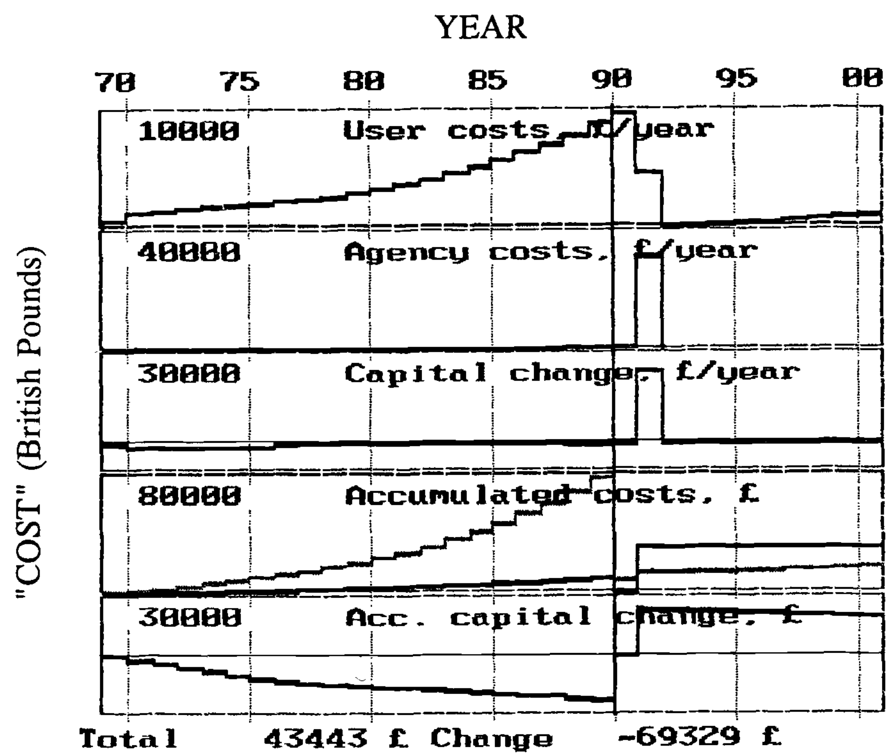

FIGURE 4 — Five Economic Indicators (in British Pounds) vs Year (1969 - 2001), with Assumed DBM Overlay in 1992

Figure 4 is parallel to Figure 3, but with a Dense Bitumen Macadam (DBM) overlay placed in 1992. Not surprisingly, agency costs for the analysis period increase while the user costs decrease. The <u>total</u> costs, however, decrease considerably (to about 40% of the costs assuming routine maintenance only).

When used in the automatic mode, all possible M&R strategies will be evaluated using PERS. Those that are both economically and technically feasible will be stored in a database for later use with an optimization module.

CONCLUSIONS

An enormous amount of data is presently being collected for pavement management purposes by different highway agencies, often at considerable cost. The "comparability" of the data, over time or between districts or agencies, is sometimes very important, for political reasons as well as for research purposes. This calls for standardization and/or calibration procedures with respect to reference systems, measuring equipment & procedures, and data reduction as well as methods of prioritization or optimization.

It is, however, very important that this "standardization" is done in such a way that it does not negatively influence the development of rational methods for forecasting future pavement condition or for evaluating the "usefulness" of a given pavement. Pavement structures are extremely complex and difficult to evaluate by analytical tools and have, until recently, been evaluated using purely empirical (as opposed to analytical or mechanistic) methods. This situation is rapidly changing, however. New tools, and in particular the ever increasing availability of microcomputing power, is opening the field of pavement engineering to rational, analytical methods such as the one outlined herein.

This paper presents one example of the new generation of computer models that are presently being developed by various pavement engineers. Such models make it possible to base prediction of future pavement condition, at a network level, on the actual physical processes which occur in a pavement structure, under the effects of load and environment, and to carry out a rational analysis of the "utility" of a given pavement section. It thus appears desirable that standardization within the field of Pavement Management will be based on standard, or rational and fundamental, engineering principles, rather than on arbitrarily defined indices and threshold values.

Of course, the examples shown in the foregoing were for a single pavement subsection, not a whole "network". In actual practice, changes to the performance relationships used in the PMS and PERS would *not* be carried out based on a single pavement section within the network, but rather only after a series of pavement sections indicate the same general trends in performance vs time. PERS allows this to be done very quickly, by viewing the same PC video display screen for any number of pavement sections in immediate succession. The form, as well as the constants, of the relationships themselves may be specified by the user, although the present version of PERS incorporates specific relationship forms which will be discussed by the authors in another paper, at the 1992 "Seventh International Conference on the Structural Design of Asphalt Pavements" in Nottingham, England.

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Alaeddin Mohseni, Michael I. Darter, and James P. Hall

EFFECT OF SELECTING DIFFERENT REHABILITATION ALTERNATIVES AND TIMING ON NETWORK PERFORMANCE

REFERENCE: Mohseni, A., Darter, M. I., and Hall, J. P., "Effect of Selecting Different Rehabilitation Alternatives and Timing on Network Performance," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: Several different methods of pavement network rehabilitation management are compared. These methods range from random selection, to worst first ranking, to different methods of optimization. The results of applying each method on a sample highway network show for the first time, greatly different benefits and overall performance for the same budget expenditure. Optimization methods provided the best network performance over other methods, however, different optimization methods provided comparable results. The needs method provides a reasonable estimate of pavement rehabilitation needs when the network budget is unlimited. Incremental benefit-cost ratio algorithm is found to be a very efficient and practical algorithm for use in pavement management system (PMS). An objective benefit function is also recommended for use in the network-level PMS.

KEYWORDS: pavement management, pavement network optimization, pavement rehabilitation, pavement benefits.

A comprehensive pavement management system (called ILLINET) has been developed for the Illinois Department Of Transportation to assist in the programming of optimal pavement rehabilitation strategies. Performance prediction models and cost models are used to generate several feasible strategies for each pavement section in the network over a period of 10 years. All strategies for all sections are then analyzed together to find answers to a variety of "what if" questions regarding network budget levels and rehabilitation policies. Four different network management procedures are available, including needs, simple ranking, incremental benefit cost, and multi-year optimization. ILLINET also contains several project level analysis options (e.g. decision tree and life cycle cost) and several methods of defining pavement rehabilitation benefit.

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ILLINET produces both tables and graphical maps to illustrate the immediate and long term effects of applying pavement management strategies and budgets. The pavement management system can be used to illustrate many different rehabilitation strategies and their effect on costs and performance for the network. ILLINET is currently under trial implementation in the Illinois Department Of Transportation (IDOT) and is used for planning and programming of the Illinois Interstate Highway rehabilitation.

To provide the Illinois DOT different pavement management options, different pavement rehabilitation methods are available in ILLINET and are applied to a sample network. This paper includes the discussion of the sample network, the default variables and options considered, and also the presentation and discussion of some of the output reports for ILLINET application runs. More detailed information on ILLINET are provided in References 1,2,3, and 4.

As mentioned previously, several network-level, project-level, and benefit options are available in ILLINET. These options cover a variety of methods commonly used by different transportation agencies around the world for managing pavement networks. Needs and different methods of ranking are probably the most commonly used algorithms, while benefit-cost analysis and optimization are becoming used more often. However, for some agencies the transition from simple ranking to optimization is not easy. Apart from the problem of unavailability of needed models, other problems such as complexity which results in a "black-box" approach, and the subjectivity of "optimization" criteria are the problems to overcome. Comparison of network management alternatives can demonstrate the effectiveness of each method and the advantages and disadvantages of each method over the others. Such a comparison is not known to have been performed prior to this study.

ILLINET INPUTS

The input database for the sample network includes several data items (variables) for each pavement section in the network. These data include pavement identification, design, traffic, climate, distresses, and condition. A pavement condition rating (CRS) between 1 (worse condition) and 9 (best condition) is used in Illinois. CRS is used as a measure of pavement condition in ILLINET. CRS is also correlated to the existing pavement distresses, thus providing the capability to predict CRS from predicted key pavement distresses.

ILLINET also requires several user-defined parameters to be entered for the network analysis. These input parameters consist of:

1. Length of analysis period,
2. Rate of inflation during analysis period,
3. Number of rehabilitations for a section allowed during analysis period,
4. Minimum CRS for rehabilitation and life determination,
5. Unit user costs, and
6. Decision tree trigger values, and others.

Table 1 lists the default input parameters. A 10 year analysis period during which rehabilitation costs inflate at the rate of 5 percent per year and AADT grows at the rate of 2.5 percent per year is considered throughout the analysis. Only one rehabilitation was allowed in the 10 year period for each section. It is also assumed that 80 percent of the existing deteriorated areas on the pavements are patched at the time of rehabilitation.

The unit user costs were obtained from a study conducted by McFarland (5) and inflated at the rate of 4 percent per year to reflect current costs. Unit costs of rehabilitation are the average statewide unit costs and include shoulder, drainage, and traffic control costs. The same default values for input parameters are used for all ILLINET application runs.

TABLE 1 -- Default User Input Values for ILLINET.

Default Parameter	Value	Unit
Analysis Year	1987	
Length of Analysis Period	10	Year
Analysis Interval	1	Year
Trigger for Accruing	6	CRS
Trigger for Backlog	4	CRS
Trigger for Rehabilitation	6	CRS
Inflation (future)	5	Percent
Rehabilitations Allowed per section	1	number
Percent Patching	80	Percent
User's Cost for CRS>=6	27	Cents/mile
User's Cost for 6 >CRS> 5	31	Cents/mile
User's Cost for CRS<=5	34	Cents/mile
JRCP Concrete Pavement Restoration	1,200	$/Patch
CRCP Concrete Pavement Restoration	2,300	$/Patch
3 inch AC overlay	178,000	$/two lane mile
5 inch AC overlay	227,000	$/two lane mile
Reconstruction with 10 inch CRCP	600,000	$/two lane mile

ILLINET OUTPUTS

The results from the ILLINET program are included in three computer reports which cover the range from the one page "big picture" to the multipage "most detailed" to reflect the needs of several users A sample output for each report is included in reference 1. Following is a brief discussion of each output report. Network Summary Report contains information regarding average network performance for every year in the analysis period and for the duration of the analysis period. The following summary data for every year in the analysis period are available:

1. Average network CRS weighted by section length.
2. Average remaining life of the pavement network.
3. Percent Vehicle Miles Travelled (VMT) over backlog "poor" pavements.
4. Percent length of the backlog condition sections.
5. Pavement rehabilitation priorities (PRT).
6. Quantity of rehabilitation types.
7. Amount of added benefit to the network.
8. Total cost of rehabilitation.

The network summary report provides useful statistics on pavement performance both during and beyond the analysis period. These statistics (network performance parameters) are used in comparing different network management methods and in measuring the effectiveness of each.

Network Performance Parameters

Several network-level statistics which are listed as part of the network summary output can be used to compare alternate network management options. There are five major groups of statistics: network cost, network benefit, performance during the analysis period, performance beyond the analysis period, and network rehabilitation program.

Network Cost: The cost of applying the rehabilitation program, which is the sum of the cost of rehabilitation for all sections in the network (or total amount spent on the network). The cost of rehabilitation in every year includes inflation, thus, network cost is not the present worth of the cost.

Network Benefit: The sum of benefit gained by rehabilitation of all pavement sections in the network which is available from the network summary report. Four different benefit measures considered are:

1. Added area under performance (CRS vs. time) curve (AREA),
2. Extra life due to rehabilitation (ALIFE),
3. Added Vehicle Miles Travelled on adequate pavements (VMT-A), and
4. Reduction in user cost due to rehabilitation (UBEN).

Network benefit includes added benefits during and beyond analysis period for the cost spent on the network.

Network Benefit-Cost Ratio: The total benefit derived from pavement rehabilitation divided by the rehabilitation cost spent on the network, or simply network benefit divided by network cost. This parameter provides the benefit per unit cost, which is valuable in assessing the effectiveness of each pavement management method.

Performance during Analysis Period: The following parameters reflect the overall performance of the network during the analysis period:

1. Average 10-year network CRS, and
2. Percent VMT on backlog pavements during 10-year period.

Performance Beyond Analysis Period: The two parameters listed below reflect the condition of the network at the end of the analysis period and the performance of the network beyond the analysis period.

1. Percent VMT (Vehicle Miles Travelled) on backlog pavements in the last year of analysis period (year 10), and

2. Remaining life of the network at year 10.

Rehabilitation Program: The network rehabilitation program is the 10-year rehabilitation plan for all the sections in the network. The rehabilitation programs can be used for assessing the effect of different network options in selecting rehabilitation timing and type.

APPLICATION OF ILLINET TO A SAMPLE NETWORK

Description of Sample Network

The Illinois Interstate highway network includes over 1700 centerline miles (2700 kilometers) of freeway type highways, carrying large amounts of truck traffic. The pavements were constructed beginning in the 1950's through the 1980's and represent a wide range in designs and traffic loadings. This large highway network is now requiring extensive rehabilitation work as many of the pavement sections have reached their design life of 20 years, and have carried over 3 times their design traffic.

A pavement network that includes all Interstate pavement sections in the District 5 of the Illinois Department of Transportation (Figure 1) was used as a sample pavement network in the analysis. This network includes 121 one-directional pavement sections (two lanes in each direction) with a total length of 517 miles (830 kilometers) on four Interstate routes (I-57, I-70, I-72, and I-74). The pavement sections were built as early as 1958 and as late as 1976. All pavement sections in this network were originally built as jointed reinforced and continuously reinforced concrete pavements (JRCP and CRCP); however, almost half of these sections were later overlaid with asphalt concrete (AC). This pavement network includes sections with a wide range of pavement conditions and traffic loadings.

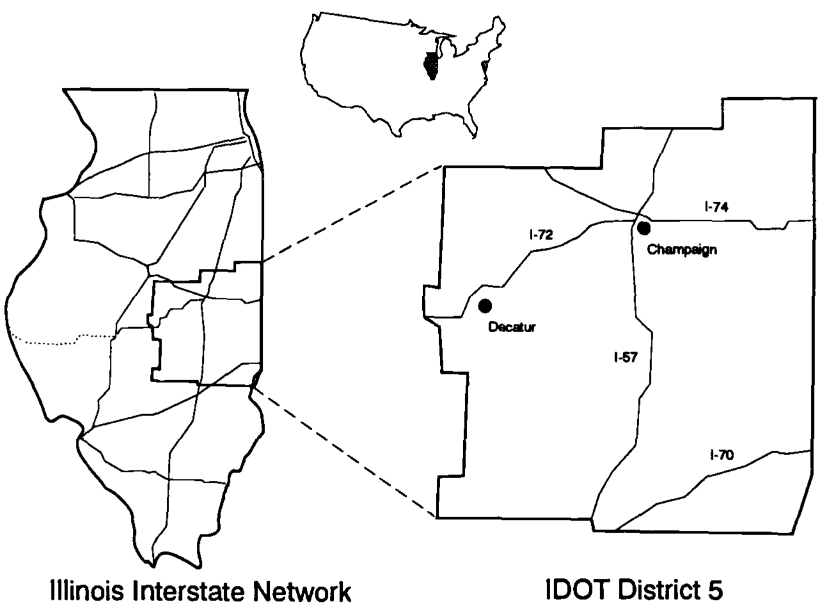

FIG. 1 -- Map of Illinois DOT District 5.

Network Management Methods Considered

Four network management methods that represent a range of options available in ILLINET were applied to the District 5 sample network using the previously mentioned default user input variables. For all runs, VMT-A was selected as the benefit function where applicable. Following are the options considered for the ILLINET runs.

NEEDS: Needs network-level option with life cycle cost (LCC) analysis for the project level and unlimited budget. In this method all sections in need of rehabilitation will receive one based on the project-level option chosen.

RANK: Ranking option with LCC for project-level and yearly budget limit of 7.5 million dollars. In this method sections are funded based on worst-first rule every year in the analysis period until the yearly budget is exhausted. Projects that are not funded in one year are delayed until funding becomes available.

IBC: Incremental benefit-cost ratio (IBC) with all project-level options (ALL) and yearly budget limit of 7.5 million dollars. In this method projects with higher IBC are chosen first every year in the analysis period until the yearly budget is exhausted. The objective is to maximize yearly benefit for a yearly budget limit.

OPT: Long-term optimization (OPT) with all project-level options and a 10 year budget of 75 million dollars. In this method there is no yearly budget restraint and projects are selected such that the 10-year benefit is maximized for a 10-year budget limit.

In addition to these methods, two other methods that are not available in ILLINET were also considered for purpose of comparison.

RAND: Randomly generated rehabilitation program as might occur when no pavement management system is used by an agency.

LIN: Rehabilitation program generated by a linear programming method using ALL project-level option and yearly budget limit of 7.5 million dollars. This option is selected since an integer programming solution to the optimization program could not be reached.

The randomly generated rehabilitation program was created using a random number generator. In this method, every section whose CRS at the beginning year of analysis (1987) was 7 or less qualified for rehabilitation. The timing of the rehabilitation during the analysis period and the type of rehabilitation was then randomly selected for the section. The rehabilitation program was then fed into the ILLINET program to produce the output reports that include performance parameters.

PRESENTATION OF RESULTS

The results for different application network management methods are presented in Table 2 and Figures 2 through 5. Different network performance parameters for each method is presented in this section.

The benefit gained by pavement rehabilitation in terms of VMT-A and the cost of rehabilitation for the different methods are listed in Table 2 and graphed in Figure 2. The highest cost belongs to Needs (about 90 million dollars) since this is the unlimited budget method. The cost of all other methods are about equal and range between 71 and 75 million dollars. The benefit of rehabilitation, which is shown in terms of added Vehicle Miles Travelled over Adequate pavements (VMT-A), is highest for Needs partly because of the higher cost of rehabilitation. The Random method offered the lowest benefit and Ranking the next lowest. The benefits for other methods (i.e., IBC, OPT, and LIN) are comparable since all these methods are based on maximizing the benefit. The network benefit to network cost ratio, which is the measure of the effectiveness of each method, is shown in Figure 3. From Figure 3 it can be seen that Random, followed by Ranking, have the poorest effectiveness of all methods. OPT has the highest effectiveness of all methods and the optimization methods are comparable in their effectiveness.

TABLE 2 -- Network Parameters for Six Application Runs for District 5.

Network-Level Option	RAND	NEEDS	RANK	IBC	OPT	LIN
Project-Level Option	Random	LCC	LCC	All	All	All
Benefit Option	n/a	n/a	n/a	VMT	VMT	VMT
Budget Limit, Million Dollars	75	n/a	75	75	75	75
Cost, Million Dollars	74	90.1	73.8	73.3	75	71.2
Average network CRS 1-9 scale	6.49	7.15	6.74	6.82	6.99	6.81
Average % VMT on Backlog	15.4	2.6	3.5	6.1	4.2	6.2
Remaining Life, Years / mile	3.5	4.7	3.8	4.2	4.4	4.3
% VMT-Backlog @ Year 10	35	10	14	17	14	17
Total CRS Area, CRS-Year / mile	21.5	37.0	26.1	28.4	31.6	29.2
User Benefit, Million Dollars	218	443	287	386	408	383
Total Added Life, Years / mile	2.89	5.9	3.4	4.7	5.2	4.8
VMT on Adequate, Billions	2.98	6.44	3.82	5.64	6.02	5.63
Benefit (VMT-A)/Cost	40	71.5	52	77	80	79

The average network CRS is highest for Needs and lowest for Random (see Table 2 and Figure 4). However, the CRS for all options only ranges between 6.5 and 7.15 and is similar for all optimization methods. The remaining life shows a trend similar to that of CRS, except that it has a wider range (3.5 years for Random and 4.7 years for Needs).

Average Vehicle Miles Travelled over Backlog pavement sections (VMT-B) and VMT-B at the end of analysis period (year 10) are listed in Table 2 and also shown in Figure 5. The highest average VMT-B is 15.4 percent for Random method and the lowest is 2.6 for Needs. The lowest VMT-B among optimization methods belongs to OPT (4.2 percent); however, for the other two methods (IBC and LIN) VMT-B is about 6 percent. The VMT-B for RANK (3.5 percent) is also lower than for the optimization methods but higher than for Needs.

One way of presenting all of the results for the different methods is to show all network parameters for all methods on one single graph. For this reason, network parameters should be normalized since each parameter has a different scale. Figure 6 shows network parameters in percentages of NEEDS parameter values for the different methods considered here. From Figure 6 it can be seen that the network parameters that show a marked difference for the different methods are benefit (VMT-A), average VMT-B, and remaining life.

The rehabilitation program for RAND is completely different than any other method since it is randomly generated. There are some similarities between programs generated by NEEDS and by RANK. This is because some of the sections that initially have poor condition are selected for rehabilitation by both methods and since the same project-level selection routine is used for both, the same rehabilitation plan is generated for these sections. Also at some years in the analysis period, the budget for Ranking may be sufficient for rehabilitating sections whose conditions just dropped below the minimum CRS. In this case, the NEEDS and RANK rehabilitation plans will be similar.

For some sections, Needs and other optimization methods (IBC, OPT, and LIN) produce identical rehabilitation timing and type. For some other sections the rehabilitation plan is similar (i.e., rehabilitation type is the same but the timing is different by one or two years). This is due to the fact that for some sections the most cost-effective timing for rehabilitation is when the CRS is about 6, which is also the rehabilitation timing for Needs.

The fact that the optimization methods try to maximize the benefit, combined with the higher priority that these sections may have due to higher traffic levels, can result in selection of a similar rehabilitation plan as Needs. Optimization methods produced identical rehabilitation plans for some sections and similar plans for some others, while for some sections the rehabilitations plans (timing and type) were completely different. IBC and LIN produced more similar rehabilitation plans since both of these methods consider a yearly budget limitation, while OPT only considers a 10-year budget limit.

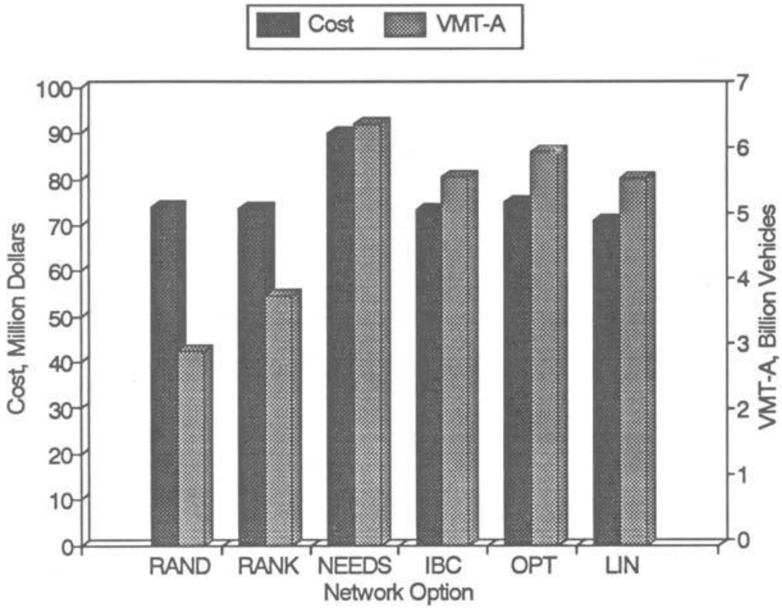

FIG. 2 -- Cost and Benefit (VMT-A Vehicle Miles Travelled on Acceptable pavements).

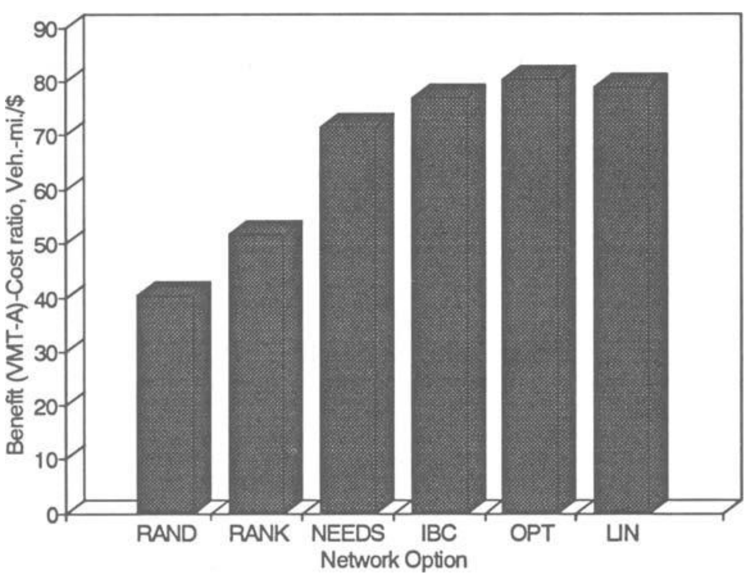

FIG. 3 -- Network Benefit (VMT-A) to Cost Ratio for Application Runs.

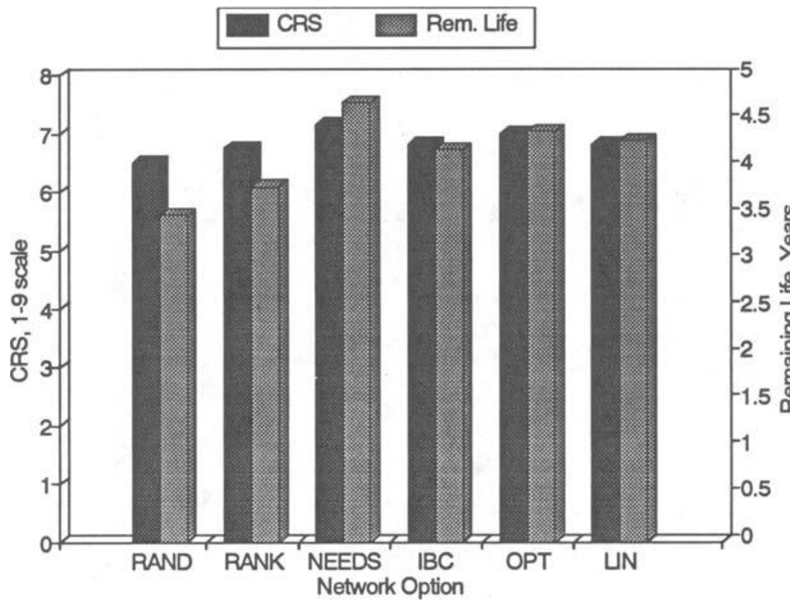

FIG. 4 -- Average Network CRS and Remaining Life for Application Runs.

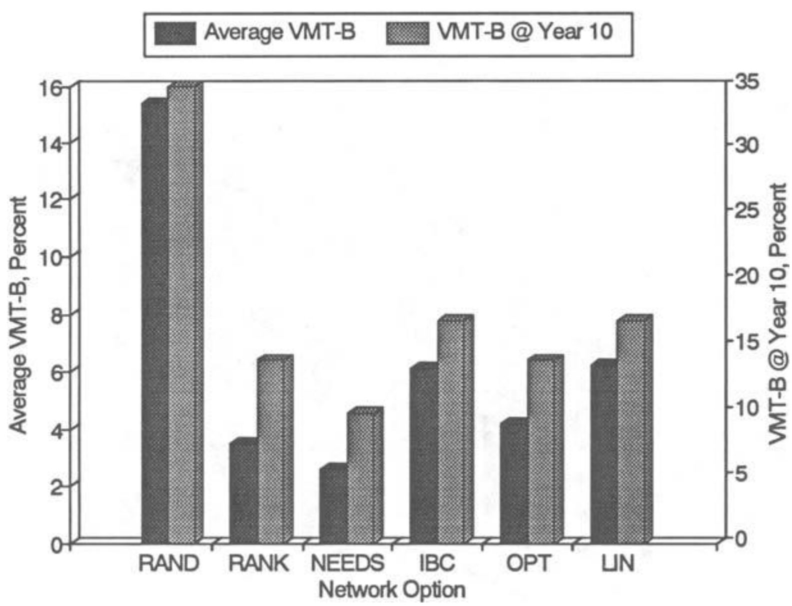

FIG. 5 -- Average 10-year VMT-B (VMT on "poor" pavements) and VMT-B at year 10.

DISCUSSION OF ALTERNATE NETWORK MANAGEMENT METHODS

To demonstrate the advantages and disadvantages of each network management method, their capabilities and results are compared with each other. Table 3 contains a general evaluation of performance of each network management method based on the results from pavement performance. The network performance for all methods are also shown in Figure 6. The information in Table 3 and Figure 6 are used to demonstrate the advantages and disadvantages of network management techniques considered.

The Random Method (RAND)

The random method (RAND) illustrates the consequences of adopting an ad hoc procedure for pavement network rehabilitation management. From Table 3 and Figure 6 it is evident that this procedure results in serious network deterioration for equal funds spent as compared to other network management techniques. The advantage of almost any rational method of pavement network rehabilitation management is shown by all statistics. For example, using this approach 15% of all VMT is on backlog pavements, while only 3-6% occur using other methods.

Ranking Method (RANK)

This method is capable of considering yearly budget limit and is based on a worst-first rule (i.e., pavements in the worst condition are rehabilitated first). Using Ranking for the selection of sections for the first year of analysis does not require any pavement condition prediction models; however, for multi-year analysis, prediction models are essential to predict pavement condition. This method is not capable of considering several rehabilitation alternatives at the network level; therefore, the trade-offs between rehabilitation types are not considered.

Rehabilitation timing is controlled by available budget and pavement condition, thus the rehabilitation of sections in need of rehabilitation whose condition are not low enough to compete for funding is delayed until funding becomes available and/or their condition is low enough to qualify.

The long-term performance and gained benefit that Ranking provides is inferior to all other options except for Random; however, the network performance during the analysis period was fair. This is because the Ranking criteria is to remove pavement deficiencies without any regard to the long-term performance of sections and rehabilitations at the network level, although long-term performance is considered at the project level. Therefore, adopting RANK can result in significant long-term performance loss, although short-term performance might not be affected significantly. The benefit in terms of VMT-A gained and the effectiveness of this method are both poor in comparison with other methods.

The Needs Study (NEEDS)

NEEDS is the unrestrained budget network management method, thus, it can not consider any budget limitation. The criterion for rehabilitation in NEEDS is based on a minimum condition level. Any pavement section whose condition falls below a minimum CRS level (usually CRS of 6) is considered to be deficient and automatically receives some type of rehabilitation without consideration of rehabilitation type and timing trade-offs. Therefore, Needs has limited capabilities because budgets are always limited.

The long-term performance that NEEDS provides is much improved over RAND and RANK; however, it is not as good as that of the optimization methods (i.e., IBC, OPT, and LIN) even when spending 90 million instead of 75. NEEDS performance during the analysis period is better than any other method partly because its cost of rehabilitation is higher than that of the other methods. The gained benefit and effectiveness of Needs is also greatly improved over Random and Ranking and is fairly good in comparing to other optimization methods.

Although Needs is very limited in capabilities, its performance is exceptionally good. This is because for most pavement sections, the most cost-effective timing for rehabilitation is around CRS of 6, and Needs takes advantage of this by allowing rehabilitation as soon as the pavement condition drops below this minimum. NEEDS is an excellent tool for estimating future unrestrained pavement rehabilitation needs for use in justifying tax revenue increase.

Long-Range Optimization (OPT)

This method is capable of considering the total 10-year (multi-year) budget limit but not the yearly budget limitation. The criterion for this method is based on selecting rehabilitations for every pavement section in the network such that the total network benefit is maximized for a predetermined budget limit. In this approach, all rehabilitation types and timings are considered such that the timing and type that provides the maximum benefit is selected. Therefore, all rehabilitation type and timing trade-offs are considered in this approach.

The long-term performance that OPT provides is better than that of any other methods. This is because the long-term benefit of rehabilitation for every section is maximized. In addition to this, since yearly budget limitations are not enforced, OPT can provide better project rehabilitation selection and thus higher benefit than other optimization methods (i.e., IBC and LIN). The performance during the analysis period is also good, although not as good as those of Needs and Ranking.

OPT is an excellent tool for multi-year pavement rehabilitation planning, nevertheless, there are some serious limitations with this approach. First, since yearly budget limitations are not enforced, the cost of rehabilitation may not be evenly distributed. This contradicts the actual budget situation, since only a certain amount of funding is usually available for pavement rehabilitation every year. Second, although multi-year rehabilitation programs are created for a network, pavement rehabilitations are actually funded on yearly basis. Thus, the rehabilitation of some sections that are originally scheduled in a multi-year program may be delayed due to lack of funds, or the fact that the section did not deteriorate as much as was originally predicted, or change of priorities. This change in multi-year rehabilitation program also changes the costs and benefits of rehabilitations accordingly.

Incremental Benefit Cost Ratio (IBC)

IBC is based on yearly optimization (maximization) of pavement rehabilitation benefits, rather than multi-year optimization as in the case of OPT. Thus, this approach easily considers yearly constraints (yearly budget limits). IBC is also capable of considering all pavement rehabilitation type trade-offs for all deficient sections every year in the analysis period. Rehabilitation timing trade-offs are not directly considered since all deficient sections that qualify for funding are delayed and considered for funding in the next year.

The performance of IBC during the analysis period and beyond the analysis period as well as gained benefit is slightly lower but comparable to that of OPT. This is to be expected, since IBC considers a yearly budget limit while OPT does not. The effectiveness of IBC is also comparable to that of OPT.

Since IBC considers yearly budget limits and allocates budget on yearly basis, it is closer to the real world situation than OPT. Therefore, it does not have some of the limitations that exist for OPT. On the other hand, benefits are maximized on a yearly basis, which does not guarantee optimized (or maximum) multi-year benefit, although it is very close to optimum.

Linear Programming (LIN)

This method provides more capabilities than any other method. The criterion is to maximize multi-year benefits in the presence of yearly budget limits. This is the only method that can consider the rehabilitation type and timing trade-offs and at the same time impose the yearly budget constraint. The performance of this method, however, is similar to or poorer than that of IBC. Notice that LIN is used as a replacement for integer programming since integer programming solutions were not possible. Thus, LIN does not guarantee that the solution is an optimal solution.

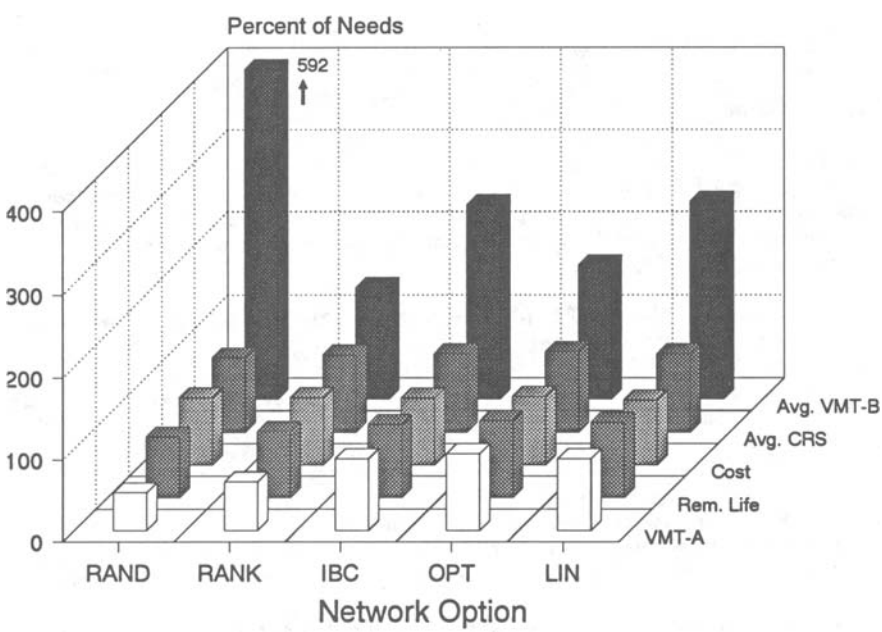

FIG. 6 -- Network Parameters as Compared to NEEDS parameters.

TABLE 3 -- Capabilities and Performance of Network Management Methods.

	Random	Ranking	Needs	IBC	OPT	LIN
Budget Limit	None	Yearly	None	Yearly	10-year	Yearly
Rehab. Type Tradeoffs	No	No	No	Yes	Yes	Yes
Rehab. Timing Tradeoffs	No	No	No	No	Yes	Yes
Long Term Performance	V. Poor	Poor	Fair	Good	V. Good	Good
Analysis Period Performance	V. Poor	Good	V. Good	Good	Good	Good
Total Added Benefit	V. Poor	Poor	Fair	Good	V. Good	Good
Overall Effectiveness	V. Poor	Poor	Fair	Good	V. Good	Good

CONCLUSIONS

Several conclusions are drawn from the application of different pavement network rehabilitation methods to a sample pavement network. These conclusions are related to the effect of each method on pavement network performance as compared to cost. Followings are a list of findings.

1. Optimization methods (OPT, IBC, and LIN) provided the best pavement network performance for a limited budget.

2. NEEDS provided a reasonable estimate of budget unrestrained pavement rehabilitation needs over 10 years to maintain all pavements above a certain condition level. Network performance for NEEDS was reasonable, although not as good as for optimization methods, and funding required varied year to year.

3. The long-term (10-year) performance of the network when rehabilitations were selected by the worst-first RANK method was significantly worse than when done by optimization methods, although the short-term performance was not different.

4. Randomly generated ad hoc pavement rehabilitation selection (the RAND option) demonstrated poor performance both in the short-term and the long-term in comparison with other methods, especially optimization methods for the same budget. The benefits of pavement management can be clearly seen by comparing these results to any of the other methods.

5. The B/C method showed improved long-term performance over RANK, although not as good as the optimization methods.

6. Long-term optimization (OPT) provided the best short-term and long-term network performance for a multi-year budget limit; however, IBC and LIN were approximately equal to OPT.

7. LIN and IBC demonstrated similar performance, while each have different capabilities. Both methods can consider yearly budget constraints. IBC considers rehabilitation type trade-offs, while LIN considers rehabilitation type as well as timing trade-offs.

8. LIN provides a solution close to optimum but not optimum, thus, this option only provides an approximation to the integer programming solution.

9. OPT and IBC are two valid methods of network management with comparable results but different capabilities. OPT is capable of considering rehabilitation type and timing trade-offs, while IBC can only consider rehabilitation timing tradeoffs. Therefore, OPT provides more benefit than IBC for the same cost. On the other hand, IBC gives a more realistic estimate since it considers yearly budget limits and rehabilitation timing is controlled by delays.

10. IBC is a very flexible and efficient method of pavement network rehabilitation management which is far better than ranking and also provides similar results as other optimization methods. This method is recommended for use by Illinois DOT for planning and programming of Illinois Interstate highway network.

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RESEARCH AND INNOVATION TOWARD STANDARDIZED PAVEMENT MANAGEMENT

REFERENCE: Huddon, W. R. and Haas, R. C. G., "Research and Innovation Toward Standardized Pavement Management," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: Pavement management implementation experience suggests that many of the same problems found in PMS in the 1970's still exist in the 1990's. A comprehensive program of research and innovation within the context of a standardized pavement management process is required to address these problems. The program should consider the issues, both process- and technology-related, and it should incorporate short-term, immediate problems, intermediate and long-term or strategic research, plus implementation. In addition, the elements of successful research must be represented, including the short-, intermediate- and long-term planning effort, top-level commitment plus sufficient financial support, flexibility and freedom for innovation, development of research capability, and dissemination of the research results. Finally, there are many specific opportunities for innovation and major advances in pavement management technology and application within several broad areas ranging from the development of long-term performance-based specifications to a major program for codifying the next generation of pavement management.

KEYWORDS: pavement management, research needs, issues, standardization, framework, generic, planning, innovation, implementation, opportunities, specifications, technology, advances

INTRODUCTION

Pavement management has progressed from a concept in the 1960's to a working process in the 1970's to a significant degree of implementation in the 1980's. The principles have been formulated and much has been learned from implementation experience at the federal, state/provincial and local levels in various countries. By the year 2000 many more agencies will have adopted pavement management systems.

But the improvements in application and implementation have not been matched

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by improvements in the component technology of pavement management. Many of the same problems that existed in 1970, such as the lack of good, long-term performance prediction models, still exist in the 1990's.

A substantial amount of innovation will be necessary if we are to realize a standardized pavement management process with widespread or universal applicability. Such a PMS must be technically sound and comprehensive underpinnings yet having sufficient flexibility for tailoring to individual agency needs and resources. The required innovation and research should range from short-term problem solving to strategic efforts for technology and application improvements.

This paper presents an outline for a program of research to develop innovations which can achieve the desired improvements. More specifically, it has the following objectives:

1. Review the changing nature of pavement research and the associated issues or needs.
2. Describe a standardized or generic structure for pavement management within which the component activities, and research toward their improvement, can be incorporated.
3. Describe the major types of research which must be carried out for a successful program of improvements in pavement management technology and application.
4. Define the major elements of successful pavement research.
5. Identify some of the opportunities for innovation and major advances in pavement technology and application of the process.

CHANGING NATURE OF PAVEMENT RESEARCH AND THE ISSUES

In order to develop a program outline for innovation, it is useful to first review the changing nature of pavement research and the issues it has addressed in historical context. Table 1 provides a listing which illustrates the emphasis of research over the past 30 years. Also listed are some of the needs which had an influence on the direction and emphasis of the research. Table 1 is not complete; rather, it shows that while the issues and the research emphasis have changed to a considerable degree, many of the problems are still with us. For example, the needs for better performance predictions, materials, construction and maintenance technology, data bases, energy conservation, traffic and load input data, are as important as ever, if not more..

Table 2 shows some of the needs expected to be of key importance in the 1990's. The breakdown into General System Technology-Related vs More Specific Technology-Related is intended more for broad identification than for sharp classification. How pavement research will respond, and what the emphasis will be, still remains to be determined. Certainly, the Strategic Highway Research Program (SHRP), initially formulated in the mid 1980's and initiated in 1987 [1], addresses a number of the issues from Table 2. However, it should be noted that SHRP is technology-related and does not address pavement management per se. Moreover, SHRP cannot address or solve all the pavement problems that exist. Adoption or incorporation of the results into the technology base for pavement management still largely remains to be carried out over the next decade or two.

TABLE 1 -- Changing nature of pavement research and associated issues/needs

	Research Emphasis	Needs/Demands
Pre-1950	• Empirical observation of what works • Development of load spreading concept; Westergaard and Burmister theory • Development of empirical test methods (CBR, Marshall, Hveem) • Specifications (materials, construction)	Provide pavement structures for increasing loads and traffic; all-weather surfaces for rural needs; wartime "lessons" on needs for structural design procedures, specifications, test methods, improved construction, etc.
1950's	• Tying down basic properties of materials (asphalt, cement mixes); standardizing test equipment and procedures; developing improved specifications • Develop better materials processing and construction technology • Designing and carrying out AASHO Road Test	Providing materials and technology for initiation of the post-war road-building boom, including start of the Interstate system; lack of knowledge on relative damage effects of heavy roads
1960's	• Relating asphalt properties to observed pavement problems (i.e., cracking, durability) • Analysis of AASHO results (load equivalency factors, serviceability - performance concept, design equations) and adoption to state practice • Initiation of satellite tests and long-term pavement performance observations • Initiation of computer-based layer methods of structural analysis • Initiation of pavement management research	Need for solving major distress and performance problems appearing in pavements; demands for better-quality materials; adopting AASHO Road Test results (i.e., new Guides); developing more fundamentally based methods of structural design; need for performance and distress models

TABLE 1 -- continued

1970's	• Developing improved structural design technology • Equipment and procedures for in-service measurements and evaluation • Develop pavement design and management methods (FPS, RPS, SAMP, OPAC, etc.), including life-cycle economic analysis and priority programming • Development of recycling technology • New materials (sulfur-asphalt, polymers)	Need for better, more comprehensive data bases, performance estimates for design alternatives, identifying most economic alternatives, better traffic and load inputs; need for improved priority programming procedures and more comprehensive pavement management in general
1980's	• Network-level PMS application • Automation of in-service pavement evaluation • User/cost relationships • Microcomputer-based PMS methods, models and procedures • Maintenance and rehabilitation (treatments, performance predictions, economic evaluation) • Initiation of SHRP studies • Reliability concept in AASHTO guide • Performance based specification	Energy conservation; user costs; effects of loads, environment and their interactions on pavement deterioration; cost allocation; premium or new, improved materials; implementation of pavement management at state and local levels; improved airport PMS.

TABLE 2 -- Key pavement issues in the 1990's

A. <u>General system-related issues</u>

- Efficient, reliable tools for determining and interpreting physical conditions of pavements
- Rehabilitation of an agency highway network
- Automation of construction and maintenance
- Relevancy between specification and quality and performance of the end-product
- Toward true end-product specifications (based on long-term pavement performance)
- Reliable measurements and forecasts of traffic and loads
- Long-term monitoring of performance and behavior (in-service sections, test roads, relationships between controlled, laboratory measurements and in-service observations)
- Broader application and implementation of pavement management and equitable allocations of funds; assessments of long-term implications of funding decisions
- Fair, user-tax assessments from different classes of vehicles
- Better evaluation of variability and formal incorporation of risk management procedures and decisions
- Attraction of qualified people, improved quality of training and education (including continuing education)
- Improved productivity and better utilization of technology from other fields
- Energy conservation in construction, production and processing of materials, vehicle operation
- Integration of pavement management with other facilities management systems

B. <u>Specific technology-related issues</u>

- Solving specific asphalt distress problems (stripping, thermal cracking, rutting, binder aging, reflection cracking through overlays) and specific Portland cement concrete pavement problems (faulting at joints, spalling, cracking)
- Alternatives and timing for preventive and corrective maintenance treatments to maximize cost-effectiveness
- Recycling of waste and reclaimed materials (asphalt, concrete, bricks, tires, plastics, spent foundry sands, fly ash, roofing materials, etc.) into pavements
- Modified, premium-quality asphalts (through polymer or other related processes)
- Fundamentally based test methods and compositional analyses for binders, and relationships to in-service behavior
- Upgrading of marginal materials and/or selective use in pavement type and structure
- Performance prediction models which identify load, environment and interaction-related losses
- High-speed, automated, reliable methods of deflection and surface distress measurement

TABLE 3 -- An activity/decision-based generic structure for pavement management

Basic Blocks of Activities	Network Level (Administrative and Technical Decisions)	Project Level (Technical Decisions)
Data	• Sectioning and data acquisition (field data on roughness, surface distress, deflection, etc., plus traffic, cost and environmental data); portrayal of present status • Data processing and evaluation	• Subsectioning and detailed data acquisition (materials, traffic, unit costs, traffic, etc.) • Data processing and evaluation
Criteria	• Minimum or maximum acceptable levels (serviceability, surface distress, structural adequacy, etc.) • Maximum program costs • Maximum levels of traffic interruption • Selection basis (i.e., cost-effectiveness	• Minimum or maximum as-built conditions (roughness, structural adequacy, surface friction, etc.) • Maximum project costs • Selection basis (i.e., minimum net present worth of costs)
Analyses	• Present needs sections, deterioration predictions and future needs sections • Maintenance and rehabilitation alternatives for needs sections, deterioration predictions, life-cycle costs and benefits • Priority analysis for different budget levels or for specified performance standard(s)	• Within project rehabilitation or maintenance alternatives, detailed field and laboratory tests • deterioration predictions (serviceability and distress) for alternatives • Economic evaluation of alternatives
Selection	• Determination of final programs of rehabilitation and maintenance • Program recommendations, administrative and elected body approvals	• Best within project or section maintenance and/or rehabilitation alternatives
Implementation	• Establishment of work schedules and sequences, contract tenders and awards • Program monitoring • Budget and financial planning updates • Inventory and data base updates	• Construction activities, work control and quality assurance, as-built records • Maintenance activities and management, records • Data base updates

STANDARDIZED (GENERIC) STRUCTURE FOR PAVEMENT MANAGEMENT

In order to realize maximum benefit from the results of pavement research, a structure or framework for incorporating resulting innovations into pavement management practice should exist. Such a structure facilitates the actual mechanisms for adapting and implementing innovative results.

One of the first definitions of a standardized pavement management structure for both the network- and project-level sets of activities was set out by Haas and Hudson (Ref. 2, 3) and later updated (Ref. 4). Table 3 provides a summary outline of the structure and a listing of some of the key component activities or decisions. This is a framework only. An actual operating system for a particular agency would have a linked set of their specific models, methods, and procedures which comprise these activities. However, a framework combined with an agency's specific system (which may or may not include all the activities of Fig. 1), can enhance the identification of issues and needs, research priorities, and the implementation of the results, as subsequently discussed.

The question of whether the future evolution of pavement management will require a different structure than shown in Table 3 has been considered in Ref. [5]. It was concluded that this should not be necessary for at least the next decade because the structure is quite amenable to progress, it allows for agencies to exercise flexibility, and it provides a consistent philosophy for addressing issues and needs. Moreover, because of its generic basis, it is in fact applicable to the management of other facilities, with of course some modifications of particular terminology.

MAJOR TYPES OF RESEARCH AND BENEFITS OF A COORDINATED PLAN

Many state and federal agencies have prepared statements of pavement research needs, research plans, and programs of technology transfer. These are necessary and a large amount of useful research has been carried out. However, what is often lacking is an overview of what is required for a successful program of research, and the associated long-term benefits or payoff.

To achieve such success, the following four major types of research should be incorporated in the overall approach:

1. Developing solutions to short-term, more immediate problems and applications,
2. Intermediate-term research and development,
3. Strategic or long-term research,
4. Implementation, including technology transfer and the development of research capabilities.

Emphasis in pavement research for the past several decades has been on items 1 and 4, short-term research and implementation. Lack of support in intermediate and long-term efforts leave us facing in the 1990's many of the same problems we faced in 1970. On the positive side, SHRP, which began in 1987, and has provided a focal point for reevaluation of some overall pavement research needs (although it does not address PMS research needs per se). Of particular importance to pavement managèment are the Long-Term Pavement Performance (LTPP) Study, the asphalt studies, and the maintenance studies of SHRP.

Because of the predominant short-term focus, however, some of the problems identified in previous decades still limit the use of current research findings, including the development of new models. In addition, because there is not a truly universal PMS available, much of the knowledge gained from past highway experience is being lost as staff retire. Literally, the experience gained in the 1950's, 60's and 70's is rapidly disappearing from the scene with continued retirement of senior staff.

It is important to have an overall, coordinated plan to guide future funding and to address future needs. Benefits that can derive from such an overall plan for PMS research include the following:

1. Provide the means for seeking and organizing results of research that is performed both nationally and internationally.
2. Provide direction for future research funding and enable personnel to tailor research to future national needs.
3. Provide a coordinated avenue to implement innovation more readily.
4. Limitations and shortcomings of existing and historical methods can be more rapidly identified and lead to the recognition of important research projects.
5. Current knowledge, data, and research results can be integrated into a coherent strategy that is consistent with long-term needs.of standardized PMS.

ELEMENTS OF SUCCESSFUL RESEARCH

Among the elements of a successful program of research are the following:

1. Having an overall plan for short-, intermediate-, and long-term research.
2. Top-level commitment and support plus sufficient funds.
3. Continuity of funding, not stop and start.
4. Providing the flexibility and freedom for innovation.
5. Developing research capability (people, facilities, etc.)
6. Cooperation between practitioners and researchers.
7. Disseminating the results of the research (publications, conferences, workshops, seminars, short courses, etc.).

1. An overall plan

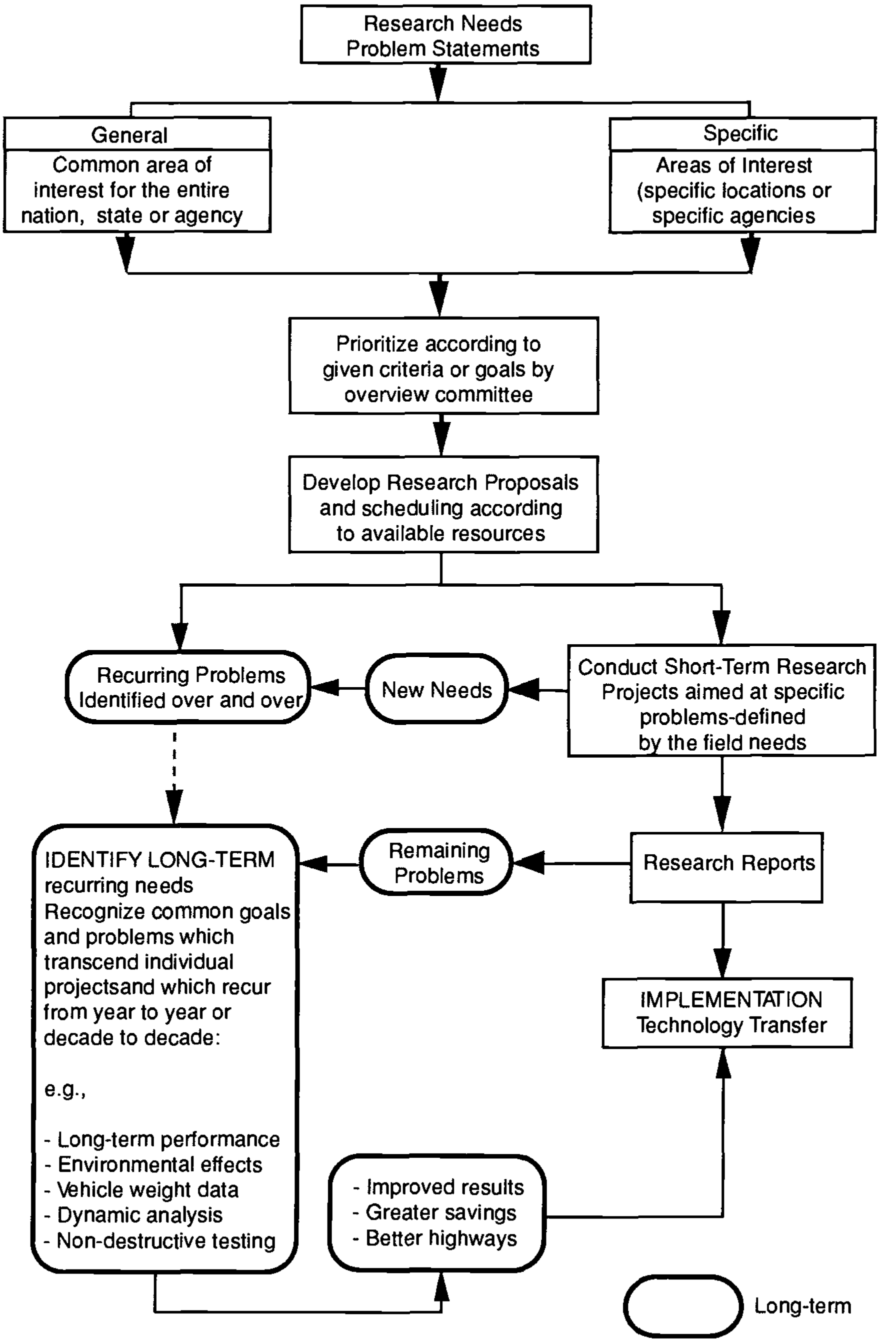
An integrated, overall plan covering short-, intermediate-, and long-term research is particularly essential for state and federal agencies. The issues of current concern might carry the primary focus but a "macro" approach will allow for better interaction between projects, better identification of priorities, preserve the long-term integrity of the research, and permit more efficient, overall program management. Figure 1 provides a framework for such an overall approach, applicable to states.

2. Commitment and funding support

Successful pavement management systems at both the state and local levels have had, without any known exceptions, strong, top-level commitment and support in the organization. Similarly, pavement research programs must have such commitment and support, in addition to the expected commitment of the researchers themselves.

Sufficient and consistent funding with a reasonable degree of flexibility is also necessary. This is not to say that justification for funding and identification of expected payoffs aren't necessary. If these payoffs are to be realized and the opportunity for innovation is to exist, such funding support and flexibility are essential components.

Fig. 1 -- Pavement research for the state DOT's (conceptual approach).



Organizational support in terms of facilities, staff, opportunities to interact with practitioners and researchers both within and outside the agency, and very importantly encouragement, is also important to successful research.

3. Continuity of funding

To be successful, research funding must have reasonable continuity. This does not mean a blank check but rather the opportunity to meet real breakthroughs with adequate support and funding. Innovation does not occur on a schedule, it happens in unique and unexpected ways and should be nonrestricted.

4. Flexibility and freedom for innovation

A common thread of successful, innovative research has been the degree of flexibility and freedom provided to the researchers. Innovative results cannot be mandated. They come from hardworking, innovative people who are not placed in a bureaucratic straightjacket of administrative control. Particularly constraining is a detailed, procedural environment where more time is spent in progress reporting than in actually doing research. A research management team should select researchers in whom they have confidence. A multi layer mixture of administration and control is the key to good results. The AASHTO Road Test is the prototypical example where Bill Corey had the authority and the freedom to fulfill the project mandate.

It must also be recognized that research may carry a considerable degree of risk, and that the payoff in terms of implementation may be some distance in the future. Thomas Edison tried more than 100 material combinations before he succeeded in unveiling the first electric light bulb. He "failed his way to success."

5. Developing research capability

Research capability resides in universities, institutes, consulting organizations, state, and federal research groups. While much of this capability has been acquired "on-the-job" research projects, the basic source is the universities. Many graduates who are active in pavement research have post-graduate degrees and they learn the basic concepts of statistics, analysis, etc., required for research success.

Development of capability at the source requires dedicated, competent students, research support, coursework and direction from professors. If one looks at the highly regarded pavement researchers in the U.S., Canada, and abroad, at the universities, public agencies, and in the private sector, a substantial number of them come from places having an extensive track record of educational excellence and research accomplishments.

It is essential that continued regeneration of research capability occur, with universities playing an integral part, and that there be a strong interaction between the public and private sectors and the universities.

6. Cooperation between practitioners and researchers

Successful innovation can best be implemented if the practicing engineer is involved from the beginning. A PMS makes this possible because the feedback loop for new innovation is hinged on the results of field use and upgrading of the PMS. It is important for practitioners to recognize that there is such a thing as appropriate research methodology which must be used to produce the best results.

7. Dissemination of research results

Research results need to be disseminated within organizations and externally for peer review. Of course much of the internal success is in terms of implementation and improved efficiency or cost-effectiveness, but external judgements are also important to follow-up work and its long-term success. There are many new techniques for dissemination of results which include, for example, videotapes, multi-media presentations and user friendly computer software programs.

The forums for dissemination of research results include journal publications, conferences, workshops, and seminars. The latter two forums are also often applicable to internal dissemination. Another important forum is represented by the "Advanced Course in Pavement Management Systems" of the FHWA, which has been held in a number of U.S. cities in 1990 and 1991 and which incorporates both up-to-date practice and recent research results [6].

CURRENT OPPORTUNITIES FOR INNOVATION

Evolution of pavement management

The evolution of the pavement management process provides a good context for identifying opportunities for innovation and major advances in technology, as well as the application of the process itself. Figure 2 provides a summary of this evolution at the network level. The assumption is that the process per se will not likely change substantially for at least the next decade, for two basic reasons: 1) implementation experience has shown that PMS is acceptable in its present form to most agencies; moreover, a period of time is needed for consolidation and for the large remaining number of agencies to install their systems; and 2) the major current thrust is improvement of the technology within the process, rather than the process itself. Research is needed on the process of pavement management.

The evolution of public sector network-level pavement management can be summarized in terms of two "streams," state/provincial/federal and local, as shown in Figure 2. Pavement management is expected to exist as a distinct and stand-alone process for the first stream during the 1990's. The reason is largely related to the size of the networks, the organizational structure, and the methods of budget preparation and administration for the state/provincial/federal situation. These authorities deal with a number of quite large management systems even within their transportation departments (i.e., airports, highways, pavements, safety, bridges, etc.) and it is extremely difficult to combine the benefits of each into a single stream. Consequently, the interfacing has to be done on a broad policy level.

For local agencies, it is quite likely that pavement management will evolve into a larger, integrated "Total Facilities Management" (TFM) type of system. This is indeed desirable where one office or individual, such as a Commissioner of Public Works, is responsible for underground services, traffic, pavements, bridges, parks and recreation, etc. Where pavement management systems can be valuable is that they represent the most advanced and comprehensive system development of all the facilities involved and can thereby provide the keystone or guidance for the development of TFM systems.

Fig. 2 -- Evolution of network level pavement management

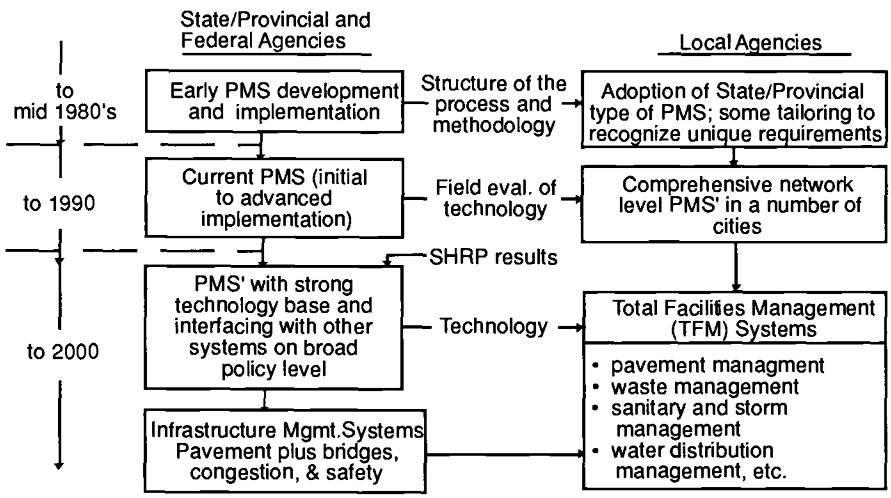
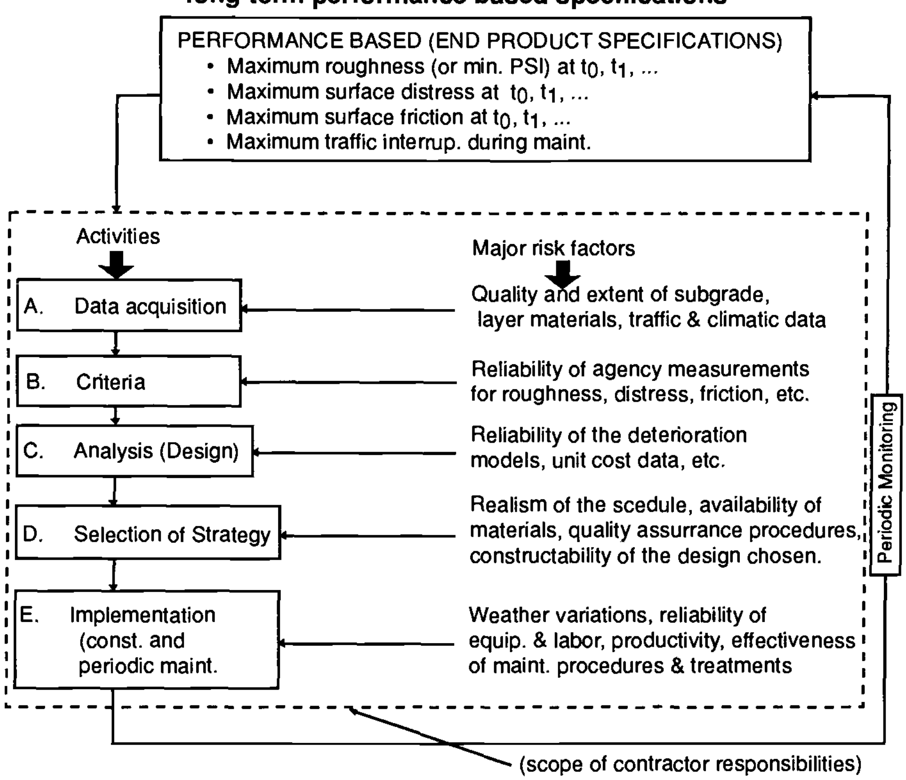


Fig. 3 -- Basic elements in the concepts of (end product) long-term performance based specifications



The opportunities for innovation thus lie in the areas of new and improved technology, process integration, and standardization of pavement management, as subsequently illustrated.

At the project level, pavement management will likely continue in the same generic form for at least the next decade. The major opportunities for innovation will therefore lie in the areas of:

1. Technology improvements (materials, processes, automation, characterization, analyses, equipment, etc.) and
2. Long-term performance prediction models for pavements.

The first area of opportunities is relatively self-explanatory but the second area represents something more long-term in nature, as subsequently described.

Areas of opportunities

Literally hundreds of specific opportunities exist for innovation in PMS technology and application of the PMS process. While comprehensive national and regional efforts to identify and prioritize these opportunities are very important, it is most useful within the scope of this paper to identify several broad areas of opportunity as shown in Table 4. Table 4 is not meant to be exhaustive, and the assignment of network- vs project-level applicability, degree of risk and short-to-long-term payoff is largely subjective. However, the areas listed represent a considerable range of opportunities and the context for many specific opportunities with regard to the following five areas:

1. Incremental improvements in technology,
2. Utilization of experience from more widespread and longer-term implementation of PMS,
3. Development of new equipment and methods, and their automation,
4. Application of new technologies (i.e., expert systems),
5. Design, construction, and maintenance of long-term performance "guaranteed" pavements.

The latter item depends on the development of long-term performance-based specifications (see Table 4, item 2). It represents a significant, albeit high-risk, opportunity which will require considerable standardization, particularly regarding the specification elements.

Figure 3 illustrates the concept of long-term performance-based specifications, using the generic structure described earlier in Table 3. Ultimately, this concept could function with the agency required to set the life-cycle, performance-based specifications and carrying out periodic monitoring. The contractor would be responsible for all project-level activities. This true end-product approach transfers the risk from the authority to the contractor. Its appeal lies in the innovation that can be explored between a premium pavement and a low first cost pavement with more extensive periodic maintenance. A specification on maximum traffic interruption would limit the extreme of a low-cost initial pavement with subsequent extensive maintenance and/or rehabilitation over the life-cycle.

TABLE 4 -- Ten areas which present substantial opportunities for major advances and innovation in PMS technology and application of the process

Opportunity	Network (N) and /or Project (P) level applicability	Degree of risk: High (H), Medium (M), Low (L)	Short (S), Intermed. (I) or Long-term (L) payoff
1. Development of a widely accepted, standardized structure or framework for pavement management which: a) allows flexibility for alternative models and tailoring to individual agency situations, b) includes staged implementation guidelines, and c) identifies or specifies deliverables of each stage for various types of agencies.	N & P	L	S
2. Development of long-term performance based specifications for pavements.	P	H	L
3. Development of an equitable and efficient method of: a) determining pavement damage due to loads, environment and their interactions, b) assessing the component damage costs, and c) assigning them to vehicle classes.	N & P	M	L
4. Quantification of the behavior, performance, rehabilitation strategy, and user-cost effects of various preventive and corrective maintenance treatments under various conditions.	P	M	I
5. Development of incentive programs for contractors, researchers, and public agêncy specifiers to realize full benefits of PMS improvements (i.e., encouragement of innovation by contractors, follow-through by researchers, and incorporation of new ideas or research results by specifiers).	N & P	M	S
6. Comprehensive identification and quantification of payoffs for technology improvements (truck suspensions which minimize damage, effective drainage systems, etc.) and solution of specific technical problems (rutting, reflection, cracking, etc.).	N & P	L	S, I and L
7. Development of comprehensive programs for improving the technical capabilities of contractors, public agency specifiers, and researchers to realize the full benefits of PMS research results.	N & P	L	S, I and L

TABLE 4 -- continued

8. Resolution of the inconsistencies between sophisticated analytical methodologies and the relative lower quality or approximation of input data (traffic, environment, material).	N & P	M	L
9. Development of effective "interfacing" between network and project-level PMS so that decisions are consistent.	N & P	L	M
10. Planning and executing a major (funded) program to codify the next generation of pavement management (including the standardized framework, incorporation of SHRP and other results from practitioners and researchers, etc.)	N & P	L	M

The approach of Figure 3 will of course necessitate certain practices related to performance bonds, financing, and the like which are different than generally used today. However, the basic concept of performance-guaranteed pavements can be advantageous to both the consumer and the contractor.

The last item of Table 4 would involve an effort similar to that required for developing the latest (1986) AASHTO Pavement Design Guide. It is important that the next generation of pavement management be codified or comprehensively described, and that it incorporate the latest technology and research program results (including those from SHRP) if the potential benefits of the vast amount of knowledge and experience available are to be realized. In addition, it is important that the team chosen to do this includes practitioners and researchers, as was included for the AASHTO Guide effort, and that they have sufficient freedom to innovate.

CONCLUSIONS

Pavement management systems have been implemented at the federal, state and local levels in many countries. The implementation experience gained suggests that there is a standardized or generic framework within which individual systems and their particular methods, models, and procedures are carried out. However, substantial improvements in this component technology are needed. Innovation and research are necessary to achieve these improvements. A starting point for identifying research needs is to consider the past, current, and future issues in the pavement field, and how the research emphasis has changed in response to these issues, as described.

The definition of a standardized structure for the pavement management process is also valuable in realizing maximum benefits from the results of research.

An overall approach to research planning should incorporate: a) development of solutions to short-term and immediate problems; b) intermediate- and long-term or strategic research; and c) implementation. Much of the past work on pavements has been short-term in nature; however, intermediate- and long-term research are needed for substantial payoffs.

The elements of successful research include the foregoing planning effort, top level commitment plus sufficient financial support, providing the flexibility and freedom for innovation, developing research capability and disseminating the results of the research.

There are many specific opportunities for innovation and major advances in pavement management technology and application. Comprehensive national and regional efforts are required to identify and prioritize these opportunities, but their scope are illustrated by several broad areas of opportunity. These range from the development of long-term performance-based specifications to the planning and execution of a major program for codifying the next generation of pavement management.

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CRITERIA FOR EVALUATING PAVEMENT MANAGEMENT SYSTEMS

REFERENCE: Paterson, W. D. O. and Robinson, R., "Criteria for Evaluating Pavement Management Systems," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: Agencies wishing to procure an available pavement management system appropriate to their institution and circumstances are faced with a complex series of tradeoffs between many system features and the probable need for system modifications. A set of generic criteria is presented for use in evaluating the completeness and appropriateness of a system, and in ranking alternative systems when a quantitative evaluation is desired. The fifteen criteria cover system completeness, the user interface, the analytical model, and data collection and management. The scope covers strategic planning, network programming and budgeting, project design and implementation (construction) monitoring. A supporting checklist of over 100 detailed criteria is provided for help in reaching a quantitative assessment.

KEYWORDS: Pavement management systems, evaluation, budgeting, programming, highway information systems, data collection.

Highway agencies wishing to procure a pavement management system (PMS) are faced with a complex series of tradeoffs which have to be made between a large number of system features. Some features relate to management systems in general and some to the institutional structure, practices and responsibilities of the particular agency. For example, the requirements of an independent agency with a single tier of administrative responsibility for highways differ from those

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of an agency with two or more tiers of responsibility and partially decentralized decision-making. In order to meet an agency's specific requirements, systems which are available may need to be modified or extended, and the agency would have to define precisely how far an available system meets its needs and the extent of the modification required.

This issue is addressed by developing a set of generic criteria for evaluating the appropriateness of a candidate system from the perspective of the client enduser. These consider the functional completeness of the system required to assist managers in forming various decisions and on the major features that are likely to determine the utility and credibility of the system. The criteria were originally developed for a systems evaluation for the ten countries of the Southern Africa Development Coordinating Conference region, but the criteria have now been revised for more general use. The scope is suited to the requirements of a major highway agency, and can easily be adapted for a local authority through adjustments to the scope of the completeness criteria and certain of the features.

DEFINITION AND FEATURES OF A PMS

Important to the definition of any criteria for evaluation is the understanding of what pavement management is to provide. This is an area in which applications of this methodology may be modified for individual circumstances. Pavement management should be viewed as a part of an overall highway management system comprising a Highway Information System (HIS) and several application modules or decision-support models. The classic definition of pavement management embraces the range of pavement-related activities from long-range planning to project design and implementation, and includes information gathering and feedback. Certain elements of this, however, are part of broader functions of a highway agency, such as planning, budgeting, routine maintenance and monitoring, where the pavement element is only one of several inputs (the others including new highway construction, structures, appurtenances, safety and operations). Thus, it is appropriate to focus the scope of a pavement management system more specifically to four functions which may constitute separate but linked management processes, namely:

a. Long-range planning of pavement standards, maintenance policy and needs, meeting economic goals and evaluating investment priorities;
b. Annual or near-term programming and budgeting of pavement works;
c. Project design of major pavement works; and
d. Monitoring the implementation and quality of works.

Each of these has distinctly different scope and periodicity, and may be operated by different divisions within an agency. The maintenance intervention standards and budget levels developed through the Policy process are inputs to the Programming process, but such Policy tools are rare [1, 2] and the standards and budget are frequently fixed independently by the agency. For some agencies, particularly those without central budget-disbursing functions, a policy optimization and planning tool may be considered unnecessary. The Programming and Project Design processes need to be compatible in analytical concept and decision criteria. In practice, many pavement management systems comprise only the works programming and budgeting function (b. above), while the pavement and rehabilitation design function is independent, which potentially may lead to designs, costs and priorities that conflict with those estimated in the program and budget. The implementation monitoring function (d.) facilitates project management and quality control, as well as automatically building up a comprehensive as-built inventory, but is the rarest component found in practice, as yet.

A distinguishing feature of systems is the way in which they acquire and process data for these different levels of usage and timing. For strategic planning, sample data (typically 1 to 10 percent of the network, depending on the type of information and reliability required) are sufficient for estimating trends reliably, e.g., [3]. However, where data with full coverage of the network are available, these can be used for strategic applications also by aggregating data of individual segments into classified groups, by mathematical sampling, or by summarizing results (which is viable when the network is fairly small). For example, if full coverage of the network is achieved with data suitable for the purpose of programming, designated sample sections can be obtained from the database without the need to make a separate survey. Alternatively, a coarse survey with light data collection over the entire network can be sufficient for strategic planning and identifying potential project sections which would then have a detailed survey and analysis at a later stage. This latter approach would be a distinctly two-phase data collection - periodic full coverage with few data items, and separate detailed surveys when and as required for project design.

The two-tier approach helps to concentrate expensive engineering resources on the detailed treatment selection and design of projects that are strong candidates, while the routine processing of large volumes of network data is carried out automatically at the summary network level. On the other hand, automated composite equipment that measures several parameters of road condition and characteristics simultaneously at traffic speeds and stores the data directly in computer-readable format, is making the acquisition of detailed data network-wide more efficient and feasible. Guidelines for evaluating these options are under preparation [4].

Institutional Setting

The institutional context has a strong bearing on the type of PMS which is likely to be successful. The rating of individual features should be in the context of the network characteristics, organizational structure, managerial style, and technical capability of the agency. The current practice of maintenance management, the acceptability of introducing a PMS, and the anticipated commitment to it need to be identified. Approaches to assessing the capability of the institution in this way have been documented elsewhere [5], and such an institutional appraisal will assist greatly in putting the criteria into context.

EVALUATION CRITERIA

A set of criteria have been defined for evaluating a system in respect to its utility and its appropriateness to the intended applications and institutional setting. These are grouped under four main headings, viz:

- completeness with respect to all applications required of the system, and the resources required to complete it;
- user-friendliness;
- reliability and validity of the decision model; and
- data management.

The fifteen criteria are listed in Table 1. These criteria and the balance of scoring are considered to represent the balance of features important to a highway agency from the perspective of end-users. The weighting is designed to give 60 points to the overall completeness relative to the requirements and equal weight (40 points each) to each of the last three features. Within each category, relative weightings are assigned to individual aspects, as shown in the table, but these may be varied to suit particular agency objectives.

Completeness and Completion of System

Completeness of System (1): Completeness is viewed in relation to all stages of the decision-forming process of the highway agency for all parts of the network. Three decision-making levels and two monitoring levels constitute a complete system, and the various attributes to be considered in evaluating completeness are as follows. The general compatibility of the system with the agency's management framework, network location reference system, and objectives can also be assessed.

Information Subsystem (1a): The data collected and stored should be relevant, complete and represent an appropriate quality of information for the decisions to be made [1]. The subsystem should comprise survey planning, data collection, processing, auditing, storage, communication and reporting.

TABLE 1 -- Key criteria for overall Eealuation of pavement management systems

	System Characteristic	Maximum Score
COMPLETENESS AND RESOURCES REQUIRED		
1.	Completeness of System for:	
	a) Information sub-system	8
	b) Multi-year planning and network trend analysis	8
	c) Network works programming and budgeting	10
	d) Project design and analysis	8
	e) Implementation and quality monitoring	6
2.	Resources required for completion, implementation and operation:	
	a) Information system	5
	b) Decision-support modules	15
USER INTERFACE		
3.	Efficiency of overall system	10
4.	User-friendliness of overall system	10
5.	Facility for interactive refinement of works program and budget	5
6.	Quality, extent and flexibility of reporting from analyses	10
7.	Robustness and security of system software	5
MODELS		
8.	Technical analysis	10
9.	Validity and calibration	10
10.	Sectionization	5
11.	Economic evaluation	5
12.	Prioritization and optimization	10
DATA MANAGEMENT		
13.	Data item requirements	10
14.	Data collection and processing procedures	15
15.	Data storage, retrieval and communication	15
Subtotals:		
	Completeness and resources required	60
	User interface	40
	Model	40
	Data management	40

Strategic network-level planning (1b): This module should represent the road system as a whole, distinguishing needs by functional and budgetary categories and not by individual links or sections. At this level, multi-year forecasts of key trends should be produced, linking needs, expenditures and the impacts on physical and functional performance indicators. Typical expenditure categories are new construction (capacity expansion, network extension), rehabilitation, resurfacing, and routine maintenance (or, e.g., the 4-R categories in USA). Key performance and other indicators include: a) pavement condition (roughness (IRI), serviceability, global indices, etc.), b) utilization (veh-km/yr, mean annual average daily traffic, ESAL/veh, ton-km etc.), c) functional level of service (veh-h delay, or other congestion measure); d) economic impact (total user costs, net benefits, rate of return). Ideally, the module should extend beyond pavements to all highway expenditures, including also, e.g., structures (bridges and tunnels), operations (safety, traffic management, enforcement). All these should show the impact of alternative budget scenarios on the condition and performance indicators for all the network over a medium term of two to five years, or longer.

Tactical network-level programming (1c): This module should identify specific sections and treatments, and either prioritize or optimize these to develop an annual (or/and rolling) program and budget. Preferably, the identification of the treatment should be sufficiently rigorous and compatible with the project design method that the work program needs little or no adjustment after the project design phase. Otherwise, the module should provide the means for iterative adjustments between the programming, project design and budget processes so that convergence can be facilitated. Differences in quantities arise from approximations in data and analysis, and in estimates of ancillary works. When the details of the work items are handled instead in the project design module, the programming module needs to make adequate allowances for them. The cost estimation procedure should approximate the actual costs of implementation so that budget estimates are reliable. The programming capability should extend beyond one year to two or preferably three years so that deferral of projects is properly evaluated in relation to near-term future needs and budgets, and reflects any cost-increase consequences of deferral. A lack of forecasting ability seriously distorts the priorities of short-term low-cost options relative to higher cost long-term options, and of deferment options. Lacks of predictive capability, post-maintenance performance evaluation, and economic benefit analysis, should be reflected in the rating of completeness (but note that the quality and reliability of these components are evaluated separately under "Model"). Finally, this module should assist in the preparation of relevant budget documentation.

Project-level design (1d): This module has to make a detailed analysis of pavement strengthening requirements to carry the applicable traffic loading; of surfacing and shape correction requirements to provide surface integrity, skid resistance, longitudinal evenness, transverse evenness and crossfall; of preliminary corrective maintenance; and of ancillary works including repairs to shoulders, drainage, minor structures and furniture. The most advanced versions combine the maintenance needs of individual subsections into project lengths which satisfy practical constraints such as suitable contract size, designated standards of uniformity along a link or route (avoiding the 'patchwork' effect), production efficiency in the execution of the works, and provision for ancillary and functional works (crossfall correction, shoulder repair, etc.). Typically, this module requires more detailed data than are used at the programming stage and these are usually gathered in a separate, project-specific field investigation. To be complete, this module should review economic benefits and priority in comparison to the original estimate from the programming module, and produce a bill of quantities, detailed cost estimates, and contract documentation.

Implementation and quality monitoring (1e): This should facilitate the monitoring of physical progress on committed works, quality control data, financial disbursements, and variation orders, and provide informative reports and graphics for the implementation and administration of projects, and feedback of the data to the road data bank.

Need for System Development or Customization (2): Candidate systems will almost inevitably require resources to modify and extend them to the level of completeness required by the agency user. Some of these modifications will customize the system to the agency environment, for example budget categories, work items, design codes, road monitoring measures, output reports, and so on. The scores in this case reflect the readiness of the system for implementation, and the costs and time required to achieve the desired system, with full marks representing full readiness and marks decreasing as development costs or time increase. The four decision modules may be rated collectively or else separately (e.g., as under item 1. in Table 1).

User Interface

Of great importance to the institutional acceptance and continued future use of the system is the system's interface with users in the agency. Considerations include the amount of effort and level of skill needed by an individual to operate the system, the flexibility and responsiveness of the system to user intervention, and system security.

System Efficiency (3): This rates the computational speed and analytical efficiency of the system in processing the data and producing outputs and reports. Any special devices offered or required by the system provider should be evaluated for efficiency under this heading, and under item (2) for cost implications.

User-friendliness (4): This rates the ease with which a user can gain access to and communicate with the system, operate the various parts, be aware of the stage of processing, enter instructions and data, retrieve and format outputs, resolve difficulties, and so on. Automatic linkages via screen menus are preferable to a necessity for using operating system commands. The user should not have to cope with widely differing software, instruction languages, or screen formats in the various modules. Documentation should be clear and comprehensive for user operation, system maintenance and system modification.

Interactive Capability (5): A PMS is a tool and aid to decision-making rather than a decision-taker. Thus, the facility for the user to interact with the system to modify the output, test sensitivity to alternative options or constraints, and evaluate the impact of changes is essential for the consultation phase of the decision process. User interventions need to be recorded so they are traceable, and need to show the financial, economic and physical consequences of the changes.

Reporting (6): This rates the appropriateness, legibility, appeal and comprehensiveness of the standard reports produced by the system, the ease of producing *ad hoc* reports, the graphics capability, and so on. The reports and outputs, on hard-copy and on screen, are the sole means of communication between the system and the great majority of end users, including top management, so this item is important and should be evaluated from the enduser's perspective.

Software Robustness and Security (7): Robustness is a measure of the system's immunity and response to errors in data, usually range and missing values, and other operator errors. Security is a measure of the provisions for preventing unauthorized access, controlling who may make changes in the system and to the data and how these may be done, and so on. Some software has standard security levels that can be utilized for this purpose.

Models

The credibility of the system depends ultimately on the accuracy and appropriateness of the analytical model for determining treatment needs, costs, benefits and priorities, making tradeoffs between alternatives, and preparing practical programs and budgets. Five evaluation criteria are identified, and a means of grading them from basic (Grade 1) to advanced (Grade 3) is suggested below. As the system may comprise different models for the Planning, Programming and Design Modules, the evaluation may be done separately for each one. What follows applies primarily to the programming module, and the criteria need adjustment when applied to other modules.

Technical Analysis (8): Grade 1 - thresholds of present condition and traffic, with standard prescription of treatment (one option per section); a variation indicates also the condition and life after treatment. Grade 2 - predicts structural behavior and functional performance of pavement, time to future threshold, and allows comparison of performance and life of various options (few primary options per section). Grade 3 - full life-cycle prediction of deterioration, maintenance effects, deterioration of maintenance surfaces, and the interactive effects of maintenance timing, traffic loading, volume, pavement strength and type, environment, and non-traffic-related deterioration; and simulation of physical impacts on users (speeds, delays, vehicle operations) (multiple options per section).

Validity and Calibration (9): The validity of the algorithms used in the models for predicting deterioration, maintenance effects, vehicle operations, etc. should be rated in terms of the applicability to prevailing pavement types, defects, maintenance types, environments, vehicles, etc., and of the predictive accuracy required for the decisions to be made. Theoretical models require rigorous calibration. Empirical models derived elsewhere may transfer poorly unless they include all major factors. An empirically validated empirical-theoretical model is usually most reliable. Ready facility for the user to calibrate and update the models to local circumstances and data is essential, and this should be through externally accessible parameters. An agency should expect to review and modify models periodically.

Sectionization (10): This is the basis on which individual road sections are aggregated to homogeneous segments for the purposes of a) analysis, b) uniform treatment, and c) contract packaging. Grade 1 - Fixed sectioning based on data collection intervals. Grade 2 - Pre-analysis sectioning based on pavement and traffic characteristics, with intervals and combination determined in relation to broad expected treatment categories such as routine, resurfacing, rehabilitation, reconstruction. Grade 3 - Post-analysis sectioning with modification to combine adjacent section-treatments into larger uniform treatment segments to achieve production and construction efficiency, and review of priority and economic returns for the segment-treatment combinations.

Economic Evaluation (11): Grade 1 - present costs of treatment and other works. Grade 2 - present and future costs, with breakdown for budgeting and cost-accounting categories, and benefits measured by cost-performance surrogate (e.g., area under the performance curve) or cost-effectiveness. Grade 3 - full economic (costs excluding taxes) and financial (costs including taxes) analysis of road costs, user costs (vehicle operating costs, delays, pollution, noise), discounting of the time-stream of costs to present value terms, and determination of net benefits by comparison of strategies.

Prioritization and Optimization (12): Grade 1 - Ranking by priority, defined by an *ad hoc* function of costs, condition and road class; and budget cutoff with spillover into succeeding year. Grade 2 - Ranking of best options by priority to maximize an objective function of economic benefits, cost-effectiveness, etc.; with annual budget cutoff, spillover, and evaluation of deferment options. Grade 3 - Formal optimization of multiple options (of sections, treatments and years) network-wide and over a multiyear period, allowing choice of best or non-best options to maximize an economic benefit function (or minimize a total cost function) within a series of specified annual budget constraints.

Data Management

Having reliable information is a prerequisite for successful pavement management, but to be valid and appropriate, the data must be relevant to the decisions to be made, must be affordable so that regular collection and updating can be sustained, must be reliable and adequately accurate for the intended purpose, and must be accessible to those who need to use them. Early generation PMSs included dedicated data collection and storage as a subsystem. In modern systems, the information system typically serves more than highway pavements, pavement management is just one application subsystem among others, and data must be managed in a wider context. The amenability of the information subsystem to upgrading and enhancement is the alternative to replacement. Guidelines [4] can be helpful in determining the information quality level (IQL) and data item list which are appropriate, and in specifying an information system.

Data item requirements (13): The data item list should include all items essential to the decision processes which are within the scope of the management application systems. The rating should thus reflect the relevance of each item and the completeness of the item list, taking account of the decision-making levels the HIS is to serve. The amount of detail which is appropriate for the size and capacity of the institution, and the level of application can be assessed in terms of the IQL and the data item list can be compared against the guidelines [4]. In particular, there should be a distinction between data for network level applications which must have full coverage, and data for project-level applications which may (and preferably should) have coverage only of recently identified or constructed projects.

Data collection and processing (14): Several aspects need to be assessed because methods vary from multi-step manual methods to composite automated methods. In particular, the collection method should be compatible with the IQL which is appropriate to the institution and the chosen applications. An assessment can be made for the following aspects:

a. flexibility of PMS to accept alternative collection methods;
b. efficiency and productivity of collection;
c. staff resources and skills required;
d. equipment resources and costs required;
e. training requirements;
f. reliability and accuracy of data;
g. use of sampling appropriate to network- and project-levels;
h. planning and scheduling of surveys;
i. data entry ease, efficiency and reliability;
j. data entry auditing; and
k. data reduction (ease, efficiency, appropriateness).

Data storage, retrieval and communication (15): The extent to which the database of the PMS is compatible with, or convertible to, the database management system of a full HIS, or specifically the institution's information system, should be assessed. Some thought may need to be given to a benchmark here, because a candidate system may have an inherently better DBMS than the institutional system, in which case penalization should be considered only if the candidate is incompatible, system-independence is undesirable, and there is no plan for the institutional system to be upgraded. Other factors to be assessed include:

a. efficiency of data storage and manipulation;
b. security of data storage;
c. efficiency, flexibility and quality of database enquiry and reporting facilities; and
d. amenability to future enhancement and extension.

DISCUSSION

Experience suggests that it can be helpful sometimes to first use a more detailed checklist when trying to reach a quantitative score. Table 2 shows a supplementary list for this purpose in which details can be scored on a 0 to 5 scale. When panel members have compiled their individual scores, the panel as a whole should review all items where the range of scores is wider than two, so as to resolve possible misunderstandings and reach reasonable consensus. Results from the detailed checklist can then be combined on a percentage basis to give the scores used in the main list in Table 1, weighted by importance (scaled A, B, C) where appropriate. Each item in the Table 1 list should be discussed by the panel to reach an overview perspective, when appropriate by consensus. In this way, an overall score can be built up for a system to see whether it achieves a minimum level of acceptability for a particular institutional environment. It also makes it possible to compare alternative systems on a quantitative basis.

TABLE 2 - Supplementary checklist

		Importance	Value
COMPLETENESS			
1. System Design			
1.1	Functionality as a component of a comprehensive road management system	C	S
1.2	Ability to work with location referencing system	A	S
1.3	Ability to accommodate future changes in scope of system, and upgrades of system components, hardware and operating systems.	C	S
1.4	Ability to support remote multiple users	C	Y
1.5	Relevance to implementing agency		
	a. directly (with only data entry)	B	S
	b. by modification	A	S
1(a)	Multi-year budget and network trends		
1(a).1	Applicable to network-level multi-year planning	B	S
1(a).2	Trend Analysis:		
	a. future trends	B	S
	b. past trends	C	Y
	c. aggregate indices	C	S

		Importance	Value
1(b)	Network programming and budgeting		
1(b).1	Network-level programming and budgeting	A	S
1(b).2	Network-level maintenance treatment selection	B	S
1(b).3	Multi-year prioritization	C	S
1(c)	Project design and analysis		
1(c).1	Applicability to:		
	a. project-level evaluation	B	S
	b. project-level design	C	S
	c. Implementation (scheduling, specification, control)	C	S
	d. Monitoring and feedback	B	S
1(c).2	Project level treatment selection	B	S
1(c).3	Comparison of treatment and intervention options	B	Y
1(c).4	Estimation of treatment quantities and costs	A	S
1(c).5	Audit:		
	a. technical, of work estimated/performance	C	S
	b. financial, of costs estimated/actual	C	S
2. Resources required			
2.1	For system implementation:		
	a. computer equipment procurement	B	S
	b. resources for software development and customization	B	S
	c. duration for software development and customization	B	S
	d. numbers and level of staff to be trained	B	S
	e. duration of training	B	S
2.2	For system operation (excluding data collection):		
	a. training	A	S
	b. staff numbers	A	S
	c. level of staff expertise in computing	A	S
	d. level of staff expertise in engineering	A	S
USER INTERFACE			
3. Efficiency			
3.1	Appropriateness of response times when dealing with input and output:		
	a. network analysis	C	S
	b. project analysis	C	S
	c. standard report	C	S
	d. ad hoc reports	C	S
3.2	Programming language used	C	S
3.3	Database management system used	C	S
3.4	Interface with data storage system	C	S
3.5	Efficiency of operation	B	S

		Importance	Value
4. User friendliness			
4.1	Ease of use and user-friendliness of software		
	b. quality of help screens	C	S
	b. quality of user documentation	B	S
	c. integrity of software	B	S
4.2	Facility for choosing level of analysis, and transferring results	B	S
4.3	Flexibility for specifying scope and constraints of analysis	A	S
4.4	PMS database:		
	a. Facility for enquiring and reporting	C	S
	b. Facility for manipulating data in database	C	S
5. Facility for interactive refinement			
5.1	Adjustment for program through optimization across projects and options	B	S
5.2	Budget preparation:		
	a. flexibility of budget breakdown	B	S
	b. regional allocation	B	S
6. Reporting			
6.1	format types: tabular, graphic, mapping, photographic	C	S
6.2	Relevance and usability of standard reports	A	S
6.3	Flexibility of standard vs ad hoc reporting	B	S
7. Robustness and security			
7.1	Reliability and robustness in connection with ease of use	A	S
7.2	Security		
	a. of software	A	S
	b. of application	C	S
	c. of data and access to data	A	S
7.3	Data entry and checking		
	a. Reliability of entry	B	S
	b. Validation and integrity checks	A	S
MODEL			
8. Technical analysis			
8.1	Type of decision model: [Present condition - treatment matrix (0-3); simple life and performance prediction (3-6); full life cycle of deterioration, maintenance, vehicle operation (6-10)]	A	S
8.2	Traffic congestion and geometric improvements	C	S

		Importance	Value
9. Validity and calibration			
9.1	Applicability to:		
	a. existing pavement types	A	S
	b. prevailing environments	A	S
	c. road classification and hierarchy	B	S
	d. road defects apparent in network	A	S
	e. existing vehicle classification	A	S
9.2	Prediction of pavement deterioration:		
	a. accuracy	A	S
	b. distinction of major distress types	B	S
9.3	Prediction of maintenance effects:		
	a. distinction between major treatment types	A	S
	b. allowance for quality of workmanship	C	S
	c. Influence of prior condition	A	S
9.4	Provision for calibration by user through parameters	B	S
10. Sectionization			
10.1	Pre-analysis	B	S
10.2	Uniform treatment (post-analysis)	A	S
10.3	Contract packaging (post-programming)	C	S
11. Economic evaluation			
11.1	Approach [e.g., present costs (0-2); cost breakdowns and surrogate benefits (3-5); road and user costs (5-8); full economic analysis, discounting future costs (6-10)]	A	S
11.2	Economic indicators	B	S
11.3	Cost Analysis:		
	a. Road costs	B	S
	b. User costs	B	S
12. Prioritization			
12.1	Approach (cost ranking, priority ranking, maximization function, economic maximization)	A	S
12.2	Multi-year, multi-section, multi-option optimization	B	S
12.3	Constrained budget optimization	C	Y
12.4	Facility for user-specific objective function	C	Y
DATA MANAGEMENT			
13. Data Requirements			
	Rate each data category (inventory, pavement structure, surface condition, traffic, costs) for the following:		
	a. Appropriateness of detail to network level	B	S
	b. Appropriateness of detail to project level	B	S
	c. Completeness for paved roads	A	S
	d. Completeness for unpaved roads	C	S

		Importance	Value
14. Method of data collection			
14.1	Collection of each data category (inventory, pavement structure, surface condition, traffic, costs) rated separately or collectively for:		
	a. Flexibility	C	S
	b. Facility of automation	C	S
	c. Productivity	B	S
	d. Staff resources	B	S
	e. Equipment resources	B	S
	f. Training requirements	A	S
	g. Reliability	B	S
	h. Use of sampling	C	S
	i. Network vs. project-level differences	C	S
	j. Survey planning	C	S
14.2	Data entry		
	a. Ease of entry	B	S
	b. Flexibility of entry	C	S
14.3	Data reduction		
	a. Availability of software	C	S
	b. Flexibility of software	C	S
15. Data Storage and Management			
15.1	Archiving of data from database	C	Y
15.2	Interface between form of data collected and data analyzed	B	S
15.3	Ease of future enhancement of data management	C	S

Note: Importance: A = essential, B = important, C = useful.
Value: S = score; e.g. 0-5. C = comment; Y = yes or no.

Development of a PMS from scratch by an individual agency is a very expensive and time-consuming operation. In addition, few agencies have the full range of management, systems and engineering skills that are required to design a complete, robust and data-efficient PMS. It makes practical and economic sense to purchase an off-the-shelf PMS from among the many now available. However, systems currently on the market range from the comprehensive, well-designed, robust and supportable commercial systems to those which, in reality, are little more than informally-developed products.

The purpose of developing the evaluation criteria here was to assist prospective procurers of a PMS in making objective and appropriate decisions. A further advantage is that such an objective approach may be helpful in justifying funding requests. However, it must be recognized that such a checklist of criteria provides only a basis for selection and assistance in reaching a good decision. Other, more subjective criteria may also be appropriate, such as the vendor's understanding of highway management issues, system concepts, communication skills (oral and written, for training), ability to understand the agency's needs and wishes, and training skills.

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Experience Section

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HISTORY AND IMPLEMENTATION OF PAVEMENT MANAGEMENT IN KENTUCKY

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ABSTRACT: Initiation of a pavement management system in Kentucky occurred in the early 1980's. Since that time, the system has continued to evolve into a more complex and extensive working system. This paper documents current pavement management practices and identifies future needs. The current organizational plan of the pavement management system is described. The goals, functions, and major tasks of the Pavement Management Branch of the Kentucky Transportation Cabinet are listed. A brief description of some of the pavement evaluation procedures currently being used is also included. It is concluded that Kentucky's pavement management system is well advanced, particularly in the area of pavement evaluation and condition assessment.

KEYWORDS: pavement management, pavement distresses, roughness index, rideability index, pavement condition.

INTRODUCTION

Transportation systems have developed rapidly during the past several decades and now represent considerable investment of resources. As these facilities age and traffic usage increases, the need for improved management of transportation facilities becomes more essential. The pavement structure is one of the most significant components of the road transportation system and represents a significant cost in providing transportation services. Sound pavement management practices are essential to provide acceptable service through efficient and effective allocation of funding, equipment, personnel, and other resources.

The fundemental objective for pavement management is effective and efficient directing of the various activities that deal with providing and sustaining pavements in a condition acceptable to the travelling public at the least life-cycle cost. The 1986 AASHTO "Guide for Design of Pavement Structures" states that "pavement management in its broadest sense encompasses all the activities involved in the planning, design, construction, maintenance, evaluation, and rehabilition of the pavement portion of a public works program." A pavement management system (PMS) is a set of tools or methods that assists decision makers in finding optimum strategies for providing, evaluating, and maintaining pavements in a serviceable

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condition over a given period of time.

The development of appropriate methodologies and procedures will vary widely depending upon the specific organizational structure and needs of the transportation organization. In spite of this wide variability in detail from one pavement managementsystem to another, nearly all systems require accumulation of some of the following information:

1. Observable pavement distresses,
2. Pavement rideability and associated level of serviceability,
3. Pavement deformation characteristics,
   a. Deflections under actual wheel loads,
   b. Dynamic deflections from such devices as the Dynaflect, Road Rater, and the falling weight deflectometer,
   c. Pavement rutting,
4. Pavement fatigue (ESAL's) information determined from
   a. Traffic volumes,
   b. Vehicle loadings,
   c. Traffic distributions,
5. Other pertinent data (skid resistance and safety),
6. Inventory information (length, width, etc.).

The exchange of information is one of the most important aspects of any pavement management system. There must be a continuing flow of information to other functions and management personnel regarding the performance and effectiveness of design, materials, construction, and maintenance. This flow of information necessarily makes a pavement management program an evolutionary process. Refinements and adjustments may be made as more data become available. In most cases, the pavement management system will become more encompassing and reliable as the size of data banks increases and histories of performance increase. Information derived from pavement management activities may be used at the network level for programming and funding allocation purposes. Similarly, pavement management data may be used to rank and establish priorities for specific projects and for making preliminary project design decisions.

The highway system in Kentucky consists of 112,362 km (70,226 miles). Of this 43,808 km (27,380 miles) are under the jurisdiction of the Kentucky Transportation Cabinet. This includes 1,221 km (763 miles) of Interstate, 1,013 km (633 miles) of Parkways (toll roads), 5,227 km (3,267 miles) of State Primary, 12,952 km (8,092 miles) of State Secondary, 19,474 km (12,171 miles) of Rural Secondary, 3,925 km (2,453 miles) of Supplemental Roads, and approximately 160 km (100 miles) of other roads. The first centralized efforts to manage this vast system of highways in a more structured, objective manner began in the early 1980's with the creation of the Pavement Management Branch within the Division of Maintenance. Much progress has been made in the last nine years in Kentucky's pavement management system. This is particularly so in the areas of sophistication, reliability, and in the use of the information obtained and distributed by the Pavement Management Branch.

ORGANIZATION OF KENTUCKY'S PAVEMENT MANAGEMENT SYSTEM

Major Areas of Responsibilities in Kentucky's PMS

Figure 1 illustrates, in a very general way, the major areas of responsibilities for the various divisions within the Kentucky's Department of Highways. The design of pavements for new and reconstructed roadways is the responsibility of the Division of Design. Included in the Division of Design's responsibilities is the use of pavement performance prediction models to develop designs, economic analyses, and optimization of alternate designs. Designs for rehabilitation projects are analized in the Division of Design based,in part,on recomendations made by the Pavement Management Branch. Final designs are selected by the

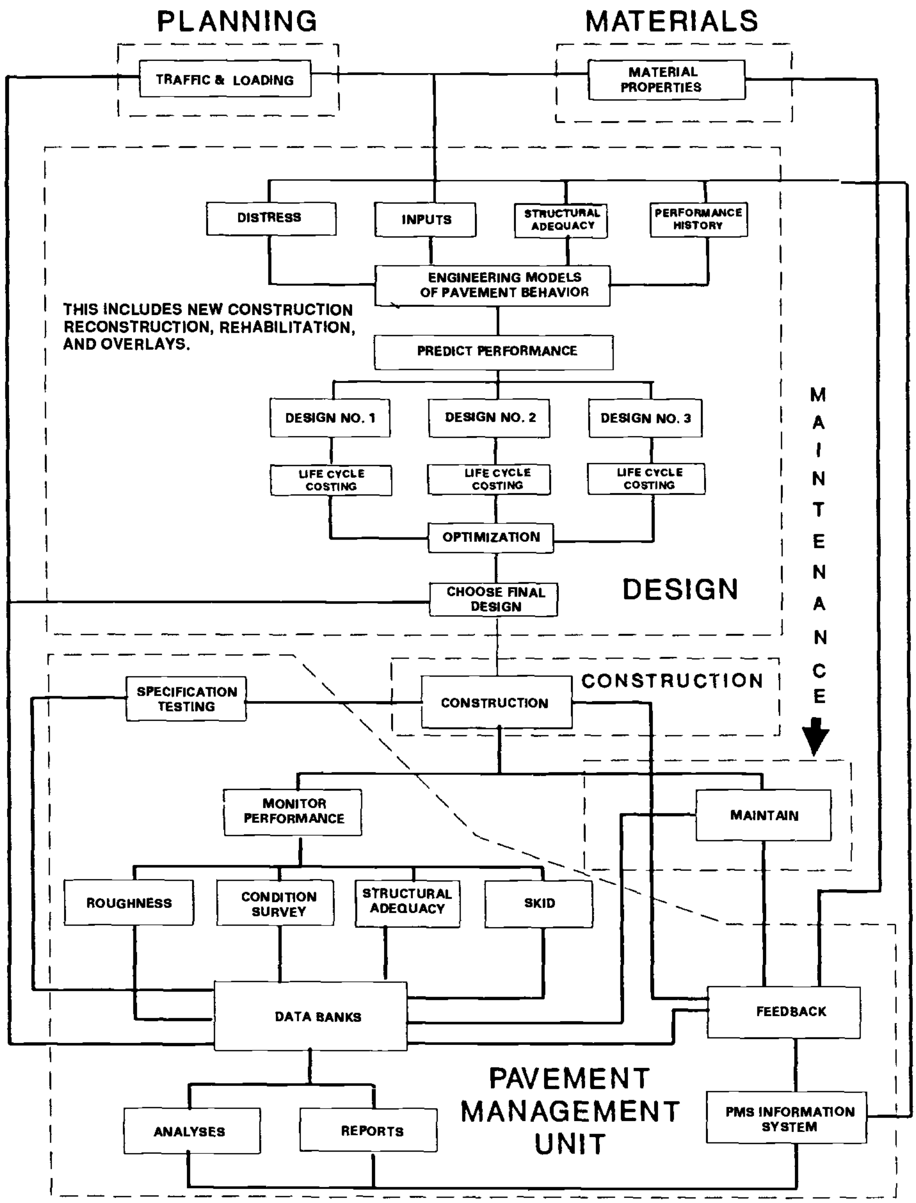


Figure 1. Flowchart of Kentucky's Pavement Management System.

pavements for new and reconstructed roadways is the responsibility of the Division of Design. Included in the Division of Design's responsibilities is the use of pavement performance prediction models to develop designs, economic analyses, and optimization of alternate designs. Designs for rehabilitation projects are analized in the Division of Design based,in part,on recomendations made by the Pavement Management Branch. Final designs are selected by the Division of Design after consulting with the Department's Pavement Committee.

The Division of Materials provides information on material properties and makes recommendations on suitable mixes. The Division of Planning provides traffic and loading histories,and projections. for pavement designs. The Division of Construction,of course, oversees the building of roads and rehabilitation of older pavements.

The responsibilities of the Pavement Management Branch will be discussed in detail in subsequent sections. However, briefly, the responsibilities of the Pavement Management Branch include system inventory, performance monitoring (this includes roughness surveys, structural testing and analysis, and detailed distress surveys), maintaining all pavement data bases, analyzing and reporting on performance histories, establishing pavement rankings according to needs, analyzing and reporting network conditions, reporting on network trends and needs, identifying projects that need structural rehabilitation, recommending rehabilitation strategies to the Pavement Committee, developing pavement performance databases, forecasting future trends, and providing other administrative units with reports as requested.

The Division of Maintenance is charged with the responsibility of performing routine maintenance activities on all pavements and is responsible for selecting and programming rehabilitation projects for all roads except for Rural secondary roads.

A permanent, standing Pavement Committee comprised of personnel from various divisions of the Department of Highways determines strategies for pavement rehabilitation, restoration, reconstruction and/or resurfacing. The Committee is the focal point for most pavement decisions. The Committee consists of representatives from the Division of Design (Pavement Design Branch), the Division of Specialized Programs (Pavement Management Branch), and the Division of Maintenance. The Committee coordinates (through its Chairman) with other divisions (Construction, Materials, Planning, etc.) within the Transportation Cabinet and outside agencies (Kentucky Transportation Center, FHWA, AASHTO, etc.) as necessary for pavement concerns.

The Committee reviews the priority listing of projects. The Committee is specifically responsible for reviewing rehabilitation projects for Interstates and Parkways and other road projects where pavements exhibit severe deterioration including rutting, excessive and severe cracking, excessive and/or severe base failures, and thereby require more detailed analyses. The Committee may also reviews proposed resurfacing projects where the interval between resurfacing has been less than five years. The Division of Design presents results of comparative analyses of alternative strategies to the Pavement Committee for review and concurrence. The Pavement Committee may make recommendations concerning reconstruction strategies.

Communication and Interaction within Kentucky's PMS

As stated previously, the Pavement Management Branch (PMB) is the primary source and repository of information in Kentucky's PMS. Information exchange occurs between the PMB and most of the technical divisions of the Transportation Cabinet, as well as the 12 District Offices, the Federal Highway Administration, the State Highway Engineer's Office, national technical organizations, and research agencies. Figure 2 is a flow chart that illustrates the flow of information to and from the pavement management

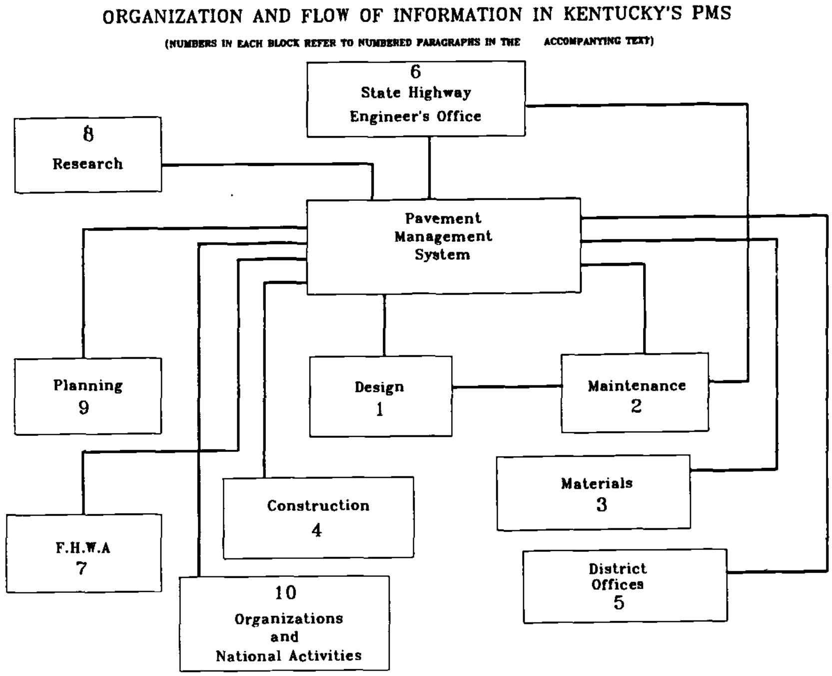


Figure 2. Organization and Flow of Information in Kentucky's PMS

unit. The number in each block refers to the numbered paragraphs that follow which describes the information that is normally exchanged between these agencies.

1. Design. PMB supplies the Division of Design with the results of structural analysis, the latest pavement condition information, and recommendations on treatments for specific projects. The Division of Design supplies PMB with detailed design information on alternate strategies for specific projects, economic analyses on individual projects, specification requirements, and information on which projects to specify rideability requirements.

2. Maintenance. PMB transmits to the Division of Maintenance information on condition evaluations and results of tests (these include deflection, roughness, and skid resistance). PMB also makes recommendations on resurfacing needs, project rankings, and treatments. Recommendations are presented on the allocation of resurfacing and machine patching monies for the Districts. PMB makes recommendations on the levels of funding for pavement improvements. The Division of Maintenance consults with PMB on rehabitation programs development. The Division of Maintenance also makes special requests of PMB for evaluation's and testing.

3. Materials. PMB provides results of skid tests and performance analyses to the Division of Materials. PMB also provides consultation on surface treatments. PMB receive requests from the Division of Materials for skid testing on specific types of surfaces, and the Division of Materials provides recommendations on applicability of various mixes.

4. Construction. PMB receives requests from the Division of Construction for rideability requirement testing on newly constructed and rehabilitated pavements. Results are transmitted to the Division of Construction when the testing is completed and the results are analyzed. Changes in requirements are proposed by the PMB,or others.

5. District Offices. District Offices provide PMB with a list of pavements the district wishes to be evaluated for the resurfacing program. PMB provides the results of pavement evaluations, and subsequent points ranking the pavements, and recommended treatments. District personnel will provide their priorities, treatment recommendations, and cost estimate.

6. State Highway Engineer's Office (SHE). PMB provides the SHE with pavement condition reports and reports on funding needs for pavement improvements. PMB also provides consultation on project selection and recommended treatments. Advice is also provided on pavement-related policy. PMB also assists the SHE in special analyses and requests.

7. Federal Highway Administration (FHWA). PMB provides FHWA with pavement condition information, justification for rehabilition of pavements on Interstates and the Federal Aid Primary System.

8. Research. PMB maintains a close relationship with the Kentucky Transportation Center (the research agency for the Kentucky Transportation Cabinet). Personnel of PMB provide advice and monitors research studies. PMB also provides data to be used in various research studies.

9. Planning. PMB provides updates on pavement condition surveys and systems analyses. It also provides roughness data on the Highway Performance Monitoring System (HPMS) statistical sections. Planning provides PMB with traffic data, ESAL data, and system classification data.

10. National Organizations. PMB maintains technical contact with such national organizations as the Transportation Research Board, the National Cooperative Highway Research Program, the American Society for Testing and Materials, and the Strategic Highway Research Program (SHRP).

Organization of the Pavement Management Branch in Kentucky's PMS

The Pavement Management Branch was organized within the Division of Maintenance in 1981. Shortly thereafter, the unit was moved to the State Highway Engineer's Office under the Assistant State Highway Engineer for Operations. The decision to place the unit at that level allowed for greater and more effective interaction of the Pavement Management Branch with other units within the Transportation Cabinet. In 1987, the unit was moved to the Division of Specialized Programs which is composed of several staff functions. The unit is staffed with three engineers, five technicians, and a secretary shared with another function.

GOALS AND FUNCTIONS

The concept of service to the highway user has guided development of the pavement management program by focusing efforts on functions that have a clear impact on the highway user.

Important pavement management functions necessary to address the objective are as follows:

- Measure quality of all pavements to assess general conditions and estimate current and anticipated improvement needs.

- Evaluate pavements to select those in need of rehabilitation or restoration and priority rank for programing.

- Assess impacts and recommend changes in programs, practices, policies and specifications affecting condition and performance of pavements.

- Maintain Pavement Database information base for effective communicating and coordinating of pavement related activities within the Department of Highways.

- Provide data, information, and results of analyses to other Transportation Cabinet units whenever necessary.

MAJOR TASKS

Although the major goals have not changed significantly in several years, current major tasks to implement the functions are as follows:

1. Conduct annual roughness surveys of all roads and summarize present condition of pavements by highway system, district, and county. Identify needs for pavement improvements, estimate funding needs, and allocate rehabilitation funds among highway districts on the basis of pavement conditions and other factors. Evaluate the relevance and significance of specific programs, construction procedures, specifications, and other practices. Identify pavements that may need rehabilitation.

2. Perform detailed pavement condition evaluations and analyses, including roughness, skid resistance and deflection testing, and observable distresses. Annually evaluate all Interstate and Parkway pavements and other selected pavements in relation to rehabilitation programs. Select and rank pavements for rehabilitation, recommend treatments and estimate costs.

3. Test for skid resistance and evaluate the performance of various pavement types. Recommend modifications of Departmental guidelines for selection of bituminous surfaces. Perform tests on pavements subjectively identified as being slippery and make recommendations on the basis of Departmental guidelines for de-slicking.

4. Test newly constructed and rehabilitated high-type pavements for conformance with Departmental rideability requirements.

5. Compile and maintain computer files of pavement related information.

TEST METHODS AND PROCEDURES

Roughness

Roughness measurements are made with six sedans equipped with Mays Ride Meters and on-board microprocessors designed to provide results at the time of testing and to record data for computer processing later. Tests are made at 80 kph (50 mph) and in accordance with ASTM E 1082. Test speed is reduced whenever geometrics of the roadway, posted speed, or traffic congestion prohibited testing at the standard speed. Roads less than 0.64 km (0.4 miles) long are excluded. Testing is confined to ambient temperatures above 10 degrees Celsius (50 degrees Fahrenheit). The results, in inches per mile, are converted to rideability index (RI). The RI scale ranges from zero to five. Zero means the pavement is too rough to be traveled at a reasonable speed of the road without high risk to the driver, while five means the pavement is perfectly smooth. The RI's may be viewed from rideability standpoint as follows:

Rideability Index	Rideability Assessment
4.0 to 5.0	Very Good Rideability
3.0 to 3.9	Good Rideability
2.0 to 2.9	Fair Rideability
1.0 to 1.9	Poor Rideability
0.0 to 0.9	Very Poor Rideability

Rutting

Rutting of asphaltic concrete pavements or wear of portland cement concrete pavements are measured with a ruler and a 1.7-m (67-inch) straightedge which is a sufficient length to span the ruts to obtain an accurate measurement.

Skid Resistance

Skid resistance measurements are made using a pavement friction tester in accordance with ASTM E 274. Pavements are selected for testing if slippery conditions are suspected based on either prior test results or visual condition surveys or when accident data indicate a disproportionate number of wet-pavement accidents. The measurement is expressed as skid number (SN), and the scale ranges from 0 to 100. Tests are made in the left wheel path of each lane at 0.8-km (0.5-mile) intervals.

Structural Evaluations

Pavement deflection measurements are not obtained routinely. Deflection testing is conducted on pavements where subjective evaluations indicate potential structural inadequacy. Pavement deflection measurements are made with a Model 2000 Road Rater (trailer mounted). The device, even though able to apply much larger dynamic loads (up to peak-to-peak of 24.46 kN [5,500 lb.]), is used to obtain measurements at peak-to-peak of 2.67 kN (600 lb.), 5.34 kN (1,200 lb.), and 10.68 kN (2,400 lb.) at a frequency of 25 Hz. The static load is 15.57 kN (3,500 lb.). Falling weight Deflectometer tests are also available through the Kentucky Transportation Center as is an additional Road Rater (Model 400).

Evaluation of asphaltic concrete pavements utilizes elastic layer concepts to determine, for each test location, the theoretical deflection basin that best matches the measured deflection basin. Pavement behavior is expressed as the effective thickness of crushed stone, the effective thickness of reference quality asphaltic concrete (modulus of elasticity of 3309 MPa [480 ksi]) and a subgrade modulus.

These values are used in combination with the design fatigue estimated from traffic projections to determine thicknesses of bituminous overlay to meet projected design ESAL's for each test location. Computed overlay thicknesses for the test locations are analyzed statistically to determine the 80th percentile overlay thickness requirement for the project length.

Structural evaluations of rigid pavements are more subjective and procedures are still evolving. Limited analysis to date involves relative comparisons of deflection measurements for one slab versus another slab. Additionally, the efficiency of load transfer has been estimated by comparing deflection basins for midslab versus deflection basins at a joint (or major crack) where the load is applied to one side of the joint but deflection measurements are obtained on both sides of the joint or crack.

Observable Distresses and Conditions

Cracking, base failures, faulting, raveling, spalling, and out-of-section are subjectively evaluated for Interstates and Parkways in terms of extent and severity. For other roads, edge failures are also included. Appearance of pavements is assessed from the perspective of the highway user in terms of good to very poor. Extent of pavement patching is considered only for Interstates and Parkways because prevailing practice on other roads is to do full-width, long-segment patching that must be considered as a capital improvement. Symptoms of distress are subjectively evaluated and are defined in terms of demerit points.

Interstates and Parkways: Pavements are visually inspected to assess conditions according to six elements and assigned condition points (demerits) as shown in Table 1.

Distresses and conditions are noted in both directions of travel by driving at reduced speed on the pavement and slowly on the shoulder for short intervals. The vehicle is stopped as necessary to inspect the pavement and to measure rut depths.

Other Roads: Pavements are visually inspected to assess conditions according to six elements and assigned condition points (demerits) as shown in Table 2.

Distresses and conditions are first noted during roughness testing in both directions of travel. Pavèments are then traversed again, if necessary, at a slower speed, and, where feasible, slowly on the shoulder for short intervals. The vehicle may be stopped as necessary to inspect the pavement and to measure depths of ruts or wear.

REHABILITATION STRATEGIES

General

Current practice for resurfacing asphaltic concrete pavements involves leveling and wedging and application of a 25-mm (1-inch) bituminous surface course. Structurally adequate pavements which have rutted to a depth of 9.5-mm (3/8-inch) or more may be milled to minimize leveling and wedging requirements and to improve rideability. Structurally adequate pavements may also be milled as much as 1 inch prior to overlaying to maintain shoulder or curb heights. Thicker overlays are recommended on the basis of subjective assessments and deflection analyses. Overlays of 51 mm (2 inches) or more (two pavement courses -- surface and binder) are considered thick overlays.

Extensive maintenance or restoration of rigid pavements has typically not been performed. The prevailing practice of overlaying rigid pavement, except for Interstates and Parkways, involves leveling and wedging with asphaltic concrete and overlaying with a 1-inch bituminous surface course. Thick overlays (102 mm to 203 mm [4 to 8 inches]) have been placed on Interstate and Parkway pavements in an attempt to minimize thermal expansion of the portland cement concrete slabs and thereby minimize reflective cracking. The practice of breaking the existing rigid pavement into 457-mm to 610-mm (18- to 24-inch) fragments, seating the fragments, and overlay with 140 mm (5.5 inches) or more

TABLE 1 -- Condition Points for Interstates and Parkways

	EXTENT FEW TO EXTENSIVE			SEVERITY SLIGHT TO SEVERE			MAXIMUM
Cracking	3	to	18	3	to	13	31
Base Failures (Faulting)	3	to	9	3	to	9	18
Raveling-Wear (Spalling)	2	to	6	2	to	6	12
Out-of-Section	2	to	6	2	to	6	12
Patching	2	12	12				12
Appearance	Fair to Very Poor (3 to 15)						15
							100

TABLE 2 -- Condition Points for All Other Roads

	EXTENT FEW TO EXTENSIVE			SEVERITY SLIGHT TO SEVERE			MAXIMUM
Cracking	1	to	6	1	to	4	10
Base Failures (Faulting)	1	to	3	1	to	3	6
Raveling-Wear (Spalling)	0.6	to	2	0.6	to	2	4
Out-of-Section	1	to	3	1	to	3	6
Edge Failures	0.6	to	2	0.3	to	1	3
Appearance	Fair to Very Poor (1 to 5)						5
							34

of asphaltic concrete has been used extensively on Interstate and Parkways. This treatment (first used in 1982) has been successful in controlling reflective cracking. Other rehabilitation practices for rigid pavements have involved installing edge drains, resealing joints, and diamond grinding surfaces. Full-depth and partial-depth portland cement concrete patching also is being done to extend the life of some pavements.

De-Slicking

Guidelines for selecting slippery pavements prescribe levels of skid resistance and benefit/cost requirements for pavements to qualify for de-slicking. Those guidelines state, in part, that roads (other than Interstates) having ADT's between 1,000 and 10,000 qualify for de-slicking when the skid number (SN) is less than 25 or SN is 26 to 32 and the benefits (accident reductions) and costs associated with de-slicking result in a benefit/cost ratio above 2. All Interstates and roads having ADT's above 10,000 vehicles per day qualify when the SN is 28 or lower or the SN is 29 or higher and cost associated with de-slicking results in a benefit/cost ratio above 2.

Selecting Bituminous Surfacing Courses

Performance and suitability of pavements have been analyzed to establish the Cabinet's selection guidelines for bituminous surface courses, which specify surface courses to be used for various traffic volume and travel speed levels. These are listed in Figure 3.

PAVEMENT CONDITION--INTERSTATE AND PARKWAY

Evaluations

Data regarding pavement and roadway sections are stored on discs and a form (Figure 4) is automatically printed for all routes according to construction termini. Data include location, construction and design information, traffic volumes, etc. The form provides for entry of demerit points associated with the various evaluation elements and results of roughness, skid resistance, and rut-depth measurements. The form also provides for entry of recommended treatment and ranking if the pavement needs rehabilitation, and assesment of shoulder and guardrail conditions.

Needs Estimate and Priority Ranking

Pavements on interstates and parkways in need of rehabilitation are identified each year from pavement condition evaluations. These evaluations along with historic rideability data and, since 1981, yearly pavement condition evaluations (Figure 5) provide a basis for estimating when other pavements may need rehabilitation. Pavements judged as needing rehabilitation are ranked in order of conditions. Pavements are ranked according to RI level, change in RI with time, deterioration (demerit points) from condition surveys, increase in deterioration (demerit points) with time, severity of rutting, and results of deflection testing. Pavements ascertained as needing rehabilitation later are tabulated by year through the next several years. Rehabilitation remedies and costs are estimated for each pavement. Costs are accumulated to quantify funding needs and for projections of programming needs.

Allocation of Funds

Allocation of funds for pavement rehabilitation of Interstates , Parkways, and other high-type facilities is based on demonstrated need. Those pavements which are judged in greatest need are given the highest priority. For interstates, the 4-R federal monies apply; however, pavement rehabilitation projects must now compete with other than pavement improvements. Priority rankings may be subjectively modified in consideration of other factors not related to relative conditions of the pavements.

PAVEMENT CONDITION--STATE PRIMARY, STATE SECONDARY AND SUPPLEMENTAL ROADS

Need Estimates

Detailed pavement condition evaluations are not performed on all pavements. Rideability indexes, however, are obtained for all state-maintained pavements. Analyses of rideability index, average daily traffic volumes, and subjective assessments of the need for resurfacing have indicated that need for resurfacing are associated with some critical RI (Table 3). Pavements at or below critical RI's, based on traffic volumes, are considered

GUIDELINES FOR SELECTION OF BITUMINOUS SURFACE COURSES

CATEGORY	TRAVEL SPEED (mph)	SURFACE COURSE
I.	All Interstate Roads	
		Bituminous Concrete Surface, Class AK
II.	High Volume Roads -- Roads with ADT of 6,000 and higher	
	A. 50 or higher	Bituminous Concrete Surface, Class AK
	B. Below 50	Bituminous Concrete Surface, Class I (40% polish resistant aggregate required and limit uncrushed sand to maximum of 20%)
III.	Medium Volume Roads -- Roads with ADT between 3,000 and 6,000	
	All speeds	Bituminous Concrete Surface, Class I (20% polish resistant aggregate required and limit amount of uncrushed sand to maximum of 30% except when the High Type Facilities Note applies the maximum uncrushed sand will be 20%).
IV.	Medium Low Volume Roads -- Roads with ADT between 1,500 and 3,000	
	A. 45 or higher	Bituminous Concrete Surface, Class I (20% polish resistant aggregate required)
	B. Below 45	Bituminous Concrete Surface, Class I (No restrictions on aggregate type)
V.	Low Volume Roads -- Roads with ADT below 1,500	
	All	Bituminous Concrete Surface, Class I (No restrictions on aggregate type)

OTHER SURFACES - Considered on a project to project basis
Bituminous Concrete Surface, Class N, and Bituminous Concrete Binder, Class I, and Sand Asphalt, Type II.

Note 1. Traffic volumes shown are for two lane roadways. For four lane roads, determine the equivalent two lanes volume for the shoulder or outside lanes from the attached chart.

Note 2. Lower category surface may apply when the project quantity of the wearing course is less than 500 tons.

Note 3. Stage construction or special mixtures may be specified for roadways where pavements may develop significant rut depth.

Note 4. Exceptions to these guidelines may be made with the approval of the State Highway Engineer in special cases when warranted by design, materials, or traffic consideration.

APPROVED: ____________ DATE: 11/30/90
State Highway Engineer

APPROVED: ____________ DATE: 1/14/91
Federal Highway Administration

Figure 3. Guidelines for Selecting Bituminous Surface Courses.

ROAD NO: I 64 ROAD NAME: Lexington - Ashland

COUNTY: CLARK DISTRICT: 7

FROM: Fayette County Line MP: 89.48
TO: KY 1958 MP: 94.23

ADT(89): 22200 LENGTH: 4.75

CONSTRUCTED NOV 63 DGA: 15 INCHES CBR: 5

CONTRACTOR FOR AUG 85 ACTION: Eaton

DATE	ACTION	PAVEMENT INCHES	PAVEMENT TYPE	SURFACE TYPE	REMARKS
NOV 63	CONSTRUCTED	7.5	AC		
OCT 73	RESURFACED	2.5	AC		
SEP 84	MILLED	-0.5	AC		
SEP 84	RESURFACED	2.75	AC		2.25" WB
AUG 85	SURFACED			OGFC	

VISUAL CONDITION SURVEY

(DEMERIT POINTS)	MAXIMUM EXT	MAXIMUM SEV	EB EXT	EB SEV	EB SUM	WB EXT	WB SEV	WB SUM
CRACKING	18	13			0			0
BASE FAILURES - FAULTING	9	9			0			0
RAVELING - WEAR SPALLING	6	6	4	3	7	4	3	7
OUT OF SECTION	6	6			1			1
PATCHING	12				0			0
APPEARANCE	__	15			0			0
>---- TOTAL ---->	51	49			8			8

REMARKS: ______

GUARDRAIL: POOR FAIR (GOOD) SHOULDER: AC : POOR FAIR (GOOD)

NUMBER OF LANES: 4	EB INN	EB OUT	WB INN	WB OUT
PREVIOUS RI (88):	3.7	3.8	3.8	3.8
RI:	3.8	3.7	3.8	3.8
DECREASE IN RI:	-	.1	0	0
RUTTING (INCHES): Varies up to 1/2"		5/16		3/16
SKID NUMBER:				

RECOMMENDATIONS: OVERLAY MILL GRIND YEAR: ______

OTHER ______

RATERS: RIZENBERGS BURCHETT [redacted] DATE: 10/12/89

REMARKS: ______

RANKING

Figure 4. Pavement Condition Evaluation Form.

to be in poor condition and may require rehabilitation. Current needs are estimated by identifying pavements having RI's at or below the critical level and totaling the mileages. The critical RI's are not sufficiently precise to conclude that pavements so identified require rehabilitation, but these pavements are selected for visual inspection the following year. Mileages estimated as needing rehabilitation now or in the near future are tabulated by year and by system. Average costs for resurfacing are applied to the mileages and total funding needs are estimated for use in budget requests.

Evaluations and Priority Ranking

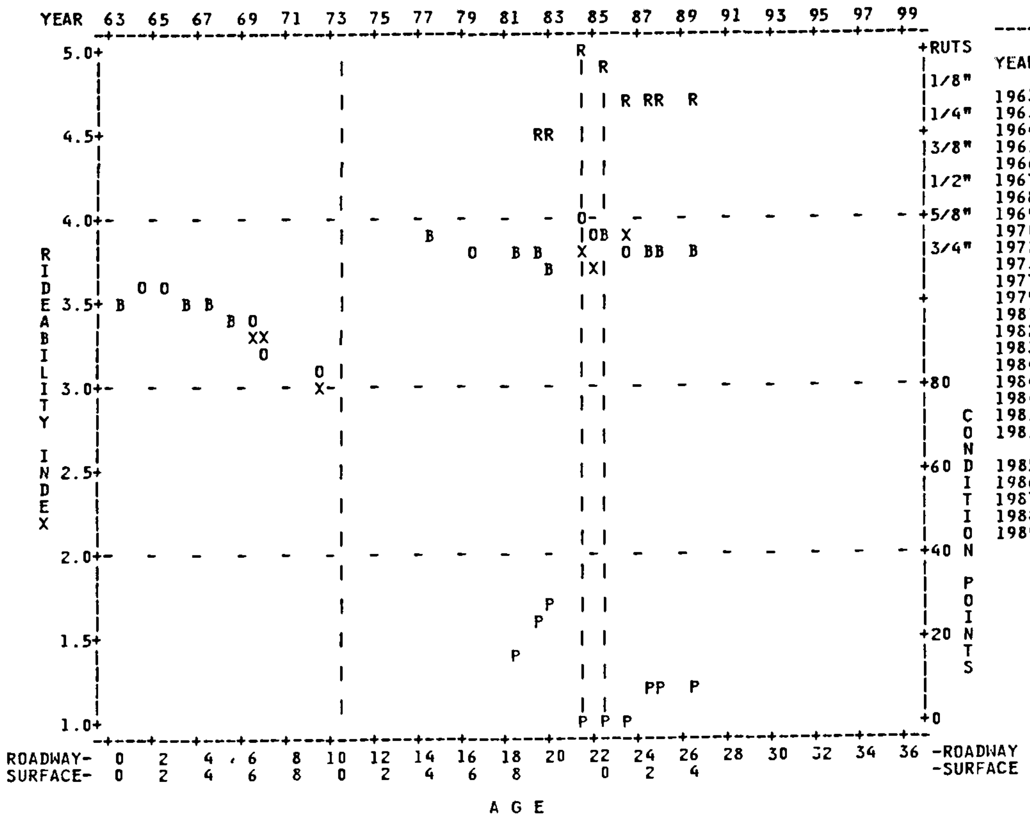
Rideability data are provided to each highway district to aid in their selection of pavements for detailed evaluations by the Pavement Management Branch. The selections

ROAD NAME: Lexington - Ashland

FROM: MP 89.48 Fayette County Line
TO: MP 94.23 KY 1958

O = OUTER LANE
X = INNER LANE
B = BOTH LANES

P = CONDITION POINTS
# = INDEX & POINTS
R = RUT (@ = INDEX & RUT)



YEAR	RI OUT	RI INN	CONDITION POINTS	ADT
1963	CONSTRUCTED		- AC	
1963	3.5	3.5		8950
1964	3.6			6190
1965	3.6			10600
1966	3.5	3.5		10200
1967	3.5	3.5		10170
1968	3.4	3.4		11500
1969	3.4	3.3		13700
1970	3.2	3.3		12560
1972	3.1	3.0		13400
1973	RESURFACED		- AC	
1977	3.9	3.9		15300
1979	3.8			14600
1981	3.8	3.8	17.6	15200
1982	3.8	3.8	23.0	16300
1983	3.7	3.7	27.0	19100
1984	MILLED		- AC	
1984	RESURFACED		- AC	
1984	4.0	3.8	0.0	18900
1985	3.9	3.7		19400
1985	SURFACED	OGFC	- SURFACE	
1985	3.9	3.9	1.0	19400
1986	3.8	3.9	1.6	20400
1987	3.8	3.8	7.0	22080
1988	3.8	3.8	7.0	21900
1989	3.8	3.8	8.0	22200

Figure 5. Plot of Rideability Indices, Condition Points, and Ruts.

are reviewed and a final listing of projects is mutually agreed upon. Additional pavements, selected by the Pavement Management Branch primarily on the basis of RI's at or below critical levels, or requested by others are added. The evaluation schema is based on a maximum of 100 rating points incorporating the following:

1. Distress and Condition Survey -- maximum 34 points

2. Rideability -- RI = 3.1 (1 point) to 1.4 or lower (26 points)

3. Rutting -- 6.4 mm [1/4 inch] (3 points) to 15.9 mm [5/8 inch] or greater (10 Points)

4. Skid Resistance -- SN = 36 (1 point) to 24 (13 points, adjusted according to traffic volume)

5. Traffic Volume -- ADT = 401 (1 point) to 7,501 or higher (12 points)(8,951 for 4- lane roadways)

6. Travel Speed -- 64 kph [40 mph] (1 point) to 88 kph [55 mph] (5 points)

Demerit points applicable to various rating elements are cited on a rating form Distribution of points is linear for rideability and skid resistance but curvilinear for all other elements.

Table 3. Rideability Indices and Corresponding Pavement Condition Indices for Estimating General Condition of Pavements.

	RIDEABILITY INDEX (PAVEMENT CONDITION INDEX)		
ADT	POOR CONDITION	FAIR CONDITION	GOOD CONDITION
Above 8000	*2.7(0.0) or lower	2.8(0.1) to 3.1(0.4)	3.2(0.5) or higher
6201- 8000	2.6(0.0) or lower	2.7(0.1) to 3.0(0.4)	3.1(0.5) or higher
4401- 6200	2.5(0.0) or lower	2.6(0.1) to 3.0(0.5)	3.1(0.6) or higher
2701- 4400	2.4(0.0) or lower	2.5(0.1) to 2.9(0.5)	3.0(0.6) or higher
1501- 2700	2.3(0.0) or lower	2.4(0.1) to 2.8(0.5)	2.9(0.6) or higher
1101- 1500	2.2(0.0) or lower	2.3(0.1) to 2.8(0.6)	2.9(0.7) or higher
901- 1100	2.1(0.0) or lower	2.2(0.1) to 2.7(0.6)	2.8(0.7) or higher
701- 900	2.0(0.0) or lower	2.1(0.1) to 2.7(0.7)	2.8(0.8) or higher
601- 700	1.9(0.0) or lower	2.0(0.1) to 2.6(0.7)	2.7(0.8) or higher
501- 600	1.8(0.0) or lower	1.9(0.1) to 2.6(0.8)	2.7(0.9) or higher
401- 500	1.7(0.0) or lower	1.8(0.1) to 2.5(0.8)	2.6(0.9) or higher
301- 400	1.6(0.0) or lower	1.7(0.1) to 2.5(0.9)	2.6(1.0) or higher
201- 300	1.5(0.0) or lower	1.6(0.1) to 2.4(0.9)	2.5(1.0) or higher
1- 200	1.4(0.0) or lower	1.5(0.1) to 2.4(1.0)	2.5(1.1) or higher

*Critical RI's

The total points from the evaluations are used to rank pavements within each highway district. Raters indicate on the evaluation form specific rehabilitation needs. Raters also provide information on width and type of existing pavement, extent of patching, shoulder characteristics, and use of roadway for industrial haul. Completed forms are forwarded to each highway district office for information and use in assigning priority rankings, recommended treatments, and estimated costs. District recommendations are reviewed by the Pavement Management Branch and statewide rankings are assigned. Ultimately, the forms, along with explanations of variances with District rankings and recommended treatments, are submitted to the Division of Maintenance for preparation of the annual resurfacing program.

Allocation of Funds

Bituminous resurfacing program: State-funded resurfacing program monies are allocated to the highway districts on the basis of lane-miles of roads, cost of bituminous surface course materials, and conditions of pavements in each district. Pavement conditions in each district are characterized in terms of difference in RI's between measured values and critical values. The RI of each homogeneous pavement section is deducted from the critical RI assigned for the particular traffic volume and is known as the pavement condition index (PCI). The PCI difference at 15 percent of the pavement mileage in the poorest condition in each District is determined. The largest negative PCI identifies the District having the poorest pavements. Conversely, the largest positive value identifies the highway district having the best pavements. A modifying factor permits the extent to which pavement conditions influence allocations to be varied. A factor of zero would completely remove pavement condition from influencing the allocations. On the other hand, as the factor is increased, highway districts with the poorer pavements would receive proportionately larger allocations.

Each year the percentage of poorer pavements used in characterizing pavement conditions is examined in light of funds budgeted. When the budget is large, a percentage higher than 15 percent may be selected. Also, several modifying factors are used to generate sets of allocation figures; those are reviewed from the standpoint of minimum and maximum allocations to any highway district. The concern is to assure a competitive paving industry in all highway districts and yet to assure that excessive allocations may not overburden the industry in any district.

The allocation formula is unique because it incorporates condition of pavements along with miles of roads maintained and cost of bituminous materials. From its first use in 1982, it has been well accepted. This acceptance stems from recognition of differences between districts and that an equitable allocation of funds is essential.

Complete equalization in pavement conditions statewide is not sought because traffic loading, subgrade conditions, climate, terrain, etc. distinguishes one District from another and significantly affects pavement performance. The intent, however, is to achieve, in time, more equal conditions without unduly draining the state's resources.

Machine patching: Historically, allocations to the districts for machine patching have been based on lane miles maintained and perceived needs. District managers administered the program and, in many instances, patching was done not only to maintain pavements at some reasonable level of service, but to achieve general improvements. These full-width, short-length (sometimes long-length) patches were often unwarranted, usually unsightly, too often had poorer rideability, and were more costly than equal length's of pavement resurfaced.

Beginning in 1986, efforts have been made to base patching allocations on pavement conditions in each district and to adjust patching to conform to and be compatible with the resurfacing program. Limited patching of the worst segments of pavements improve condition and extend life. However, continued, extensive patching results in quality that is not desired by the highway user and, instead, the pavement may warrant resurfacing. Pavements likely to be resurfaced next year should not be extensively patched. Pavements likely to need resurfacing within two to three years should not be extensively patched if possible and, if necessary, perhaps resurfacing should be done sooner.

When budgets for improvement (patching plus resurfacing) are small, a greater proportion of the money must be spent on patching. In fact, with a very small budget, only patching may be feasible. With a large budget, less money needs to be spent on patching.

PAVEMENT CONDITION--RURAL SECONDARY ROADS

Rural Secondary Roads are under the jurisdiction of the Department of Rural and Municipal Aid and a report is provided for use in their pavement management activities. In general, the report includes rideability and estimated, general condition of pavements by county, district, and statewide. The report also cites trends in conditions and resurfacing needs (miles and dollars). The appendix of that report contains information for the 8,000 pavement sections in the state.

COMPARISON OF KENTUCKY'S PAVEMENT MANAGEMENT SYSTEM WITH FEDERALLY MANDATED POLICY ON PAVEMENT MANAGEMENT

On March 6, 1989, the Federal Highway Administration published Transmittal 428 of the Federal-Aid Highway Program Manual. This transmittal presents FHWA's Pavement Management and Pavement Design Policies. State highway agencies must be in compliance with this policy on or before March 6, 1993. The general statement of this policy is "each State Highway Agency (SHA) shall have a pavement management system (PMS) that is acceptable to FHWA and is based on concepts described in American Association of State Highway and Transportation Officials publications including its 1985 'Guidelines on Pavement Management'." A comparison of the various elements of that document with Kentucky's PMS indicates that nearly all of the items addressed in that document have already been implemented or are in some stage of development and implementation.

CONCLUSIONS

The growth and evolution of Kentucky's pavement management system has been rapid in the past decade. Kentucky's pavement management system appears to be advanced beyond the stage of those used in many states today. The majority of the elements described in Transmittal 428 are addressed in some capacity, or are in various stages of development.

Development of more refined economic analysis procedures are in progress. The major portion of this development is the descripton and integration of remaining-life models into the procedures. Also some form of user costs models and maintenance costs models need to be established.

Kentucky's pavement management system lacks a formal feedback mechanism. Some type of formal feedback mechanism is needed wherein the impact of changing policies, design procedures, maintenance procedures, and new materials are followed.

Roughness measurements are presently made with a "response-type" measurement system. This system measures the response of the vehicle to the irregularitites of the pavement surface. Consequently, the measurements are highly dependent upon the reaction and condition of the vehicle's suspension system. This necessitates frequent recalibration of the system of wear and other changes in the suspension system. A more direct method of measuring roughness (one that is more independent of the vehicle) would be helpful.

Another area which bears some discussion involves the area of visual distress identification and determination of causes of distress. The current method involves a windshield survey, and involves identification of pavement distress in seven general areas: (1) cracking, (2) base failures, (3) raveling, spalling or wear, (4) out-of-section, (5) patching, (6) appearance, and (7) pavement rutting. The rating procedure has served Kentucky well for the past several years and results in realistic rankings of pavement projects on the basis of extent and severity of observable distress. However, this procedure does not always lend itself to identification of the causes of the distress. As referenced in the FHWA pavement policy statement and other literature concerning pavement rehabilitation, the identification of the causes of pavement distresses are critical for the development of alternate rehabilitation strategies. While it is not preceived necessary to specifically identify the cause of distress for ranking of pavements, it is concluded that final design of rehabilitation alternatives should address not only the distress but also the cause of the distress.

FUTURE

Most of the present operating system will be applicable many years into the future. However, improvements will continue to be made in the system. More data and more history will be available, making the analyses and projections more reliable. Better statistical and performance models will undoubtedly become available. These also will produce greater reliability. Research will continue to be stressed to determine more efficient ways to obtain data, to store and retrieve data, and to utilize data.

James P. Hall

IMPLEMENTATION PROCESS USED IN THE DEVELOPMENT OF THE ILLINOIS PAVEMENT FEEDBACK SYSTEM

REFERENCE: Hall, J. P., "Implementation Process Used in the Development of the Illinois Pavement Feedback System," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: Addressing the institutional issues is one of the most important criteria in implementing an effective pavement management process in a state highway agency. This paper describes the organizational issues involved in the implementation effort including resistance to change, not-invented-here syndrome, misdirected outputs, turf issues, and the long time frame required for development. The implementation process used by the Illinois Department of Transportation is outlined including the use of committees and the long-term planning of development and implementation phases. Finally, the paper portrays general concepts which can be utilized to effect implementation in state highway agencies.

KEYWORDS: Pavement Management, pavement management implementation, information, communication, and organizational issues.

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OVERVIEW

In 1982, the Illinois Department of Transportation (IDOT) formed a Standing Committee on Pavement Management to formally address its pavement management responsibilities. Since there were deficiencies in the existing process, IDOT in 1984 undertook the long term development of an Illinois Pavement Feedback System (IPFS). The Illinois Pavement Feedback System is a formalized process for the collection, storage, retrieval, and analysis of pavement design, materials, traffic, condition, and performance data for the interstate pavement network.

Although much progress has been made, work is still needed to integrate IPFS capabilities into IDOT operations. The focus of ongoing efforts is the recognition and accommodation of institutional and communication issues.

This paper will describe the broad organizational issues involved in the implementation of a pavement management process. The procedures the Illinois Department of Transportation undertook to address these organizational issues will be discussed in detail. Finally, general concepts will be presented for effective implementation in state highway agencies.

PAVEMENT MANAGEMENT AND THE ORGANIZATION

Pavement management implementation in a state highway agency is a very complex issue. Pavement management responsibilities are located in many functional areas through the organization. The purpose of a pavement management system is to integrate these areas and activities into a usable department-wide system. Key to this development is the identification of information which is necessary to a functioning pavement management system to meet the needs of users in the agency and ultimately the public needs. As such, the pavement management system cannot be designed in a vacuum. Instead, it must be developed to fit the needs, wishes, and idiosyncracies of the agency.

When an agency undertakes a concept such as pavement management, it frequently looks at a stand-alone system with all of the necessary elements included therein. In reality, however, a large highway agency has much of the information required already in place but scattered across various organizational areas and data systems. Due to this department-wide focus, a formalized process is required to achieve a unified effort.

A pavement management system can be thought of as being modular in concept. That is, detailed information is located in various areas in the agency. For example, detailed pavement condition analysis may be gathered by an organizational area responsible for friction, roughness, and distress surveying. However, design details of the pavement network are often located in microfilmed or hard copy at both the district and central offices. Programming of highway improvements requires integration of this information across organizational lines. Thus, the development process must address this inter-communication throughout the organization.

PAVEMENT MANAGEMENT IMPLEMENTATION PROBLEMS

Implementation of a pavement management system in a large highway agency requires much more effort than buying a computer package and placing it in some corner of the organization. Implementation problems center less on the technical aspects than on the vagaries of information system development and general organizational theory and behavior. Some of the major problems are a natural resistance to change, not-invented-here syndrome, misdirected outputs, turf issues, and the long time frame required for development.

Resistance to Change

State highway agencies are by their very nature bureaucratic organizations. As such, the organization is not structured to quickly adopt change. Since pavement management implementation often necessitates change in job duties, information systems, and decision making processes throughout the organization, a natural resistance develops.

Not-Invented-Here Syndrome

Acquiring a pavement management package from a vendor, or developing a system in-house without overall organizational involvement and learning, will meet stiff resistance. All state highway agencies differ with respect to history of past pavement management development efforts, the roadway planning and programming process, strengths and weaknesses in their information systems and organization development, and external requirements to provide an effective transportation network. A "canned" information package will not likely fit many of the organization's needs and will be looked on with skepticism by organizational areas not included with the system's development.

Misdirected Outputs

Outputs from a pavement management system are crucial for providing information which can improve the effectiveness of decision making activities of management and users. Outputs must be directed towards decision makers in a readily understandable style. A top manager will not utilize a stack of greenbar computer paper while a lower level user may. Formats such as summarized charts and geographic summarization can portray the information more succinctly. Above all, the needs of the decision maker should dictate the style.

Turf Issues

Pavement management, to some extent, has always been accomplished in a state highway agency. Improvements in pavement decision making through a comprehensive pavement management system often necessitate some change in information acquisition and decision making procedures. Some may see this as encroachment on their "turf" especially if it is perceived that a loss of power results.

Long Time Frame

Due to the complex organizational issues and the institutional breadth of implementation, a relatively long time frame is required for pavement management implementation. The organization must have time to learn and gain confidence in the system which will eventually evolve to meet the organization's needs. Upper management emphasis and external pressures, such as the recent FHWA requirement for a pavement management system, can speed up this process. However, pavement management cannot retain a major institutional focus for a lengthy period. System evolvement should continue through the peaks and valleys of organizational commitment.

PAVEMENT MANAGEMENT HISTORY IN ILLINOIS

In 1982, the IDOT formed a Standing Committee on Pavement Management composed of upper level management. The committee was charged to:

provide a regular Department-wide forum for formulating and evaluating policies, practices, and standards related to state highway pavement management;

coordinate and integrate the broad range of pavement-related activities throughout organizational elements of the Department;

and assure the efficient and effective management of individual organizational elements by clearly identifying an overall Departmental framework and perspective.

Subsequent meetings of this committee recognized that there were some serious deficiencies in IDOT's pavement management capabilities.

IDOT's IPFS development can be broken down into the phases of Investigative Study, Requirements Definition, Logical Design, Physical Design, and Implementation. Further details of these phases can be found in references [1], [2], and [3].

Investigative Study/Operational Analysis

IDOT investigated the general need for pavement management information by interviewing affected areas throughout the Department.

Also, contacts were made with other states and FHWA to determine the current status of pavement management technology and development. This investigation was undertaken in 1983 and 1984 through a research project with the University of Illinois.

A proposal of the overall concept for development of IPFS was then presented to the Standing Committee on Pavement Management. At this meeting, a budget, time schedule, and general direction for management issues to be addressed were approved.

An IPFS Steering Committee was established with upper level management representing the affected areas of design, materials, research, planning, programming, finance, administration, data processing, the districts, and the Federal Highway Administration. This committee's function was to set the overall direction of the system development and maintain upper and lower management support and involvement.

The IPFS Steering Committee then appointed a Pavement Feedback User Team to identify the broad organizational needs, and to develop a comprehensive understanding of pavement management practices in place and improvements which would be needed.

Personnel from the University of Illinois and IDOT's Bureau of Materials and Physical Research were selected to form a project team to spearhead the day-to-day development process with the organizational responsibilities of keeping the IPFS development on schedule while maintaining communication flows. Close communication was required between these three groups to ensure compatibility of effort.

The investigative study provided a basic outline of the areas within IDOT which were interested in pavement management. Organizational analysis required a detailed identification of existing data bases, existing pavement management activities, information flows, and affected personnel within the Department.

This analysis went further than the simple, direct lines of an organizational chart. It involved human interactions and informal operating procedures which were not written down anywhere. Figure 1 portrays a simplified version of the actual pavement related information flow within IDOT. [4]

The Pavement Feedback User Team provided an effective method to determine these interrelationships. Initial meetings concentrated on identifying all of the parameters involved in pavement management and what could realistically be included in the IPFS. Through group discussion, the major organizational issues were identified and recommendations were developed. These issues, including such items as project scope, budgeting, hardware acquisition, personnel required for the development effort, and restructuring of organizational resources, were brought to the attention of the IPFS Steering Committee for resolution.

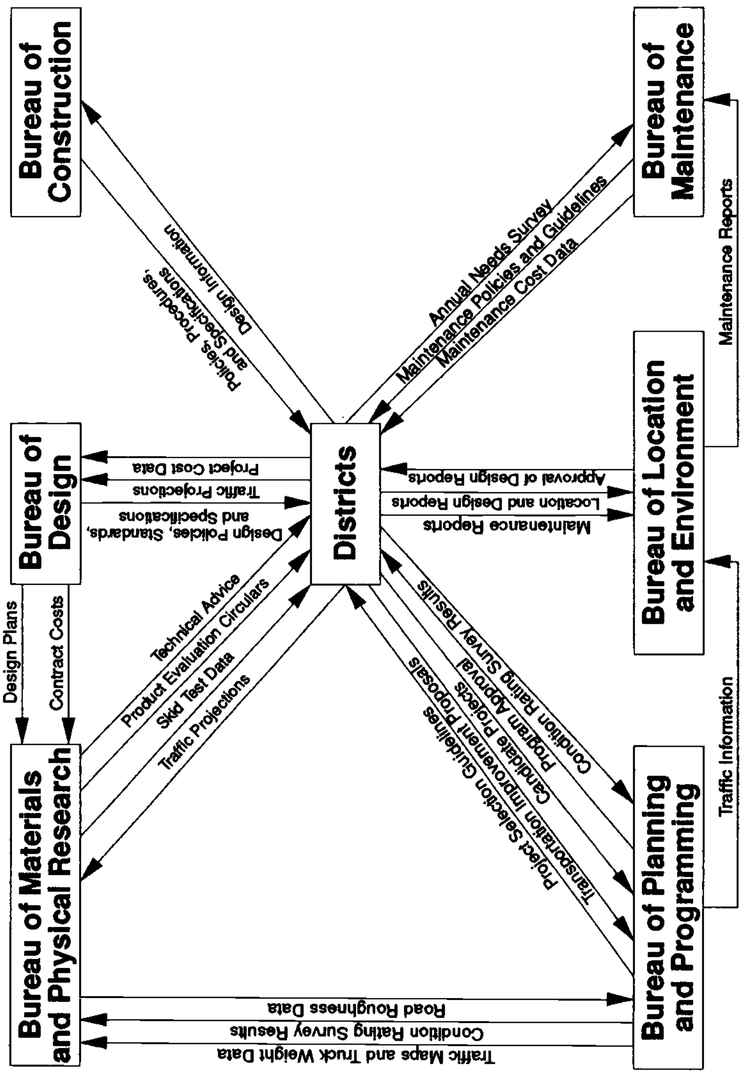

Figure 1. Flow of Major Pavement Related Information in IDOT.

Requirements Definition

Following completion of the investigative study the project team began work on the definition of system requirements. Written questionnaires were distributed and follow-up interviews were conducted. These efforts enabled the project team to determine what outputs should be developed to assist IDOT's offices in performing the following pavement management-related activities as defined in the investigative study:

- Development and evaluation of design procedures and standards.
- Development and evaluation of policies and guidelines.
- Special studies and research.
- Development of performance models.

From the interviews, the project team compiled the following general applications of the IPFS:

- Detailed information on a specific pavement section or network.
- Summary information on a specific section or network.
- Prediction of future performance.
- Evaluation of IDOT pavement policies, design, and construction procedures.
- Evaluation of rehabilitation strategies.
- Special pavement studies and research.
- Life-cycle costs for various pavement types.
- Answers to "What if" questions to help improve management strategies.

Above all, the users wanted the system to generate reports quickly and in a user friendly fashion for a wide variety of decision making needs across the Department. In addition to standardized reports, a strong emphasis was placed on flexible, user specified reports for the many ad hoc special studies. Business graphics, statistical analysis and graphical mapping were also identified as primary needs.

Illinois has over 17,000 centerline miles of State maintained pavements. The interstate highway system includes approximately 1,850 of the 17,000 miles. In order to facilitate implementation of the IPFS, the scope of the initial data bank was limited to the interstate highway system. The interstate system includes a sufficient number of sections to compile a prototype database to perform evaluations of many of the specific designs that are used on the remaining primary and secondary routes.

This effort provided the broad framework for IPFS development. Activities were then directed towards gathering information which was not currently accessible in the organization. In IDOT's situation, information regarding pavement design details and construction history were severely lacking. A significant manpower effort was required to retrieve this information. This included reviewing microfilmed plans and interviewing knowledgeable engineers about pavement information. Also, prototype output reports were developed using this information in order to get feedback and reaction from the organizational entities.

Logical Design

The first step in the Logical Design of the IPFS was to mock up versions of all of the output reports that the primary users felt were needed to address the applications determined in the Requirements Definition. Initial drafts of reports were created by the project team and reviewed first by the Pavement Feedback User Team and then the Steering Committee. These reports were created without regard to existing IDOT data handling systems and without regard to the existing pavement data being collected or to existing hardware or personnel constraints. A total of 45 reports were created to demonstrate the required capability of the IPFS.

A list of required data elements was derived from these reports. These were divided into three groups based on their primary purpose. The first group consisted of those data elements necessary in the programming of improvements. These elements would be collected for each management unit and would be the first ones to be collected. By consensus, a management unit was defined as a section of roadway, at least 1/4 mile long, which had uniform characteristics along its length, including:

- Pavement structural design
- Truck traffic/total traffic
- Responsible District
- Structural condition

The second group consisted of data elements necessary for evaluation of design policies. They would also be collected for every management unit. The third group consisted of those data elements needed for special studies and research. These data elements would be required on a portion of management units to achieve a good statistical sample.

After reviewing the report mock-ups and the required data elements, the current and future pavement related computerized data processing systems were investigated. IDOT was, and still is, undertaking an extensive Roadway Referencing effort which will develop a link/node roadway base which will allow direct integration of IDOT roadway information systems.

In analyzing IPFS hardware and information requirements, the user team determined that much of the data was already contained and accessible in various existing IDOT mainframe systems. Data which was currently not in a computerized system, e.g. plans, project records, microfilm, would be entered into a formalized mainframe data base using a fourth generation data base management software. This data base was structured to include most of the information required by IPFS for section and network inventory reports and for condition prediction and network rehabilitation. The flexibility of the fourth generation mainframe language allowed additional elements to be easily added to the data base.

Future completion of the Roadway Referencing project should allow direct access to other important pavement related data bases including accident and maintenance files.

In 1985, a new detailed distress survey was conducted as part of the IPFS project to identify the distresses present along each interstate highway, excluding the Chicago area expressways. The data collected would be used to develop pavement condition prediction models and network rehabilitation selection routines. This distress data and the other inventory and monitoring data was made available to selected IDOT users as part of a gradual IPFS implementation process.

Much of the work in the Logical Design phase was devoted to producing demonstrations of the IPFS capabilities. These included sample evaluations of pavement performance for various designs and the prototype timing and selection of rehabilitation strategies over a specified analysis period. Although preliminary in nature, the demonstrations were well worth the effort to illustrate to the Steering Committee and to Department users the value of the proposed IPFS. The demonstrations also helped build organizational commitment to the system.

Physical Design

During the physical design phase the project team then began developing the software to organize the IPFS data base. Procedures were written to convert the data collected from various sources into a uniform format. Data loading began with an emphasis on the level 1 and level 2 data elements.

Data was continually being collected and tested for accuracy. Information was collected from existing IDOT computerized files, paper and microfilm records, and from previous University research projects. Pavement distress survey and historical traffic loading information was also included. Much of this data was first stored temporarily on microcomputer files and used by the team in developing pavement condition prediction models and rehabilitation selection strategies before the IPFS data base was fully operational.

Of the 45 report mock ups, five were chosen as best representing the capabilities of the IPFS and were the first to be generated from the IPFS database:

- Detailed section information.
- Selected information for each section of a user specified network.

- o Section condition prediction.
- o Section rehabilitation strategy selection and optimization.
- o Network rehabilitation strategy selection and optimization.

The project team continued to give demonstrations to interested groups. A more intense effort was put towards developing a presentation for top level Directors of IDOT. In addition to the demonstrations, several IDOT groups requested specific information from the IPFS. This information was compiled and delivered by the project team. The project team developed methods to retrieve, summarize, and present this information, using both mainframe and microcomputer systems, on a timely basis. These activities served to increase Department wide interest in the IPFS.

IMPLEMENTATION

Current work activities center on using the pavement management information to meet management decision-making information needs, to fine-tune condition prediction models, and to prototype project prioritization and network optimization methodologies.[5] These methodologies are being tested by comparison with the existing annual and multi-year programming process. Additionally, research reports have been prepared detailing performance of various pavement designs.

IDOT is also actively pursuing the acquisition of automated devices to collect distress, condition, and roughness information. These needs had been previously developed in meetings with the IPFS Steering Committee and the user team.

IMPLEMENTATION CONCEPTS

Personal experiences with the problems inherent in implementing a pavement management system and research of management information system methodologies in general have provided the following concepts on pavement management implementation. More detailed information on the identification and accommodation of institutional issues is found in Reference [6].

Pavement Management Implementation is Incremental

One of the natural tendencies of an agency that is enthusiastic about developing a new system is to complete everything in the shortest amount of time possible. In some cases, the result is the agency ends up with a system which has not been afforded the time to grow with the agency. A system developed in this way is more prone to failure.

A more appropriate approach would be to start with an assessment of what the requirements are of the system. This may mean simply building on the highway agency's pavement management procedures that already exist and develop the pavement management system to complement the processes. This type of an approach can easily be done incrementally over time. Depending on the level of sophistication required of the system, a simple ranking procedure to identify potential project sections may be sufficient to start initial development. As the users become more comfortable with the system operation, a more sophisticated approach which incorporates optimization and/or prioritization techniques can be incorporated.

The success of this approach depends on the organization's ability to accurately assess their needs while keeping their "wish list" in check. Clearly identifying system components as "must haves" and "nice to haves" can assist an agency in distinguishing between what features are needed immediately and which can be added with time. By incorporating such an approach, which starts with a simpler decision model and allows for increasing sophistication with time, the agency can develop a dynamic system which can be tailored to meet their needs as they become more familiar and comfortable with the system.

Accommodate Future Technologies

Rapid changes are occurring in information acquisition technologies. State highway agencies are finding it difficult to integrate this new technology into their workplace. In terms of pavement management alone, the ability of a system to accommodate these changes will play a large part in the agency's successful integration of this new technology.

Changing technology will affect several aspects of pavement management. These include automated roughness and distress measurement and information analysis capabilities. The pavement management practitioner must stay abreast of these developments. The agency should ensure that historical information is not lost when moving towards new technologies.

Past studies have shown that certain organizational characteristics are present in order to effectively implement new technologies. These organizational characteristics are active participation in outside technical committees, involvement across the organization, hands on involvement by top management, prototyping the product, and using a product champion. These tools should be used when new technologies of large impact such as the acquisition of automated distress collection equipment are implemented into organizational pavement management activities.

Prototype (Get it on the Street)

Prototyping, where preliminary products of the system are developed to display to other organizational areas, provides an effective way of obtaining user feedback and increasing organizational awareness of the system. Prototyping is easier to accomplish with advances in microcomputer and data base technologies. Above all, prototyping should be accomplished in a manner to promote honest communication to identify problems with system development and to develop solutions.

Be Able to Respond When the Opportunity Presents Itself

With every crisis comes some degree of opportunity. If the pavement management system is able to respond quickly with accurate information to upper management and outside inquiries, it becomes much more important in the eyes of upper management and the users. Actual use of the data also improves accuracy and quality of the product. The pavement management practitioner should develop the software and hardware tools to stand ready to respond to these types of inquiries.

Characteristics of an Effective Pavement Management Leader

Due to the institutional issues involved, it is extremely important that the pavement manager maintain the right disposition in marketing the pavement management system. The manager's attitude should be positive, friendly, and helpful. The attributes of an effective pavement manager includes vision, creativity, and imagination. Activities require risk-taking and conviction as to purpose. Additional characteristics of flexibility and compromise prove invaluable in dealing with the very real issues of organizational constraints. A organization-wide perspective is needed.

CONCLUSION

The development and implementation of a comprehensive pavement management system should involve personnel from throughout an agency in order to realize the full range of benefits a pavement management system is capable of providing. Implementation involves much more than selecting the technical approaches which will be used to allocate budgeted dollars in future years. The system must fit the organization's needs. Ignoring this fact has resulted in the neglect of many systems developed over the years.

Most important is the recognition that each agency operates in its own way and has decision processes which have been developed to accommodate the organizational structure and the operational environment it exists in. To be successful, a pavement management system must work to ASSIST the organization's decision making process rather than attempt to modify the process to fit a computerized system. In addition, the agency must recognize the institutional and communication issues inherent in their developmental activities.

Institutional issues have become more recognized in recent years for their influence on successfully achieving the objectives of pavement management. The organization which successfully addresses these factors will have provided a means of assuring themselves that the money and manpower spent on the system development will result in true integration into pavement decision making activities and will provide long lasting benefits to the entire agency.

ACKNOWLEDGEMENTS

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THE NORTH DAKOTA DOT PAVEMENT MANAGEMENT SYSTEM IMPLEMENTATION PROCESS

REFERENCE: Cation, K.A., "The North Dakota DOT Pavement Management System Implementation Process," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: In a recent mandate issued by the Federal Highway Administration (FHWA), State Highway Agencies were required to have operational Pavement Management Systems by January 1993. The objectives of this mandate included the development of objective decision processes which would determine the cost-effectiveness of various rehabilitation strategies in order to evaluate their impact on the overall condition of the State's pavement network. In 1989, the State of North Dakota hired a consultant to assist them with the development of analytical software which would utilize their extensive pavement database and satisfy the requirements of the FHWA mandate.

There were two important features to the North Dakota System development. The first involves the DOT's use of an active Steering Committee, or User's Group, made up of individuals from throughout the organization. The group was intimately involved with the system development through the use of subcommittees who participated in all aspects of the system development. The group was very influential in ensuring the successful implementation of the system by addressing the "Institutional Issues" which play a large role in the system's overall success within the organization. This served to increase the committee's commitment to the project as well as begin to familiarize the organization with the system in a gradual manner.

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The second important characteristic of the North Dakota implementation was the State's decision to provide an opportunity for the cities and counties within the State to initiate their own pavement management implementations through a "piggy-back" arrangement with the DOT. For a minimal fee, local jurisdictions were invited to participate in the pavement management program and implement a more limited version of the State's system within their organization. Each participating jurisdiction was thoroughly trained on sectioning and data collection procedures, data entry, and data analysis. Following completion of the training session, the jurisdictions received a complete system which was completely compatible with the State system, easily facilitating the exchange of information between the two agencies.

KEYWORDS: Pavement Management Systems (PMS), PMS implementation, system development, performance prediction, rehabilitation scheduling, strategy selection, FHWA

As many State Highway Departments struggle with the maintenance and rehabilitation demands of their deteriorating infrastructure, their engineers are looking for more objective tools which can assist them in prioritizing needs and ensuring the most cost-effective use of their limited budgets. Coupled with the FHWA mandate requiring that a pavement management system (PMS) be implemented by 1993, the development of these systems for State Highway Agency use has increased significantly in the last few years.

In 1989, the State of North Dakota obtained a consultant to assist them with the development of analytical software which could operate off of the data in their existing PMS database, and provide them with the information to determine the impacts of various rehabilitation strategies on overall network condition and funding requirements. An unusual aspect to the development of the system, however, was the requirement that the system developed for the State must be able to be implemented within any of the State's local jurisdictions, to allow for the automatic exchange of information between Cities (or Counties) and the State. To facilitate this requirement, the contract was divided into two phases. The first phase dealt exclusively with the State's system development. Phase II focused entirely on the local jurisdiction's system, with the State paying for any developmental costs and training, and the cities paying a small fee for the customization of the system to their important conditions and the implementation of the system within their agency.

Another important aspect of the development of the North Dakota system was the use of an active Pavement Management Steering Committee which was formed to oversee the development of the system. Committee members were selected to work directly with the Consultant to outline the work required under the contract, assist in the technical development of each task, and oversee the requirements and capabilities which the system must address to meet the objectives identified within the Department. It was the Steering Committee's responsibility to ensure that the needs of the cities would be included in the system development.

It is the objective of this paper to discuss these important aspects of the North Dakota system development. The paper will focus on the use of the Steering Committee in the system development and the institutional issues which were resolved using this approach. Additionally, it will discuss the impacts of the requirement that the State system be useable by the Cities and Counties within the State.

PROJECT BACKGROUND

As early as 1983, the North Dakota State Highway Department (NDSHD), now the North Dakota Department of Transportation (NDDOT), recognized the importance of accurate and objective information for the evaluation of their pavement rehabilitation needs. In support of this recognition, the upper management at the NDSHD requested the creation of a formal pavement management steering committee, comprised of individuals from various divisions within the organization, to begin work on the development of pavement management system.

The State's early system was developed and operated in a personal computer environment within the Pavement Management Section of the Planning Division. The early system was primarily a database storage and retrieval system, however it was extremely comprehensive and flexible in comparison with other systems being developed at the time. The Department began collecting pavement distress data from windshield surveys, and supplemented that data with Mays ride meter data and Falling Weight Deflectometer (FWD) data. All condition information was entered into the database for the Division's use. Other data elements, such as AADT, ESALs, geometrics, maintenance records, construction history, and materials information, was stored on the Department's mainframe computer and transferred to the PCs. This master information file contained over 1000 project records for their 8500 mile highway network.

In 1989, the Highway Department issued an RFP for a consultant to assist them with enhancing their existing pavement management capabilities through the development of analytical software. The requirements of the system included the ability to provide decision makers with factual information on the consequences of past and current pavement decisions, as well as the ability to assess network trends and needs through an evaluation of the impacts of various alternative funding programs and pavement decisions. The intention was to enable the Department to measure and evaluate the impacts of various strategies in design, construction, and maintenance in order to increase their efficiency in allocating scarce transportation dollars.

At the time the RFP was issued, the Highway Department was in a very strong position to support the development of their new analytical software. They recognized the fact that most agencies, including local jurisdictions, had switched to a preservation/rehabilitation mode rather than the expansion mode of earlier years. Recognizing this fact, and the interest that local jurisdictions within the State were beginning to show in pavement management systems, the State decided to have the system being developed for them be capable of being implemented in interested local jurisdictions within the State.

The existing Pavement Management Steering Committee (NDPMSC) was involved in the development of the RFP as well as the selection of the Consultant they would be working with. Once the contract was finalized, the Steering Committee met with the selected Consultant to outline the tasks required of the system and determine the responsibilities of all parties involved in the project. Since the committee was comprised of individuals from Districts, Planning, Programming, Materials, Design, Research, and the local FHWA office, it was felt that they would provide valuable insights into the technical development of each task and ensure that the work complied with the system requirements as the development took place. Unlike other Steering Committees, the aspect that made this group important was the direct involvement they had throughout the \system development. Although their role did include reviewing the work completed on each task, they were much more involved with the development by providing project direction, feedback, and practical tests to evaluate the applicability of the system as it progressed.

SYSTEM DEFINITION

One of the most important steps in the system development took place immediately following the issuance of the contract on the project. To better understand the environment in which the PMS must operate, the first task of the project involved a meeting between the Consultant and the Steering Committee. The objective of this meeting was for the Consultant to obtain a complete understanding of the policies and procedures which were currently being used by the Department, and to evaluate the goals and objectives anticipated for the Pavement Management System.

The system definition task of the contract was completed through a series of interviews which were held with Department personnel, including both Steering Committee members and non-Committee members. Individual interviews were held with personnel representing Upper Management, Middle Management, Planning, Programming, Engineering and Design, Research and Materials, and the Districts so that participants would feel free to discuss the methodology for selecting pavement rehabilitation projects currently in place, and to focus on their expectations of the Pavement Management System and any changes which would have to occur for the PMS to be effective within the Department. Participants were free to discuss any aspect of the system development and/or implementation and were not restricted to discussing aspects which would specifically impact them. Each interviewee was also asked for their feelings on the success of the system implementation within the Department.

Through this interviewing process, the Consultant was able to gain a valuable insight into the procedures which were currently being used to program projects and the capabilities they needed the system to provide to enable them to conduct their jobs more efficiently. In general, the interviewees were overwhelmingly supportive of the system which was being developed. There was no open antagonism to the changes which were expected to take place once the system was implemented, however there was some concern that there were a number of individuals who would be reluctant to change. It was felt that with some involvement in the system development, and continual training on a system with practical outputs and a logical, easily understood decision process, these people would become supportive of the system.

As a result of these meetings, several changes were made to the original scope of work. One example included the RFP requirement that a review of existing condition survey procedures be conducted and considered as alternatives to the procedure being used by the Department. The interviewees who met with the Consultant, however, expressed overwhelming support of the system being used and felt comfortable with the ratings it was determining. A review of the system showed it to be a windshield rating system which approximated the severity and quantity of various distresses and assigned deduct values for each. The survey resulted in a condition index which ranged from 0 to 99, with a value of 99 indicating a pavement in excellent condition. The survey provided them with an overall rating which could be used to prioritize projects, but also provided them with information concerning the predominant distress types and, therefore, the presence of any structural or climatic deterioration. The procedure was felt to be adequate for their needs, and therefore more of an effort was centered on the development of performance curves for their various road classifications.

A second change to the original scope included the addition of newsletters, which were to be provided periodically by the consultant throughout the contract. Although only several newsletters were actually released by the Department, the intent was to keep the entire Department apprised of the development and to openly discuss the impacts its implementation would make throughout the Department. Holding training classes after the completion of the implementation was also discussed as a method to involve the entire Department in the system development.

The interviews also provided insight into the strong amount of support the NDPMSC had from upper management for the development of their system. This support was important as the system was developed to provide the committee members with the time to serve on the committee and occasionally served as the motivation to get things moving when committee members were too busy to meet the existing deadlines. The success of the system in North Dakota will be very dependant on the continued support of their management as it is integrated into their selection process.

The overall objective of the system, as seen from the eyes of the interviewees was for the PMS to serve as a "tool" in their planning and programming processes. The PMS was not seen as a replacement for their current processes, but was considered more of a supplement which would improve the objectivity of their project selection process and provide "ballpark estimates" of the level of repair which would be needed to be budgeted for future repairs. Their primary interests in the system were in the identification of performance trends for the State's Highway network and the ability to view the impacts of various repair strategies so they could make wiser investment decisions with the funds available to them.

SYSTEM DEVELOPMENT

Following the completion of the system design aspects of the project, work began on the development of the analytical software. There were three primary aspects to the software development, including the determination of the data required by the analytical procedures, the development of performance curves for predicting future condition, and the development of decision trees which would serve as the triggers for required levels of maintenance and rehabilitation.

In order to facilitate better use of the Steering Committee members, the group was broken down into several subcommittees, based on the expertise of each committee member. Three subcommittees were used during the design of the analytical software; the Data/Computer Subcommittee, the Pavement Performance Subcommittee, and the Rehabilitation Strategy Subcommittee. Each of these subcommittees met with the Consultant regularly throughout the development of their portion of the system. Once an aspect of the system was developed to the complete satisfaction of the subcommittee, it was presented to the entire committee for review. In that way, the entire committee was kept abreast of the work being done, but individuals were able to focus on one, important, technical aspect of the program in detail.

DATA EXCHANGE

The Data/Computer Subcommittee was responsible for the design of the data exchange between the Department's existing data files and the pavement management system. During the design phase, it was determined that a basic set of data would be required to be downloaded into the pavement management database for operation of the analytical software. This basic data set consisted of traffic and loading data, pavement type and structure data, and pavement condition data. All of this data was important to the other components of the analytical software and was determined to be the data which would trigger a rehabilitation action, or could be used in developing performance curves. Because the PMS would not operate if any of this data was missing, the Data/Computer Subcommittee designed a database structure which would be used by all potential system users, including the participating local jurisdictions. Beyond this base data, the users were free to add any other kind of data desired to the base structure.

One of the most frustrating aspects of data transfer that the subcommittee had to deal with was the number of discrepancies between data stored in different databases within the Department. The discrepancies which were observed dealt mostly with differences in the referencing systems used by each file. Rather than attempt to revise the discrepancies as a part of this contract, the subcommittee decided to delay the incorporation of all other data files until a later date, and deal only with the basic data needed to run the system at this time. Since it was not determined to be mandatory to the initial results of the system, this decision did not seriously impact the end result.

PAVEMENT PERFORMANCE DEVELOPMENT

The development of the pavement performance prediction curves is one of the most important features on any pavement management system. From a technical standpoint, they are also one of the most difficult aspects of the system to develop. The importance of their accuracy is illustrated in the selection of any rehabilitation treatment. If the performance prediction curves are not representative, the timing and costs for each recommendation made by the system will not reflect actual conditions.

The Pavement Performance Subcommittee evaluated many approaches for modeling the performance of the pavements in North Dakota. They selected an approach similar to the methodology being used for the SHRP Long Term Pavement Performance (LTPP) study where the performance history is plotted for groupings of pavements with similar characteristics (families). This technique was selected because it was easy to understand, and could account for factors which influence pavement performance, such as truck traffic, climate, pavement structure, and pavement type.

The subcommittee's first task was to identify the families which existed from data in their database, using characteristics which would distinguish their deterioration patterns. Groupings were identified based on pavement class (type), in-situ structural strength (SN Number), and Traffic (daily traffic levels). Initially, 156 different family groupings were identified. Due to the limited size of some of these data sets, several groupings were combined, resulting in a total of 42 different families.

Condition data for each pavement section in the database was assigned to one of the 42 final groupings. Age versus condition data was plotted for each family using a constrained polynomial technique which assigns a "best fit" curve to the data. In several instances, it became obvious that a seal coat program had been put into effect in the State which was preventing the deterioration of these pavements, and instead were leveling out the curves, as shown in Figure 1. Since the pavement management system requires a "do nothing" curve for comparisons between the impacts of various rehabilitation strategies, it was determined that the seal coat's impact on the performance curve had to be removed. To accommodate this need, a software program was developed which was based on historical data, but could also accommodate inputted data points.

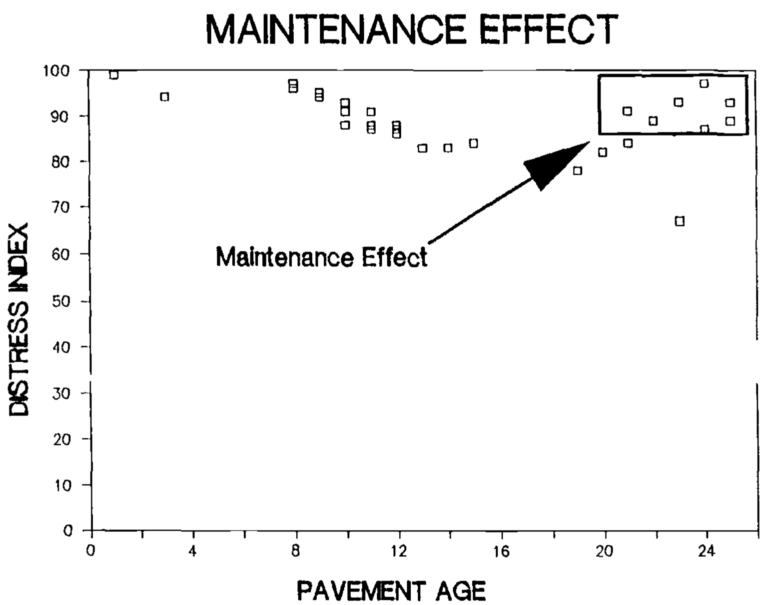

FIG. 1 -- Performance Data Reflecting Maintenance Effect

The subcommittee reviewed the initial performance curves for each of the 42 families of data and provided input for modification of these curves in three instances; when the seal coat program had influenced the deterioration, when limited historical data was available, or if there were gaps in the data available. Because the subcommittee was comprised of personnel who had spent a considerable amount of time in the field, they were able to provide this supplemental information based on their expert knowledge. In some cases, especially those where seal coats had been applied, historical condition data taken immediately prior to a seal coat application was referred to as guidance in determining what the condition would have been if the seal coat had not been applied.

The subcommittee used the same procedures to establish performance prediction curves for the structural component of the condition index for predicting the presence of structural distress. It was felt that this was needed in order to better determine the type of rehabilitation that would be required if structural deterioration was present as compared to a section which would have the same condition index, but where no structural deterioration was present. The curve was established from the total number of possible deducts possible for those distresses determined to be caused by a load related mechanism, assuming all structural distresses were present and were at the maximum quantity and extent categories. An example of a deterioration curve for both the condition index and structural component for one family is shown in Figure 2.

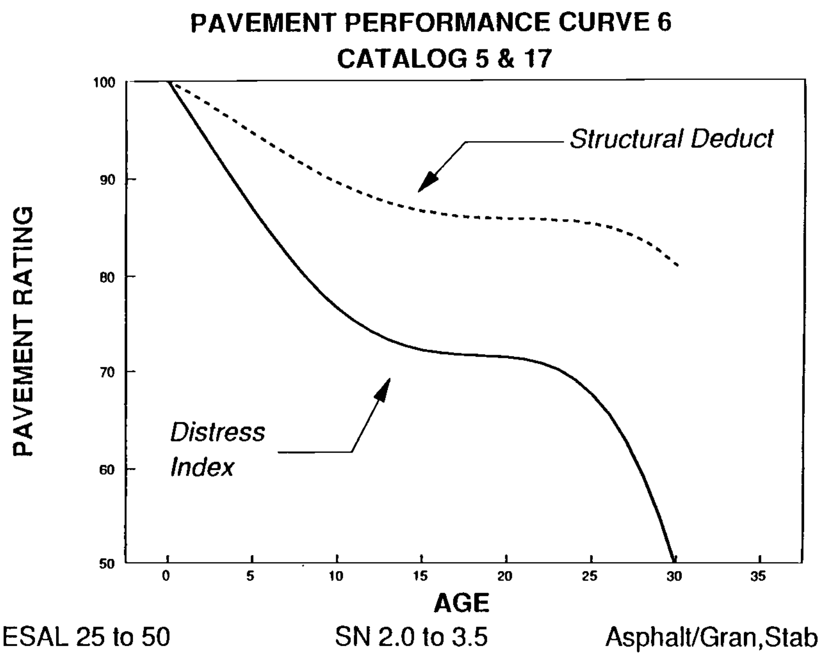

FIG. 2 -- Final Sample Performance Curve

REHABILITATION STRATEGY MATRIX DEVELOPMENT

For any single pavement section, there may be several rehabilitation strategies which could be applied to address the deficiencies present and extend its useful life. It was the objective of the third subcommittee to develop decision matrices which could be used to identify feasible rehabilitation strategies for consideration in the analytical software, as well as their effect on budgetary needs and future maintenance requirements.

The process which was used to develop these matrices involved three steps. The first was to identify the list of treatments which the subcommittee felt should be considered by the pavement management software. This list was developed to include treatments which were currently in use as well as rehabilitation alternatives which the Department wanted to consider using. Treatments were identified for both asphalt and concrete surfaced pavements and included seal coats, patch and seal, mill and seal, thin overlay (< 2 1/2 inches), thick overlay (> 2 1/2 inches), and reconstruction for asphalt pavements, and joint repair/CPR, grinding, overlay, and reconstruct/recycle for PCC pavements.

Secondly, the subcommittee identified the factors which would influence the selection of one treatment over another, and defined the ranges or values for each factor which would identify when each treatment would be feasible and could reasonably be applied to each road type. Trigger values for each treatment type were not exclusive, and in fact, trigger values for two strategies could easily overlap so that the choice between treatments would be done on a benefit/cost approach.

Trigger values were determined for each treatment type based on such factors as condition, structural deterioration, roughness, functional classification, ESALs, existing pavement thickness, pavement width, and AADT. As the subcommittee worked to identify the applicability of each treatment on their pavement network, information was pulled from the State's database to identify actual historical field values prior to the application of each treatment type included in the matrix. This approach proved to be very useful to the subcommittee because they were able to visualize the decisions they had been making historically, and made it easier to replicate on paper. In addition, it helped provide the subcommittee with the confidence they needed to make their decisions.

An example of one portion of the decision matrix is shown in Figure 3. Reading across the first line from the Figure, a thin overlay would be considered as a feasible rehabilitation alternative if the distress index fell between an 85 to 65, the surface was asphalt, the structural deducts from the distress index totalled at least 15 points and no more than 35 points, the pavement had only 0-74 ESALs, the width of the pavement was at or above the standard of 27 feet, and the ADT was less than or equal to 750. The other lines in this particular portion of the matrix reflect other circumstances where a thin overlay would be considered feasible. Similar tables were developed for other rehabilitation treatments.

The final responsibility of the subcommittee was to define the impacts of each of the treatments on overall pavement condition and the determination

Rehabilitation Strategy Matrix
Flexible Pavements

Treatment Strategies	Committed Components		Surface Components		Operations Components						
	Combined Distress	Surface Type	Structural Condition (0-54 scale)	Ride (0-5 scale	Functional Class	ESALs	Width	Pavement Thickness	ADT	SN	Rut Deduct
	High Low	Type	High Low	High Low	Number	High Low	Wide Narrow	Thick Thin	High Low	High Low	High Low
	Enter values representing ranges when these treatments are considered										
Thin OL (≤-2 1/2")	85 - 65	AC	35 - 15			74 - 0	≥ 27		≤ 750		
Thin OL	85 - 70	AC	30 - 15			74 - 0	≥ 33		2000 - 751		
Thin OL	85 - 70	AC	30 - 15			74 - 0	≥ 39		≥ 2001		
Thin OL	85 - 65	AC	25 - 15			100 - 75	≥ 27	≥ 4"	≤ 750		
Thin OL	85 - 70	AC	25 - 15			100 - 75	≥ 33	≥ 4"	2000 - 751		
Thin OL	85 - 70	AC	25 - 15			100 - 75	≥ 39	≥ 4"	≥ 2001		
Thin OL	99 - 0	AC		< 2.5			≥ 39		≥ 2001		

Figure 3

FIG. 3 -- Portion of Flexible Pavement Decision Tree

of costs which would be used in the life cycle cost analysis of each feasible strategy. These values, as well as the trigger values, will have to be reviewed periodically to ensure that they still reflect the Department's philosophy and that any successful new technologies are reflected in them. Costs will probably have to be reviewed at least annually to reflect the actual expenses anticipated, as closely as possible.

ANALYTICAL SOFTWARE DEVELOPMENT

The results of the work of each of the subcommittees was then programmed into the North Dakota Pavement Management Analytical Software System. The end result is a comprehensive system, designed by personnel within the Department, to meet their needs. The involvement of the subcommittees in the software development has provided a valuable source of training in the decision process utilized by the software. The committee members feel comfortable with the decisions being made and have a good understanding of the reasons why certain treatments are selected over others. Although this approach has proven to be very useful in the end, it has required more work on the part of State personnel up front.

As the system is being used by the Department, some modifications have been made to the rehabilitation treatment matrices already to better reflect their repair philosophy. For this reason, the Department has decided to maintain the original subcommittees used during the software development and assign them the responsibility to update their portion of the system annually.

LOCAL JURISDICTION INVOLVEMENT

As discussed earlier, the second important aspect of this State pavement management implementation involved the extension of the contract to include any interested local jurisdictions within the State. Initially, seven cities and one county have elected to participate in a "piggy-back" arrangement with the State to implement their own system. The State DOT sponsored the training aspects of the contract and the developmental costs related to ensuring that the systems were compatible. The local jurisdictions were responsible for a small portion of the total costs, which enabled the Consultant to spend three days at each implementation site to completely customize the system for their own use.

Although the system implemented in both the State and the local jurisdictions are identical, it was developed to be flexible enough to allow each implementation site to develop their own performance curves, rehabilitation strategy matrices, and costs. The city/county systems utilize a slightly modified version of the condition survey procedures utilized by the State, so that the State is familiar with the rating system used for project selection and so that there is some consistency in approach. The local jurisdictions are not required to exchange information with the State, but the consistency allows for the mechanism to be set up, if desired.

CONCLUSION

The State of North Dakota has now fully implemented analytical software which supplements their previous pavement management software and should ensure their compliance with the FHWA mandate. State personnel were fully involved in the development of the system, thus ensuring that it would meet their objectives and fit with their organizational environment. This involvement allowed for potential users of the system to have a comprehensive understanding of the decision process utilized by the software in selecting rehabilitation requirements and projecting impacts on network condition due to various budget scenarios. Although this approach required a substantial amount of time on the part of the individuals involved, the system was still able to be developed and implemented within a year and a half.

The State has also provided a mechanism for local jurisdictions within the State to enhance their own pavement management capabilities. Through a important mechanism provided by the State, cities and counties had the opportunity to implement the State system, customize it for their own use, and obtain training on its use, for only a fraction of what it would have cost them had they secured these services privately.

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STANDARDIZATION IN PAVEMENT MANAGEMENT IMPLEMENTATION FOR MUNICIPALLY MAINTAINED ROADS IN RHODE ISLAND

REFERENCE: Lee, K. W. and Bowen, G. E., "Standardization in Pavement Management Implementation for Municipally Maintained Roads in Rhode Island," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: An effort was made to implement a standardized pavement management system (PMS) for municipally maintained roads in Rhode Island. Based on the results of a questionnaire survey and comparative analysis, Micro PAVER was selected as the most appropriate microcomputer-based PMS software for this particular purpose. An instructional workshop manual was prepared with an implementation procedure which utilized Micro PAVER as the core. Statewide PMS implementation was conducted through a series of training workshops for the technical staffs of cities and towns. Surface distresses were visually observed to evaluate the pavement condition, and the prioritization was based on the derived pavement condition index (PCI). During the standardization process, a ten percent sampling technique was recommended for pavement condition surveys. A preliminary list of techniques and costs for maintenance and rehabilitation (M&R) was prepared, and a series of deterioration curves were developed for the standard network. At least sixteen Rhode Island municipalities have decided to implement this standard procedure.

KEYWORDS: pavement management system, Micro PAVER, PAVER surface distress, pavement condition index, project prioritization, pavement maintenance, geographic information system.

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In September of 1986, a report by the Rhode Island League of Cities and Towns (RILOCAT) revealed that Rhode Island ranked at the bottom of all states on state highway aid to cities and towns and near the bottom on per capita highway spending [1]. Unlike most other states, Rhode Island has not used its fuel tax revenue directly for road improvement projects. Almost all major work has been financed through federal highway aid matched by bond revenues, obligating the Rhode Island Department of Transportation (RIDOT) to costly annual appropriations.

The shortage of funds to maintain the highway system is not limited to the state level. Local governments are also faced with the problem of deteriorating roads and reduced funding. Public funds which have been designated for pavements must therefore be used as effectively as possible. One proven method to mitigate the effects of depleted finances is through the use of a pavement management system (PMS) [2]. The PMS is a set of tools or methods that assist decision makers in finding optimum strategies for providing and maintaining pavements in a serviceable condition over a given period of time [3-5]. Without such a routine pavement maintenance program, roads require more frequent reconstruction, thereby costing the state and local governments millions of dollars. Municipal highway agencies throughout the country are adopting PMSs for a variety of reasons: to develop a physical inventory; to justify maintenance budget increases; to prioritize maintenance needs; and most importantly, to attain the best possible road network for the least amount of money.

In 1987, RI state transportation officials acknowledged the absence of a systematic and rational method to manage municipally maintained pavements. Although the RIDOT has a budget for snow-plowing, pothole repair, and other related maintenance activities, a comprehensive pavement management program did not exist. Recognizing the problem of pavement maintenance, Governor Edward D. DiPrete proposed a three year, $8 million Pavement Management Program in September, 1987 [6]. The program was designed to rehabilitate the main streets and roads in cities and towns throughout the state with improvements such as resurfacing, striping, signing, sealing, and sidewalk and curb repairs. The program would be funded through the state's general fund, and would be implemented over a three year period. In July of 1988, the Governor's program also supported a research team from the Department of Civil Engineering at the University of Rhode Island (URI) to implement an appropriate PMS at the municipal level. This initial research program was jointly coordinated with the Governor's Office, the RIDOT, the Rhode Island Department of Administration (RIDOA), and the RILOCAT. The objectives of this project were to evaluate available PMSs, to identify the most appropriate PMS for municipally maintained roads in Rhode Island, and to implement the selected system by providing training and support.

STATEWIDE INVENTORY OF MUNICIPAL-LEVEL PAVEMENT MANAGEMENT PRACTICES

One of the initial tasks was to conduct a questionnaire survey of the status of municipal pavement management programs in Rhode Island's thirty-nine communities. The purpose of this survey was threefold:

1) to identify the existing pavement maintenance practices;
2) to identify the use and availability of computers within the municipalities' public works or highway department; and
3) to develop an interest in the implementation of a computerized PMS.

In July of 1988, the RIDOT and URI distributed the questionnaire. By May 1989, all thirty-nine cities and towns had responded to this survey. The reaction by the communities confirmed the need for statewide implementation of a microcomputer-based PMS in Rhode Island [7].

The questionnaire results indicated that Rhode Island communities maintain an average of 130 miles of road. Included in this total is an average of 98 miles of asphalt concrete pavements. Only one community identified maintenance responsibilities for Portland cement concrete (PCC) road surfaces (a total length of only 2 miles). The size of municipal maintenance staffs ranged from 3 to 60 people with an average of 14 people.

The written responses to deciding the most cost-effective method for spending limited resources were more varied. Eleven communities reported the use of some type of inspection or survey method, and two municipalities are currently utilizing a condition ranking system. Priority or available budget is the decision factor in six municipalities, and a comprehensive road and drainage plan is utilized by one town. Unfortunately, the remaining nineteen responses were either inappropriate or blank.

According to the survey, thirty-three communities (85 percent) utilize a regular maintenance program. These programs are conducted annually in fifteen communities, semi-annually in one community, and seasonally in six communities. Six municipalities considered their maintenance program as something other than those mentioned. Only eleven communities (28 percent) actually use computers within the public works departments. However, eighteen of the remaining twenty-eight communities have access to computers at another location. Since the survey was conducted, at least four municipalities have either purchased or obtained access to computers. Only ten municipalities do not have access to a computer.

Although all thirty-nine communities expressed concern about the deterioration of their municipally maintained pavements, an overwhelming majority of the communities (92 percent) do not have a computerized PMS in use. Further investigation of the three towns which claimed to have PMSs revealed that only one of the municipalities actually has a computerized PMS, but with limited capabilities; another has a computerized budget management system; and the third had hired an engineering consulting firm to implement its PMS. Not including the town with the PMS installed by the consultant, at least twenty two municipalities have indicated an interest in implementing a computerized PMS while four other communities may be interested.

EVALUATION AND SELECTION OF A PMS FOR MUNICIPALLY MAINTAINED ROADS

The reactions by the communities to the questionnaire confirmed the lack of rational, systematic methods for the upkeep of municipally maintained pavements throughout the state. The diversity of the responses also established the primary requirements for a standardized municipal level PMS: the system must be low cost, microcomputer-based, simple to maintain and easy to operate.

System Evaluation

The process of evaluating the multitude of pavement and infrastructure management systems was simplified by performing it in two phases. The first phase of the evaluation involved reviewing available literature and software. The second phase consisted of a more detailed comparison of the most promising programs identified in the first phase.

The first phase assessed the programs' general features, operations, costs, developer support, degree of completeness, simplicity, and capabilities. Although ratings or rankings were not assigned to each category, the following general guidelines were considered essential for the programs:

1) The overall operation and implementation of the system must be simple. The most desirable PMS would be user friendly, with menu-driven software employing an on-line self-help feature, which the municipal engineering staffs can maintain with minimal outside assistance.
2) The initial cost and annual maintenance fees should be minimal. The ideal program would be non-proprietary, with little or no development costs imposed on the users.
3) The system should be based on visual observations of pavement distresses and possibly overall riding quality.
4) The collected data should be converted into an index number which indicates the pavement performance condition. The employed distress survey methodology must be objective and repeatable, and the derived index must allow prioritization of road sections for maintenance.
5) The system should, as a minimum, have capabilities for: storing pavement condition data, developing an objective index, prioritizing pavement sections for maintenance needs, providing maintenance alternatives, performing life-cycle cost analysis, and providing annual budget requirements to keep pavements in acceptable condition.

After the preliminary review, the most promising computer programs were selected for the more thorough investigation of the second phase. The non-quantified examination addressed seven specific characteristics:

1) Ease of Program Use
2) Clarity and Completeness of Documentation

3) Accessibility and Quality of Support and Updating Procedures
4) Program Costs
5) Data Management Components
   A. Database
      * condition rating data
      * cost data
      * maintenance history
      * inventory information
   B. Retrieval methods
      * file flexibility
      * output flexibility
   C. Data analysis methods
6) Pavement Management Levels (network and project)
7) Interim and Long Term Use Feasibility

Selection of Micro PAVER

The PMS evaluation process identified several excellent microcomputer-based programs. Some useful functions were unique to certain programs; thus no single program included all the necessary capabilities of the ideal PMS. The features of Micro PAVER, however, distinguish it as the most appropriate PMS software for Rhode Island municipalities.

Micro PAVER is one of the simplest menu-driven microcomputer-based programs which features an objective and repeatable visual distress survey methodology. Since it was developed by a government agency, Micro PAVER is non-proprietary and does not require any development costs. Continuous support is provided by the American Public Works Association (APWA) and periodic updates are furnished to its users. Most recently, Version 2.1 was released in October, 1989, and the next Micro PAVER upgrade will be released in May, 1991. Accordingly, Micro PAVER is one of the most widely utilized programs; more than 110 users are organized as a non-profit user group to assist each other and facilitate program updates [8-10].

Micro PAVER provides the user with a practical decision approach for identifying cost-effective maintenance strategies for roads and streets. Micro PAVER's interface programs provide report generation capabilities for critical information which allows objective input to the decision-making process. Other important capabilities include pavement network definition, data storage and retrieval, pavement condition index/rating, project prioritization, inspection scheduling, determination of present and future network condition, determination of needs for maintenance and rehabilitation (M & R), performance of economic analysis, and budget planning [10-13].

PRELIMINARY IMPLEMENTATION OF MICRO PAVER ON PILOT NETWORKS

During the evaluation process of available microcomputer-based PMSs, two pilot networks were created. The road system of the URI Kingston campus was established primarily to investigate the adaptability of promising computer programs to an actual street layout. The larger road network of the Town of South Kingstown was instituted to test the suitability of the selected computer program in a typical community. This section summarizes the preliminary implementation of Micro PAVER on these two pilot networks, and also recommends municipal implementation guidelines which were recognized during these trial installations.

University of Rhode Island Campus

The URI Kingston campus roadway network is representative of most municipal networks in the state, but only at a smaller scale. The roadways on the campus are primarily two-lane streets with asphalt concrete surfaces with functional classifications ranging from service roads (seldom-used) to circulators (heavily traveled). The characteristics of the campus roadway network allowed it to serve many functions:

1) the suitability of Micro PAVER and other promising computer programs could be examined;
2) municipal personnel could be trained in pavement condition survey procedures;
3) the repeatability and reproducibility of the pavement condition index (PCI) methodology could be tested;
4) condition survey techniques could be calibrated; and
5) Micro PAVER could be continuously evaluated and tested.

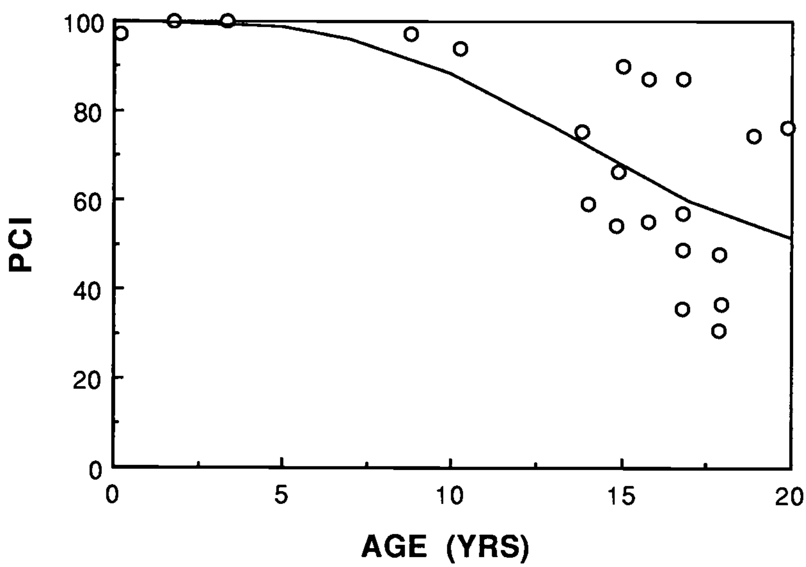
Most importantly, however, a PMS was established for the Kingston campus roadways.

One of two most important attributes of the implementation system was a preliminary list of M&R techniques and costs for both project and network level management. The list for network-level analysis is shown in Table 1, and will be used as a guide until a better list can be developed. The other important feature is the family curve developed as a pavement condition model for the network (Figure 1). This model includes a best fit curve through the family of data points representing all sections less than twenty years of age. The prediction of section condition assumes that the behavior of the section is similar to the behavior of its family. The curve has been constrained to eliminate positive slope, because the PCI cannot increase with age.

TABLE 1 -- M & R Strategies and Unit Costs for the Network-Level PMS (Asphalt Concrete)

PCI Range	M & R Strategy	Cost, \$/SY	Cost, \$/SF
0 - 20	Reconstruction or Recycling	12.00	1.33
21 - 40	Overlay (thick. may vary with PCI)	10.00	1.11
41 - 60	Stone Sealing (Surface Treatment)	8.00	0.89
61 - 80	Minor Repair	7.00	0.78
81 - 100	Routine Maintenance	3.00	0.33

The three year study results indicate that the campus network is currently in fair condition with a PCI of 48. The condition of the network is at a critical state; within four years, the PCI of the network will drop to 40 (poor) unless timely major repairs are performed. A budget condition analysis estimated a total cost of \$638,650 over a six-year period to repair all deteriorated pavement sections in the network. By 1996, this plan will result in all sections having PCIs greater than 55, and both the average section PCI and the area-weighted PCI will improve to 87 (excellent) [14].



$$PCI = .1000000E{+}03 - .6096123E{-}01\ X + .6969813E{-}01\ X^2 - .2769451E{-}01\ X^3 + .9116863E{-}03\ X^4$$

FIG. 1 -- A typical deterioration curve for the roads with known construction dates in URI Kingston campus

Town of South Kingstown

The Town of South Kingstown began implementation of Micro PAVER in June, 1988. The implementation was administered by an engineering technician, with assistance from an engineering intern during summer months. An average of ten person-hours per week were expended for collection of pavement condition data, background research of construction and major maintenance records, and data entry into the computer. These tasks were completed for the 110-mile paved municipal roadway network in July, 1989. The pavement condition surveys disclosed the average town-maintained roadway section is in "good" condition.

With data currently collected for the entire network, the Engineering Division plans to utilize Micro PAVER for routine applications. South Kingstown currently does not use life-cycle cost analysis in the selection of maintenance and rehabilitation strategies. The selection of individual projects and the treatment strategies for these projects is based on factors such as available funds, citizen complaints, political considerations, utility information and future development plans. With the Micro PAVER system operational, maintenance strategies can be related to the PCI and a more rational strategy selection process can be developed. For example, the Engineering Division has noticed the service lives of higher volume road surfaces treated with stone seals are not as long as expected. Engineering Division personnel can now analyze the collected data to determine which roads would be more cost-effectively treated with rehabilitation strategies other than stone sealing.

Although the Micro PAVER program is not yet being used to its full potential, the Town of South Kingstown is pleased with the progress and the results of the implementation thus far. The Micro PAVER program itself was easily adapted to fulfill the pavement management requirements of the Town. The Town will continue with its implementation and expects to perform pavement condition assessments on an annual basis for approximately one fourth of the road network. With condition data updated every year for at least one fourth of the roadways in the network, the Town will be able to establish a realistic long-range objective.

Recommended Guidelines for Data Collection

Before data can be collected, a municipality must first identify its pavement network components. A zone is the largest subdivision within a network. Zone boundaries are usually defined by permanent or physical obstructions (such as natural/semi-natural barriers, or state/major local roads), or less commonly, by administrative divisions (such as voting wards or school districts). The zone layout of South Kingstown is shown in Figure 2. A branch is any identifiable part of the network that is a single entity and has a distinct function, such as an individual street. Ideally, each branch should be contained within one individual zone, but occasionally, branches may be components of two or more zones. Sections are those portions of branches which are uniform in pavement structure composition, traffic, construction history, pavement rank, drainage facilities and shoulders.

Other factors to be considered in defining sections include management, data availability, costs, and whether the section limits can be changed. Since no formal length restrictions are imposed upon sections, a branch may consist of a single section. For example, minor residential streets and dead end roads typically have identical characteristics throughout, and therefore consist of only one section. Sample units are the smallest component of the network. The sample is the portion of the section which is actually inspected; therefore the sample(s) must be representative of the entire section. For sections with asphaltic surfaces, the sample unit(s) consist of 2500 $\pm$ 1000 sf (250 $\pm$ 100 m^2).

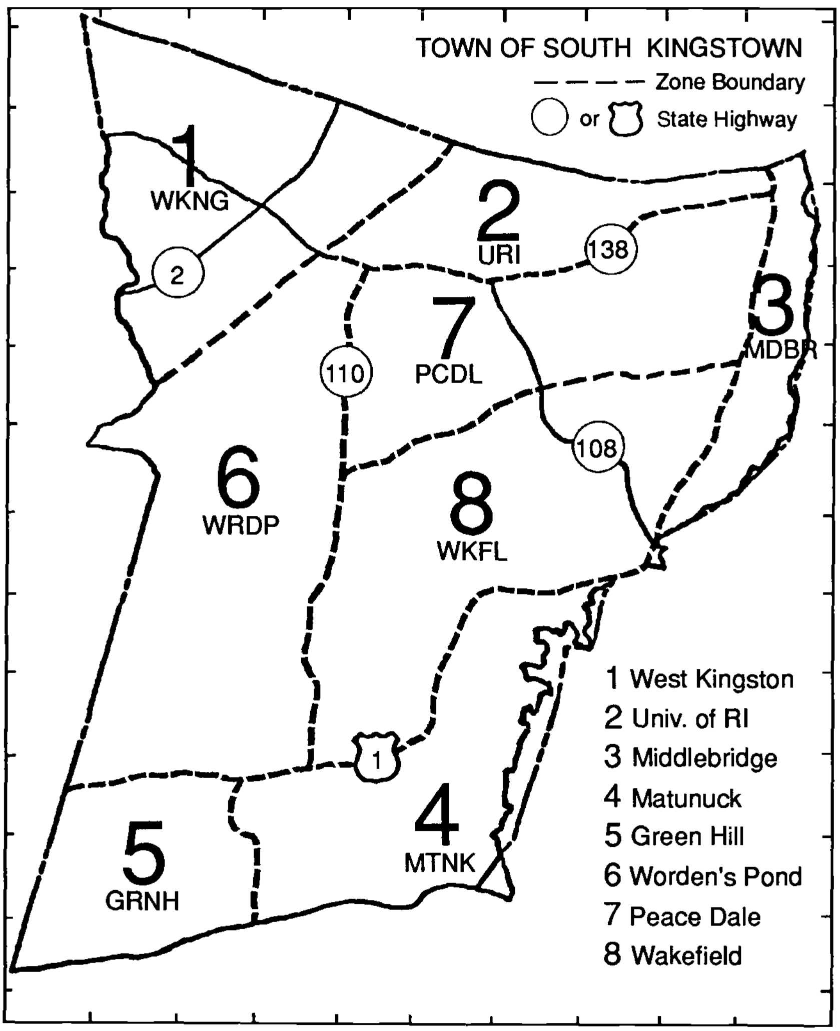


FIG. 2 -- Micro PAVER zones in the Town of South Kingstown

Accurate section PCIs are essential to both network and project level decisions. However, inspection of every sample unit within a pavement section would involve considerable time and effort. Such a practice would require more manpower, funds and time than are available to most municipalities. Since sections have been defined as having common characteristics (including surface type, structure, maintenance history, traffic conditions, and about the same level of deterioration), statistical extrapolation is applied to reduce the collection effort of distress data. Thus, only selected sample units are inspected and the PCI for the entire section is extrapolated. For initial network implementation, a ten percent sampling level should be sufficient as shown in Table 2. Figure 3 shows a typical application of sections and sample units for a branch. The first and last sample units of a section are not usually inspected since they may include pavement characteristics of the intersection.

TABLE 2 -- Recommended sampling strategy for initial implementation of Micro PAVER

Number of Sample Units per Section	Recommended Sample(s) to Inspect (if representative)
1 - 10	2nd
11 - 20	2nd, 12th
21 - 30	2nd, 12th, 22nd
31 - 40	2nd, 12th, 22nd, 32nd
...	...
...	...
...	...

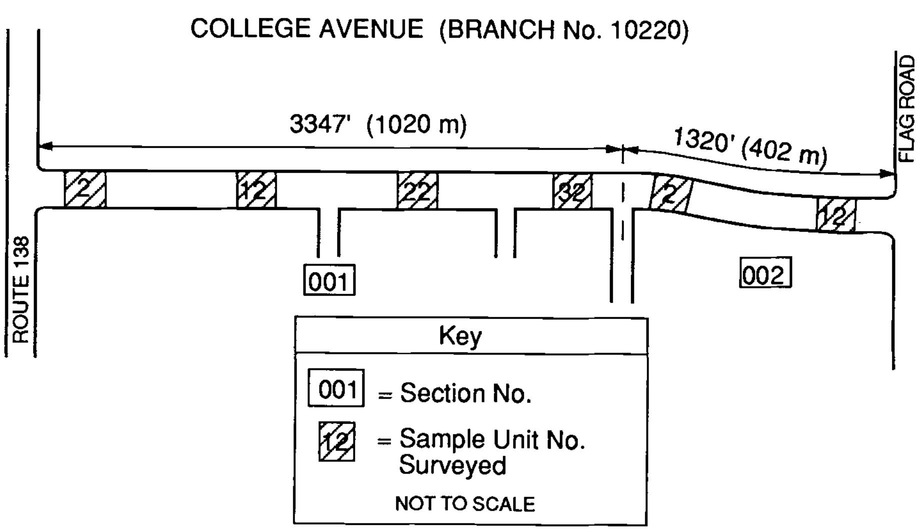


FIG. 3 -- A typical branch/section/sample unit application

A municipality should select its sampling level according to the desired level of accuracy. In fact, since additional sampling can always be performed in the future, a community's first-time sampling needs could be underestimated without jeopardizing this previously collected data. All subsequent inspections should always include the previously surveyed samples. Periodic inspection of the same sample unit assures the repeatability and reproducibility of the PCI methodology and also yields a more accurate deterioration rate for the pavement section.

PMS WORKSHOPS AND STATEWIDE IMPLEMENTATION STATUS

The preliminary implementation on the pilot networks allowed the system to be tested for widespread municipal use throughout Rhode Island. Since the program worked adequately during this trial period, the URI PMS team began the effort to implement Micro PAVER statewide. This task was accomplished through three separate informational workshops. The RIDOT/URI PMS workshops were one-and-one-half day informational/instructional sessions open to all thirty-nine municipalities. For each of the three workshops, letters of invitation were sent to the individuals designated by the communities on the returned questionnaires. Where applicable, additional personnel and previous attendees were notified with invitations, schedules and instructions.

A total of twenty-six communities, exactly two-thirds of Rhode Island's thirty-nine municipalities, attended at least one of the workshops (Figure 4). As a precaution against future implementation problems, the thirteen non-participating municipalities were asked if a particular reason existed for not attending any of the workshops. The two most common responses were personnel shortages or scheduling conflicts. Figure 4 also shows that at least sixteen municipalities have decided to implement Micro PAVER. A more detailed description of the status of these sixteen municipalities is included in Table 3.

POTENTIAL ENHANCEMENTS TO THE MUNICIPAL-LEVEL PMS

Substantial progress has been achieved in the implementation of a PMS in Rhode Island municipalities. Although Micro PAVER Version 1.0 was the most appropriate microcomputer-based pavement management program for statewide use at that time, it may not be a perfect or complete system. In fact, several opportunities to enhance the system exist.

The most obvious enhancement to the overall system will be the implementation of Micro PAVER Version 2.1 by the individual municipalities. This revised program includes many additions and new features. General changes include a utility program to convert Version 1.0 databases to Version 2.1; an unsurfaced road condition index; and extended memory to increase the speed of report generation.

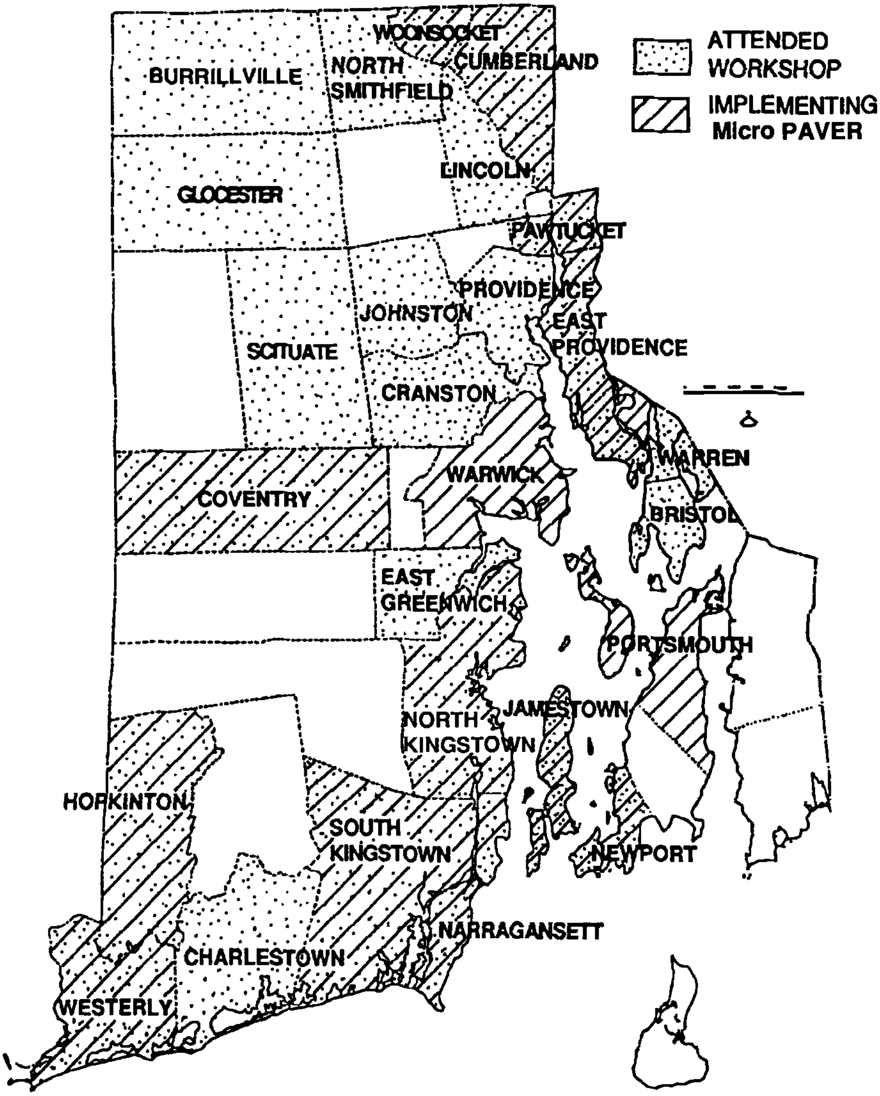


FIG. 4 -- Rhode Island municipalities implementing Micro PAVER

TABLE 3 -- Status of PMS implementation with Micro PAVER in Rhode Island municipalities

Municipality	Workshop Attended	Computer Available	Possess Micro PAVER	Established Network/Branch Numbering System	Method of Data Collection	Percent Data Collection Completed	Data Collection Completion Date (Actual or expected)
Barrington	1st	Yes	Yes	No	Students	0%	1991
Coventry	1st, 3rd	Yes	Yes	Yes	Students	100%	1989
Cranston	2nd	Yes	Yes	No	Inhouse	0%	N.A.
Cumberland	1st	Not yet	Yes	Yes	Students	0%	1991
East Providence	2nd	Yes	Yes	No	Students	0%	1991
Hopkinton	2nd	Yes	Yes	No	Inhouse	0%	1991
Jamestown	2nd	Yes	Yes	Yes	Inhouse	60%	1991
Lincoln	1st	Yes	Yes	Yes	Students	100%	1990
Narragansett	2nd	Yes	Yes	Yes	Consultant	100%	1989
Newport	1st	Yes	Yes	Yes	Inhouse/students	5%	1991
North Kingstown	1st,2nd,3rd	Yes	Yes	Yes	Consultant	100%	1990
Pawtucket	1st,3rd	Yes	Yes	Yes	Students	100%	1990
South Kingstown	1st	Yes	Yes	Yes	Inhouse/students	100%	1989
Warwick	1st	Yes	Yes	N.A.	N.A.	N.A.	N.A.
Westerly	1st	Yes	N.A.	N.A.	N.A.	N.A.	N.A.
Woonsocket	2nd,3rd	Yes	Yes	Yes	Students	N.A.	1991

Note: N.A. indicates that the information is not available at this time.

Another short-term enhancement will be to continue the process of confirming the approaches, methods, data, and costs used by both the URI PMS team and the Town of South Kingstown. Some of this information was acquired from other areas of the country and may not be appropriate for Rhode Island. Similarly, collection of more accurate costs for construction and maintenance activities will require time for several municipalities to become more proficient using the Micro PAVER procedures. Once this happens, a type of user's group may develop from which the URI PMS team may compile M&R policy, construction and maintenance costs, and other useful information. Statewide averages or default values may then be established and shared among users.

A comparison of in-house data collection efforts with contracted consultant services will also benefit the municipalities, especially those who have not yet begun implementation. With time and cost information available for both approaches, the most cost-effective method may be determined for the combined schedule and budget requirements anticipated by the individual municipalities.

Logically, the most critical modifications to the PMS are of an inherent nature; that is, they focus on ways to improve the contents or effectiveness of the Micro PAVER program itself. However, the PMS as a whole will be subject to improvements from outside sources as well. These activities may be more long-range in scope and may merge or combine the PMS with other larger systems or databases.

Some Rhode Island communities may integrate the Micro PAVER PMS with a public works management system. These systems usually include programs or modules which are relevant to pavement management. The typical street or pavement inventory program directly incorporates the numeric pavement condition rating from the PMS and generates inventory reports virtually identical to Micro PAVER's. Other typical programs, such as maintenance management, cost accounting, planning and budgeting, generate information very similar to the Micro PAVER report routines. Public works management systems normally include other computer programs which would complement a PMS: automated complaint tracking, public works cost accounting, and equipment management information. Used in connection with a PMS, these computer programs form a comprehensive public works maintenance system. The option to combine the PMS with a public works management system must be decided upon by the individual communities.

Integration of the pavement management system with a geographic information system (GIS) has the most potential. A GIS allows users to capture, edit, and display geographic data as well as perform geographic analysis and create topographical maps. A GIS not only stores the traditional elements of a street inventory (street name, pavement width, pavement condition, curbs, striping, shoulders, ditches, traffic signs, etc.), but displays the information in practically endless combinations. The database can be expanded to include any information essential to pavement management: street surface area, measurements of missing curbs and gutters, completed or scheduled utility work, unit costs for various rehabilitation processes, costs to perform rehabilitation, and recommended rehabilitation strategies [15].

A GIS can be used for daily routine maintenance scheduling. The system can also be very helpful in answering the public's questions on street conditions and expected repair dates. However, the greatest aid of a GIS may be its ability to show elected officials and public administrators the condition of streets. Plots of streets in poor condition are useful at city or town council meetings, budget meetings, and neighborhood organization meetings. The ability to show decision-makers the plots of poor condition roads can only result in a positive impact on the funding and repair process [16]. A PMS combined with a GIS is clearly one of the most powerful tools for preparing municipal-level pavement maintenance programs. The City of Cranston has already expressed a strong interest in implementing a combined GIS/PMS.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations based on the results of this study are summarized below.

Conclusions

1) Thirty-three of the thirty-nine municipalities in Rhode Island (85 percent) utilize regular maintenance programs for their highways; however, the statewide absence of a systematic and rational method to manage municipally maintained roads was evident. When this project began, only one of the communities was using a computerized PMS, a proven technique to economically administer highway maintenance and rehabilitation.
2) Micro PAVER was selected as the most appropriate microcomputer-based PMS for municipally maintained roads in Rhode Island. Micro PAVER is one of the simplest menu-driven programs which provides users with a practical decision making tool for identifying cost effective maintenance and repair alternatives for roads and streets.
3) A Micro PAVER-based PMS was successfully implemented on two trial networks: the URI Kingston campus and the Town of South Kingstown. Through these initial installations several critical functions were established:
   i) a preliminary procedure for field crew training;
   ii) databases to check the reproducibility of PCI values;
   iii) a standard network (the URI road network) which will allow for future study, training, and calibration; and
   iv) a model municipal network (South Kingstown) to encourage statewide implementation.
4) A preliminary set of M&R techniques and costs was prepared, and a series of deterioration curves were developed for the standard network.
5) Twenty-six Rhode Island municipalities (represented by a total of sixty-two participants) attended at least one of the pavement management workshops jointly offered by the RIDOT and URI. At least sixteen municipalities have decided to implement Micro PAVER. Several other communities which originally expressed little or no interest in a PMS are now recognizing the importance of a systematic and rational method to maintain their municipal pavements.

6) The integration of GIS technology with a PMS was identified as one of the most promising and logical applications to enhance the capabilities of a municipal-level PMS.

Recommendations

1) The URI PMS team should continue to assist all interested municipalities with the implementation of the developed PMS, and update the list of M&R strategies, costs and service lives of all municipal pavement maintenance practices typically used in Rhode Island.
2) Implementation and research on the Town of South Kingstown model network should be continued, and all other municipalities should consider utilizing or adapting the results of this pilot network.
3) All systems installed with Micro PAVER Version 1.0 or 1.2 should be upgraded to Version 2.1 or later.
4) Each municipality should consider incorporating their PMS into a total public works management system.
5) Integration of the PMS with a GIS should be considered at the municipal level.

ACKNOWLEDGMENTS

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Roy A. Eckrose,[1] and Wayne G. Reynolds [2]

IMPLEMENTATION OF A PAVEMENT MANAGEMENT SYSTEM FOR INDIANA AIRPORTS - A CASE HISTORY

REFERENCE: Eckrose, R. A. and Reynolds, W. G., "Implementation of a Pavement Management System for Indiana Airports - A Case History," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: The development of a Statewide Pavement Management System for Indiana airports was a multi-year project. The project has been carefully designed to ensure workability and to capitalize on changes in the state of the art in Pavement Management. The first year was an exploration of the Pavement Condition Index (PCI) inspection procedure. The first twenty eight airports were inspected in 1985, using the PCI procedures as outlined by the Federal Aviation Administration. This first step was unique in that it was the first statewide inspection conducted with the financial assistance of the FAA.

The second phase of the project, covering some twenty airports was conducted in 1986. At this stage, the basic inspection was supplemented with computer software which allowed the state to construct and manipulate Capital Improvement Programs for the pavement systems over a six year planning window.

The project continued in 1989-90 with additional updated PCI inspections at twenty one airports and with the installation of a complete Airport Pavement Management System (APMS) on state computers, which allows the state to update and maintain the system on its own. It also permits the state to conduct in-depth analysis of pavement systems and individual features including forecasts of condition and analysis of maintenance and/or rehabilitation alternatives.

After several years of development and improvement, the State of Indiana now has, in place, a comprehensive APMS which provides a significant decision making tool for planning of needs and capital expenditures for pavement systems for a ten year period.

KEYWORDS: pavement management, airport pavement, airport, pavement condition index, pavement evaluation, pavement forecast, capital improvements

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Introduction

At the present, there are several states in the United States which have implemented comprehensive Pavement Management Programs for their airports. In 1985, when the Indiana Department of Transportation Division of Aeronautics initiated its program, this was not the case. At that time, there were only a few such systems in place and these exhibited little standardization of either concept or implementation. Accordingly, Indiana elected to pursue its implementation cautiously over a period of years. The DOT's initial phase was somewhat exploratory - to assess the Pavement Condition Index (PCI) procedure as it would apply to Indiana's own airport pavements. If this inspection procedure proved to be both workable and useful to the Department of Transportation, it was the intent to expand the PCI data base in ensuing years and to gradually implement a full-scale Pavement Management Program. The Department believed, and it has proven to be so, that this procedure would allow it to work out any problems with the inspection procedures and to more carefully evaluate alternatives for the overall program. It should be recognized that the availability and sophistication of Pavement Management software was extremely limited back in 1985. Each phase of the implementation has been most instructional.

PHASE 1 - 1985

As mentioned, the Department began its program in 1985 with the inspection of airside pavements on 28 of the state's smaller airports. This inspection program covered about 14.4 million square feet (1.3 million m^2) of paved surfaces. At that time, the only guidance available for this inpection program was the FAA Advisory Circular, "Guidelines and Procedures for Maintenance of Airport Pavements", Appendix A [1]. This Circular was about two years old at the time Indiana began to plan for implementation of the program.

In addition to starting the system with few precedents, the department also embarked on a process of obtaining Federal assistance for the project. In many ways, this is the most significant portion of the first year's work. Our 1985 project was the first time in which the Federal Aviation Administration had participated financially in a statewide airport pavement inspection project. As can be imagined, this type of prototype project was difficult to get approved. Indiana DOT acknowledges the cooperation and assistance of the Great Lakes Region of the FAA in this regard.

With the limitations the DOT faced for in-house personnel, the department elected to retain a consultant for the inspection procedure. The scope of services was modeled after the Wisconsin Department of Transportation, which had conducted a similar study in 1984, although without Federal participation.

Inspection of the pavements was conducted in late 1985 at all 28 airports. The end product of this first effort was a report for each inspected airport which provided a summary of the PCI inspection information,including extrapolated distress quantities, and a series of alternative rehabilitation-reconstruction alternatives with cost estimates and service life forecast for each alternative [2]. No computer software was obtained in this phase. The analysis was conducted with the AIRPMS.216 software of Eckrose/Green Associates, Inc., the DOT's consultant on the project. The type of information gathered is shown in the figure 1.

INDPMS.216 INDIANA STATE AIRPORT SYSTEM MANAGEMENT PROGRAM MASTER FILE

ECKROSE/GREEN ASSOCIATES
6409 ODANA ROAD
MADISON, WISCONSIN 53719
(608) 274-6409

PROJECT NUMBER: 60105.077 PROJECT NAME: JVY CLARK COUNTY (JEFFERSONVILLE)
DATA COMPILE FROM DATA IN PCI PROJECT NO. 60105.077 FEATURE NO. 5001
MASTER FILE IS DESIGNATED AS: C:\AIR\300\JVYQ5001.077 ANALYSIS YEAR: 1987

FEATURE NUMBER: 5001, DESCRIPTION: R/W 18-36
TOTAL AREA OF FEATURE: 292500 S.F. SAMPLED AREA: 63000 S.F.
PAVEMENT SURFACE TYPE IS : ASPHALT CONCRETE REQ. PCI LEVEL: 60

HIGH PCI FOR FEATURE: 81 LOW PCI: 54 AVERAGE PCI: 71 VERY GOOD
FROM INPECTION CONDUCTED ON 9/8/86 RUN DATE: 03-27-1987
RUN TIME: 13:33

NOTES AND COMMENTS FOR FEATURE 5001

1981 - 3" BIT. SURFACE ON 8" AGG. BASE
*
*
*

DISTRESS CODE	DISTRESS TYPE	SEVERITY	MEASURED AMOUNT	ESTIMATED TOTAL AMT.	PERCENTAGE OF ALL DISTRESS
1	ALLIGATOR	LOW	32	148 S.F.	5.1
5	DEPRESSION	LOW	2040	9471 S.F.	25.9
8	L & T CRACKING	MED	556	2581 L.F.	14.2
8	L & T CRACKING	LOW	906	4206 L.F.	10.8
13	RUTTING	HIGH	12	55 S.F.	4.1
13	RUTTING	MED	100	464 S.F.	4.7
13	RUTTING	LOW	2064	9582 S.F.	34.8

BASIC DISTRESS CAUSES

APPROXIMATE AMOUNT RELATED TO LOAD ON PAVEMENT IS: 30 - 40 %
APPROXIMATE AMOUNT RELATED TO MATERIALS PROBLEMS IN THIS FEATURE IS: 50 - 60 %
APPROXIMATE AMOUNT RELATED TO AGE OF PAVEMENT IS: 00 - 10 %

SERVICE LIFE FORECAST FOR FEATURE 5001 CONSTRUCTED OF:
ASPHALT CONCRETE PAVEMENT

PROJECT NO: 60105.077
YEAR OF CONSTRUCTION OR OVERLAY: 1981
PCI AT TIME OF INSPECTION IN 1986 IS 71

YEAR	PROJECTED CONDITION	PROJECTED PCI
1987	GOOD	68
1990	GOOD	61
1994	FAIR	54
1998	FAIR	48
2002	FAIR	43
2006	POOR	36
2010	POOR	27
2014	VERY POOR	15
2018	FAILED	0

**** MINIMUM SERVICE LEVEL REACHED IN 1991 ****

A SERVICE LIFE EXTENSION FOR 5001 CAN BE OBTAINED BY:
RESURFACING

COST ESTIMATE FOR RECOMMENDATION IS: $ 211300 - 285900
THIS COULD CONSIST OF OVERLAY OR RECYCLING OF SURFACE

SERVICE LIFE FORECAST FOR FEATURE 5001 AFTER RESURFACING

YEAR	PROJECTED CONDITION	PROJECTED PCI
1987	EXCELLENT	100
1990	EXCELLENT	86
1994	VERY GOOD	72
1998	GOOD	61
2002	FAIR	51
2006	POOR	29
2010	FAILED	0

**** MINIMUM SERVICE LEVEL REACHED IN 1999 ****
NOTE: THIS IS A SERVICE LIFE EXTENSION OF 8 YEARS

FIG. 1 - AIRPMS.216 output provides basic file information, construction history, distress information and analysis of alternative actions.

The information gathered in the first year was found to be of significant value in assessing the needs of state airports. Based on these results, the department proceeded with the planning for the second phase. The first year was not without problems, however. From the inspection standpoint, it was obvious that the existing standards (FAA AC 150/5380-6) did not ensure that subsequent inspections of the same or additional pavement sections would yield consistent results. While distress descriptions in the AC were generally adequate, the differentiation between severities were frequently too subjective to be repeatable, unless the inspections were always performed by the same personnel. This concern was reflected in the experience of the State of Illinois, which had been conducting similar inspections with its own personnel.

Accordingly, with the consultant, the department sought to establish more stringent inspection standards for subsequent activities. In response to this concern and to similar observations in other locations, the consultant prepared a draft of what subsequently became "Airport Inspection by PCI" [3]. This draft would be field tested and modified "on the fly" during the second year of the program.

The existence of a reasonable amount of data also permitted the department to evaluate available management systems and software for potential implemenation in Indiana. By the end of 1985, alternatives to the PAVER system were available. The choice was made to implement a Capital Improvement Program on state computers rather than PAVER since the PAVER system did not provide the necessary ability to plan meaningful multi-year capital requirements on state airports.

PHASE 2 - 1986

Armed with the 1985 experience, additional pavement inspections were launched in 1986. Only 20 airports were included, but they were larger and more complex than those selected for the 1985 prototype effort. In all, some 27.4 million square feet (2.5 million m^2) of pavement were scheduled for 1986.

The advent of the inspector standards in 1986, based on Quality Control results from 1985, improved the PCI inspection considerably. The draft manual was field tested by multiple crews at a variety of sites and under a variety of conditions. In spite of the replacement of many of the subjective choices with actual field measurements, crew production was not significantly adversely affected. Constant cross-checking of crews with a quality control engineer produced inspection results which we believe were both accurate and repeatable by others.

The tested inspection standards and criteria were published in 1987 as the first edition of "Airport Inspection by PCI". By 1988, this inspection guide was republished as the 2nd edition, with additional revisions and the inclusion of photographs to illustrate each point.

The other major item which the department felt it needed, based on use of the 1985 data, was the means to manipulate and modify the multi-year Capital Improvements Programs generated from the data. Accordingly, implementation of AIRCIP, a microcomputer based Capital Improvements Progam set of software, was included in the 1986 program. This program, part of the AIRPAV software system, provided a number of capabilities which were not available with only the hard copy reports generated during the first year. These new capabilities included:

1. Ranking of pavements according to their condition, from the worst to the best, using PCI as the unit of comparison.

2. Ranking according to construction date or last rehabilitation date.

3. Ranking by available service level margin. This ranking compares existing condition to the desired minimum service level, from worst to best.

4. Ability to control unit costs - allowing us to employ local cost experience and year-to-year changes.

5. Flexible inflation factors which provided a quick assessment of the cost implications of moving project from year to year.

6. Multiple project level selection which allows changing the scope of a project, from among the various alternatives, to reflect budget limitations or program consistency.

7. Ability to move projects between years within an six year time frame to develop major programs or to address budgetary constraints.

8. Maintenance of a record of all options within the computer as an aid to future analysis and program alternative selection. These records included the results of all alternative CIP developments.

9. Provided for aggregating all individual airport CIP's into a statewide plan.

Thus, as the second year of the program was completed, Indiana felt that it had, in place, a consistent inspection procedure and the ability to use the data generated in a meaningful manner.

As with the first year, the second year was not without problems, however. These problems were not directly related to the Pavement Management Program, but rather to computer utilization and access difficulties within the Department of Transportation. The Department operated on a networked system with outdated PC's as the access terminals, and too few of these. Within the system, it was difficult to gain access when needed for the efficient use of the system. By the time the system had been on-line for a year, it was evident that the best solution to our access problems was to upgrade Division hardware and to eliminate the network dependency for the Pavement Management Program.

PHASE 3 - 1989

By late 1988, the Division of Aeronautics was able to begin the process of upgrading our in-house hardware. Accordingly, it scheduled Phase 3 of the program for 1989. Few new pavements were planned for inspection in Phase 3, but reinspection of several of the 1985 program pavements were scheduled. The original data would already be four years old by that year. All told, 21 old and new airports were included in Phase 3, encompassing some 12.2 million square feet (1.1 million m^2). In many cases, only the highest priority pavements (runways) were scheduled for reinspection. This procedure would allow the department to approach ensuing years with recent data on these sections. In addition to the inspections/ reinspections, it was decided that we now had enough experience with our system to obtain a complete Pavement Management System, freeing the State to update the database and upgrade at will in the future.

Accordingly, as part of the 1989 project, Indiana acquired the complete AIRPAV airport pavement management software series. This allows the department to handle internally all functions from the survey data input to development of the statewide Capital Improvement Program. As the system was developed, it encompasses several discrete modules, each representing a distinct step or function in the maintenance of our pavement management program. Each module is selected by a simple menu selection as shown in Figure 2.

The first of these modules (INDPCI) permits the user to input PCI survey data as well as to obtain hard copy of the survey summaries or reprints of the individual sample unit surveys. The module is free standing and may be used either in the office or on a portable or laptop computer in the field. Closely related to the input program is the file utility (INDFIL), which provides the ability to add such items as construction history, minimum required services levels, etc., to the data base.

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INDIANA STATEWIDE AIRPORT SYSTEM - PAVEMENT MANAGEMENT PROGRAM

THERE ARE SEVERAL MODULES IN THE INDIANA AIRPORT PAVEMENT MANAGEMENT
PROGRAM . BRIEF DESCRIPTIONS AND ACCESS PROCEDURES FOLLOW.

INDPCI  - For the input/printing of PCI survey information.
INDFIL  - To reduce PCI survey information and to create a data base which
          can be analyzed by subsequent modules.
INDPMS  - The basic analytical program which generates life expectancies
          and cost estimates on a feature by feature basis within each
          basis. Should be used for initial run.
AUTOPMS - This is basically the same as the INDPMS program, except that
          it can provide calculations and creation of CIP data bases for
          entire state in one operation. It is primarily used to examine
          the effect of changing threshhold values.
INDCIP  - Provides for development of Capital Improvement Programs on an
          airport by airport basis and for the entire state. Development
          can be done individually or statewide.
INDMIP  - Provides for development of Maintenace Improvement Program
          worksheets and maintenance work orders.
QUERY   - To examine your data base.
END -     To terminate this session and return to DOS.
          Use ↑ ↓ or emphasized letter.        Type D for DOS shell.
```

FIG. 2 - Indiana's software allows selection of modules from a menu.

It is not the intent of this paper to review each of the functions of our Pavement Management System. However, there are several important features which will be of interest to those planning to implement such systems in the future.

The analytical module (INDPMS) is the heart of the system. This portion of the program analyzes the distresses and selects viable alternative rehabilitation strategies which will bring the pavements up to the minimum service level. Alternatives are selected which will maintain serviceability throughout the planning window (9 years) and also those which will extend pavement life for a lesser period, but at lower cost. The alternatives are presented graphically for each pavement feature, either on the computer screen (as illustrated in figure 3) or in hard copy.

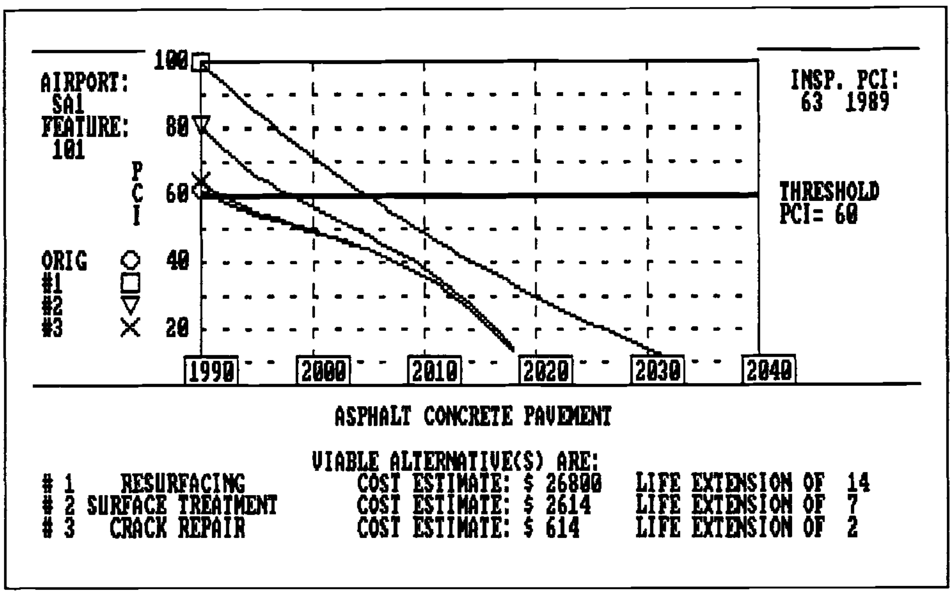

FIG. 3 - Indiana's DOT can view all alterntives and their associated costs graphically.

The results of these analyses are stored in the Capital Improvements modules (INDCIP) which, though somewhat modified from the initial version, is essentially the same format as the CIP in use since 1986. This program provides us with several tools to aid in priortizing and organizing Capital Improvement Programs. These tools are available from a menu as shown in figure 4.

Actual CIP development is done in a familiar spreadsheet format, illustrated in figure 5, which allows us the flexibility to move, add, or delete specific projects to develop consistent construction projects or to meet budget restraints.

INDIANA AIRPORT SYSTEM CIP PROGRAM

A. ORDER PAVEMENTS BY CONDITION
B. ORDER PAVEMENTS BY AGE
C. ORDER PAVEMENTS BY SERVICE LEVEL MARGIN
D. CONSTRUCT CAPITAL IMPROVEMENT PROGRAM
E. REVIEW DATA FOR INDIVIDUAL FEATURE
F. OBTAIN LISTING OF ALL REHAB. OPTIONS
G. CHECK AND/OR ALTER UNIT COST TABLE
H. TRANSFER TO COMBINED IMPROVEMENTS PLAN
I. WORK WITH ANOTHER AIRPORT
J. END PROGRAM RUN

SELECT ONE (A,B,C,D,E,F,G,H,I OR J)

PRESENT AIRPORT IS BAK

FIG. 4 - Several sorting/ranking options as well as a "worksheet" format are available for individual airports or for the statewide system.

* INITIAL RECOMMENDATIONS *

FEATURE	OPTION	1990	1991	1992	1993	1994	1995
101	3 SURF.TR.				53918		
201	5 ST. O'LAY	79650					
301	8 CRACKS	5150					
401	9 SURF.TR.	25147					
501	11 SURF.TR.	7000					
601	15 SURF.TR.	494606					
3001	18 SURF.TR.	181517					
3002	21 SURF.TR.					50488	
3003	25 CRACKS						
5001	27 SURF.TR.			281219			
5005	31 ST. O'LAY						
6001	33 ST. O'LAY	35400					
6002	36 ST. O'LAY	800040					
6004	40 ST. O'LAY	35400					

BAK
<▯>>

F1 HELP F2>STOP F3>CONT. F4>DELETE F5>ADD F6>MOVE F7>MENU F8>NEW F9>OUT F10>IN

FIG. 5 - The CIP spreadsheet provides Indiana DOT with the flexibility to develop programs to meet a variety of constraints.

From an administrative standpoint, it is often essential that an agency such as ours be able to take a quick look at our pavement data base to get an overview of pavement performance or to list upcoming projects. With this in mind, the Indiana system includes a query system (QUERY) which operates from the common data base and allows department personnel to perform such functions as obtaining a listing of all pavements requiring work in a single year, all pavements which are below standards, etc. This can be done for a single airport or for the entire state at a glance. Users can also obtain a quick graphic overview of the performance of any individual pavement (figure 6).

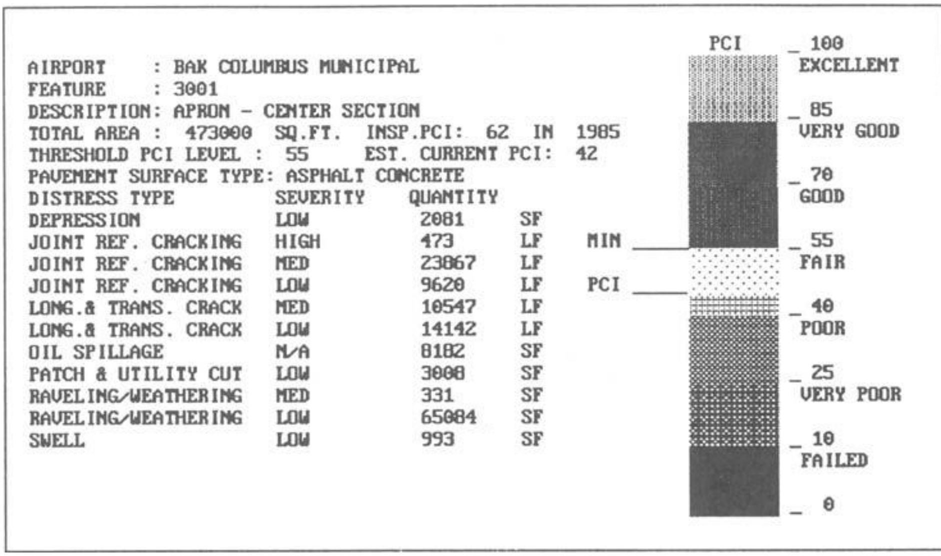

FIG. 6 - The Indiana data base can be queried on a statewide or individual airport basis.

Frequently, it is possible to obtain significant improvement in pavement life with minor, low cost maintenance activities. These will usually be of a scope which is well below that of a rehabilitation or "capital impovement" and can usually be taken care of by the airport staff. The Indiana pavement management program is structured to permit personnel to isolate such activities (see figure 7) and provide guidance to the airports with regard to the most cost effective minor maintenance requirements. This is an advisory role, but has the potential to make a significant impact on long term pavement performance.

A comprehensive pavement management program is a major, and expensive, undertaking. Accordingly, the department required that the program include all items necessary to make annual or periodic updates and changes to the system and data base. Our system includes a data base editor which is also menu driven and permits such changes. Further, it is the department's belief that the system itself should be capable of being altered without dependence on a single vendor for all such changes. Since the heart of any pavement management program is in viable service life forecasts, the Indiana system was developed with the ability to modify, with state staff, forecast parameters and formulas used in the software. This may not be necessary, but as our department gains experience with the system, or changes construction standards or specifications, it could be. Therefore the system is equipped with a menu driven, graphically displayed, program, illustrated in figure 8, to modify this important ingredient.

PAVEMENT MAINTENANCE WORK SHEET

AIRPORT : BAK COLUMBUS MUNICIPAL
MAINTENANCE CATEGORY : AC PATCH
DATE LAST INSPECTED : 9/25/85
DESCRIPTION OF WORK : AC PATCH

FEATURE	MAINTENANCE ITEM	QUANTITY	INSPECTED PCI	EST. PCI
3001	AC PATCH	708 SQUARE FEET	60	66

TOTAL : 708.0 SQUARE FEET

EQUIPMENT :Saw,Air Compressor,Heating Kettle,Hand Tools
ESTIMATED MATERIALS : 26.8 TONS ASPHALT PATCH
ESTIMATED MATERIAL COST : $ 804.00 UNIT COST : $ 30.00
ESTIMATED MAN HOURS : 88.5 MAN HOURS
ESTIMATED LABOUR COST : $ 885.00
ESTIMATED PROJECT COST : $ 1689.00

DO YOU WANT A HARD COPY? (Y/N)

FIG. 7 - Small maintenance projects can be identified from the pavement data base to isolate cost effective activities.

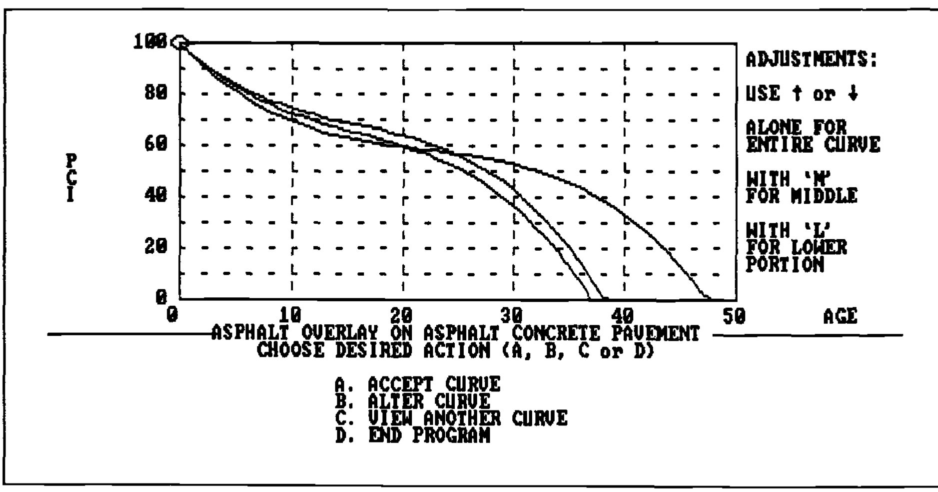

FIG. 8 - Forecast models can be modified as needed in the Indiana system.

Conclusion

Indiana's DOT began its statewide pavement mangement program at a time when there were few guidelines or precedents available for such systems. Accordingly, the department proceeded in a very careful and deliberate manner, examining results and options at each step as well as reviewing the state of development in the industry with regard to software systems.

As a result of this process, Indiana now has a comprehensive Pavement Management System in place which provides the tools to analyze pavement performance, quickly obtain information about the pavement system, develop meaningful multi-year capital improvement programs and provide the state's individual airports with substantial guidance in maintenance functions and improvement planning.

We believe that it is vital for all agencies who embark on this process to assure that the resultant system is carefully customized to the needs of the individual agency. The agency should be intimately and continuously involved in the development of its system and has the ultimate responsibility to make sure that the consultant, if any, conforms the system to the agency's needs and desires.

Many of the concepts originally developed and tested in Indiana have now been incorporated into similar systems in other states.

For any agencies which are preparing to implement similar systems, Indiana encourages you to look at its system, or at similar systems which have grown from it in other locations. The department can provide you with a list of other agencies whose systems have followed on after the Indiana program and which may have other features of interest.

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[3] Green, William H. and Eckrose, Roy A., "Airport Pavement Inspection by PCI", Fitchburg Press, Madison, 1987

Scott D. Murrell[1], Gonzalo R. Rada[2], and Charles W. Schwartz[3]

AIRPORT PAVEMENT MANAGEMENT: THE PORT OF NEW YORK AND NEW JERSEY EXPERIENCE

REFERENCE: Murrell, S. D., Rada, G. R., and Schwartz, C. W., "Airport Pavement Management: The Port of New York and New Jersey Experience," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: The Port Authority of New York and New Jersey (PANY/NJ) operates John F. Kennedy International, LaGuardia, and Newark International airports, which collectively represent the largest and busiest air transport complex in the world. To provide effective maintenance and management of the extensive network of airfield pavements at these airports, data display concepts from the field of geographic information systems were coupled with established pavement analysis techniques to create a network-level planning tool: the Integrated Airport Pavement Management System, IAPMS. This paper describes the IAPMS program and summarizes the implementation experiences at the three PANY/NJ airports.

KEYWORDS: airport pavement management, databases, geographic information systems, airfield pavement engineering.

INTRODUCTION

In the early days of aviation, pavement management consisted of a visual inspection of the airport and resurfacing or patching the pavements in the same year. The vintage engineer grew up with most of

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the pavements and was often involved in their original design and construction. As a result, he had a good, first-hand knowledge of their condition at any point in time. Based on his visual observation of the pavement distresses and his experience, the vintage engineer made repair recommendations and prepared budgets before distresses became critical. Budgets were relatively small and could be handled in a routine manner.

During the 1970's, aircraft traffic greatly increased with jumbo jets becoming a large percentage of the traffic mix. As aircraft got bigger they got heavier and pavements were not lasting as long. As airports became more congested, the need to "do it right the first time" with respect to pavement construction and maintenance became critical. At the same time, the buying power of construction and maintenance funds was shrinking due to a high inflation rate in the construction industry. In addition, the experienced engineers began to retire, without much chance to pass on the knowledge they had acquired over the years on the best methods of keeping the pavements in good shape. All these pressures were indicators that a better pavement management system was required.

In 1980, engineers from the Port Authority of New York and New Jersey (PANY/NJ) began implementation of a program to develop a pavement management system for the three New York metropolitan area airports - John F. Kennedy International, Newark International and LaGuardia, which collectively represent one of the largest and busiest air transport complexes in the world. Later in the program, the consulting firm of PCS/Law Engineering was added to the team, to provide additional pavement management and computer programming expertise. Together their goal was to develop a procedure for setting priorities and schedules for maintenance and rehabilitation programs that would also assist in budget preparation.

Towards this goal, the PANY/NJ collected nondestructive deflection and visual condition data in the field and assembled archived data relating to construction history, traffic, soils, and materials. The PANY/NJ then performed structural capacity, remaining life, traffic, functional condition, rehabilitation and prioritization analyses using these data and computer based analytical techniques. Finally, the results of these analyses were summarized in a series of reports containing extensive sets of tables, charts, and color-coded maps supported by extensive narrative [1].

Based on this initial effort, it was concluded that the access, management and analysis of the voluminous data associated with large-scale airfield pavement networks are critical issues constraining the effectiveness of the decision-making process. Most of the required data have already been collected, but it exists in a wide variety of formats; e.g., drawings, tables, charts, text descriptions, experience, etc. The engineering staff must organize these data into forms suitable for analysis, input the various sets of data into the analysis and forecasting models, and finally format the results for interpretation by the diverse groups involved in the decision making process.

In recognition of these problems, data display concepts from the field of geographic information systems (GIS) were coupled to established pavement analysis techniques to create a high-level planning tool for the management of airfield pavement systems; the Integrated Airport Pavement Management System (IAPMS). IAPMS not only provides immediate access to all pavement engineering data but also allows various data sets to be merged and automatically passed to the pavement analysis algorithms incorporated directly within the system. This, combined with GIS-style thematic mapping capabilities, enables the engineer or planner to perform parametric studies quickly and economically and to synthesize and interpret the results efficiently, leading to better and more cost-effective pavement management decisions. This paper describes the IAPMS program and the implementation experiences at all three PANY/NJ airports.

INTEGRATED AIRPORT PAVEMENT MANAGEMENT SYSTEM

IAPMS is a self-contained software package designed to run on an i386-class desktop workstation. The workstation is equipped with an interactive, high-resolution (VGA) color graphics interface to assist the engineer or planner in summarizing and interpreting the vast sets of data and analysis results for the airfield pavement network. The IAPMS code consists of a mix of QuickBasic, Assembly, and Fortran routines, with the bulk of the code in QuickBasic.

A major consideration during the design of the software was the recognition that the system will often be used on only an occasional basis by the pavement engineer or planner who is not a computer specialist. Consequently, much attention was devoted to developing a consistent and easy-to-use menu driven interface with forms-based data entry/editing screens to shorten both the initial and "refresher" learning curves for the system. An extensive context sensitive on-line help system is also included to minimize the need to refer to any separate hardcopy documentation.

Most data in IAPMS can be displayed in a variety of formats: tabular and/or text summaries, graphical displays (variations over time, etc.), and color-coded maps of the pavement network. Multiple "what if?" scenarios can be displayed in the same graphical format for quick side-by-side comparisons of various pavement management alternatives. Complete hardcopy (text, black-and-white graphics, color graphics) is available for all display and reporting routines on a variety of printer and plotter types.

A summary of the major IAPMS functions is given in Figure 1. The database management functions--data entry, editing and display--enable the user to create a database, enter or edit information in an existing database, and examine the database contents via screen or hardcopy outputs. The IAPMS analysis and forecasting functions focus on key pavement management issues related to pavement condition, traffic, maintenance and rehabilitation (M&R) needs, and budget estimates. These functions, which are the core of the IAPMS system and approach, have been designed to address typical "what if?" scenarios such as:

- "Given present conditions, what are the M&R needs and associated budgets over the next 1, 5, 10 (or more) years?"
- "What effect will budget constraint level have on M&R activities and pavement condition in the future?"
- "What impact will traffic changes (volume and/or mix) have on pavement performance and M&R budgets in the future?"
- "What are the appropriate intervention levels and priorities for M&R activities?

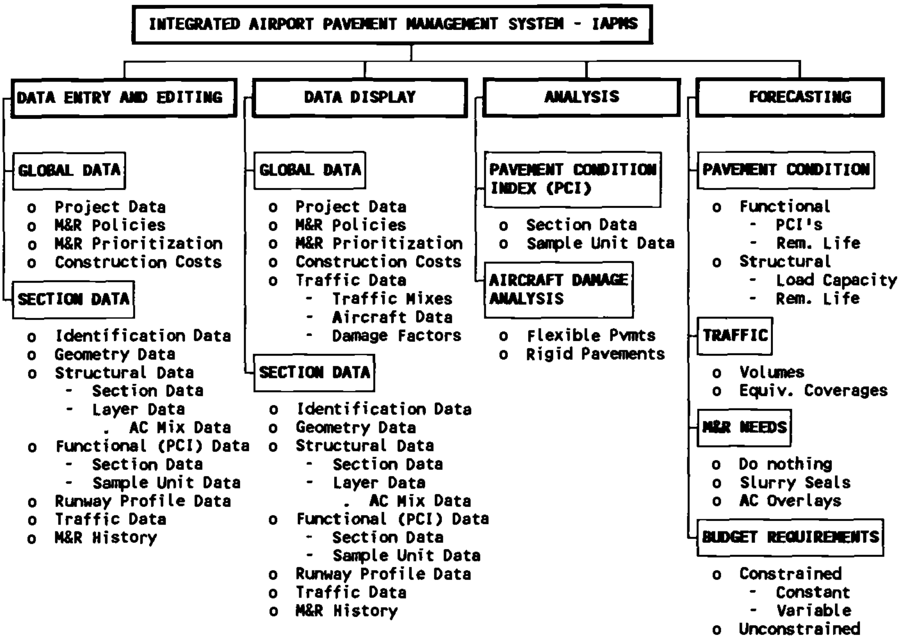

FIG. 1 -- IAPMS Functions

Figure 2 summarizes the major components of IAPMS and illustrates their interaction. Details of the database and analysis and forecasting components as well as the map query and display aspects of the user interface and display/report components are presented next.

Database Structure

The IAPMS database is the repository of all pavement information for the airfield network. The overall database design was dictated by the IAPMS functional requirements. The primary objective of IAPMS is the development of multi-year budget forecasts for all pavement-related M&R projects; therefore, the foremost requirement for the database is that it include all pavement data required for performing condition forecasts, M&R activity selection and design, and budget analyses. These data include the pavement inventory characteristics, material properties, measured condition (distress, roughness, etc.), traffic (volumes, mixes), construction history, M&R policies, and M&R activity unit cost data.

The database structure should also mirror the underlying structure of the pavement-related data. First, in contrast to highway networks, airfield pavement networks consist of relatively few sections but with generally more complete and extensive information. Second, the pavement data are strongly hierarchical in nature; at the highest level is information pertaining to the entire airport, with successive levels of

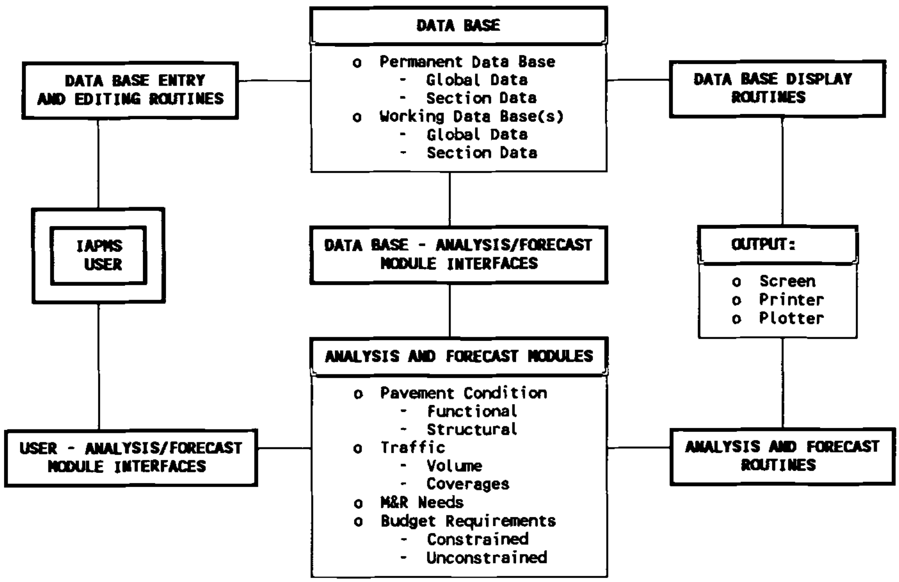

FIG. 2 -- IAPMS Components

refinement terminating at data associated with individual observations (e.g., field measurements). Third, the geographic layout of an airport pavement network is relatively stable; pavement sections are only rarely added or removed from the inventory. Lastly, historical information must be maintained for much of the data (e.g., construction activity), with new data being added to rather than superseding the prior data.

Several secondary considerations also influenced the database design. IAPMS was to be developed as custom software for use on a personal computer; the database management techniques had to be compatible with this computing environment. Geographic data for the network had to be maintained in the database to permit thematic map displays of the pavement data and analysis results. A balance had to be maintained between a flexible "what if?" analysis environment and the need to maintain the integrity of the database. And lastly, the design had to permit easy modification and future expansion. For example, the initial IAPMS implementation did not include AC mix properties or detailed roughness profile data; these were added later to the system.

Given these considerations, an "augmented" version of the hierarchical logical database model was selected for implementation in IAPMS [2,3]. The final database design organizes all data related to pavement sections (or components of pavement sections) in a hierarchical structure and uses a separate set of database files ("flat" files) to store all global data that either pertain to all pavement sections or that are unrelated to pavement sections (e.g., general descriptive characteristics of the airport).

Figure 3 illustrates the augmented hierarchical database structure implemented in IAPMS. Level I contains all information common to all

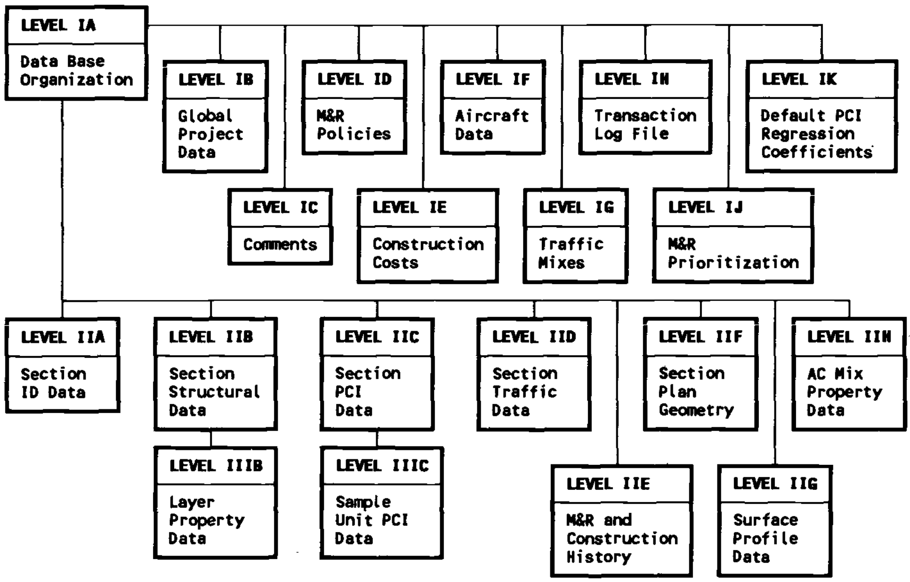

FIG. 3 -- IAPMS Database Structure

pavement sections at the airport. Level IA, the root node for the hierarchical portion of the database, contains all index information for the lower levels in the hierarchical structure; i.e., pointers to Level II data for each individual section. The remaining data at Level I consists of global information that are not related to an individual pavement section. This includes data identifying the specific airport (Level IB); criteria for selecting M&R activities (Level ID); unit construction costs for M&R activities (Level IE); damage coefficients for over 100 different aircraft types (Level IF), typical aircraft mixes at the airport (Level IG), M&R project prioritization factors (Level IJ), and default parameters for PCI forecasting equations (Level IK).

Level II in the database contains all data pertaining to an individual pavement section. It includes general inventory data for each section (Level IIA), layer thicknesses and material types (Level IIB), section PCI data, including a summary of the individual distresses found in the survey sample (Level IIC), aircraft arrival and departure volumes (Level IID), history of M&R activities (Level IIE), x-y coordinates defining the plan geometry of the section (Level IIF), and surface roughness data (Level IIG). Because the underlying structure of much of the Level data will change over time, this information is stored in the database as linked lists. Linked list storage provides an efficient and effective scheme for incorporating new data into the database in its correct geometric and/or temporal sequence with the existing data.

Level III, currently the lowest level in the database hierarchy, contains supporting information for the pavement section data in Level II. At present, Level III encompasses the detailed engineering properties--modulus, CBR values, variability, etc.--for each layer in the pavement structure (Level IIIB) and the field sample unit data from the PCI visual distress surveys (Level IIIC). Level IIIB data is intended for regular access by the IAPMS algorithms, while Level IIIC data can be unloaded after the corresponding section-level data have been derived.

Future plans include a Level IV in the database that would contain supporting data for the Level III information. An example of this would be field test data from nondestructive pavement evaluation studies; these data would be used to estimate the pavement section layer properties in Level IIIB.

The structure and contents of the IAPMS database are designed to exist in both a permanent version and one or more temporary or "working" copies that are either exact or modified versions of the permanent database. Multiple working databases can be created for a given pavement network, permitting the user to conduct numerous "what if?" analysis scenarios without risk of corrupting the master database.

Analysis and Forecasting Algorithms

The IAPMS analysis and forecasting modules provide a powerful and versatile set of tools for addressing key pavement management issues. A flowchart summary of these modules is provided in Figure 4 and a brief description of each is provided below.

Functional Condition Module [4] - used in the analysis of visual distress survey data following the PCI approach, forecasting of section-level visual distresses and prediction of time to functional failure. Forecasts are based upon the use of predictive equations derived, as a function of pavement type, from the analysis of PCI data collected at the three PANY/NJ airports.

Structural Condition Module [5,6,7] - used to evaluate the load carrying capacity of the pavement and, together with the traffic mix analysis module, to determine the structural remaining life and time to structural failure. For flexible pavements, this evaluation is based on the USACE method. For rigid pavements, the procedure is based on a modified Westergaard free edge slab theory.

Traffic Mix Analysis Module [8] - used to convert a mix of aircraft types to equivalent standard aircraft coverages and to determine the loading history for the pavement. For flexible pavements, equivalencies between a given aircraft type and the standard are established on the basis of maximum surface deflections. Free edge stresses are used to derive the equivalency factors for rigid pavements. Damage coefficients for over 100 different aircraft are stored in the IAPMS database for use in traffic mix analyses.

M&R Analysis Module - used to select appropriate M&R activities given a set of pavement conditions (functional and structural) and intervention levels. M&R needs are determined based on policies tailored to the current engineering practices of the PANY/NJ; see Table 1. If an overlay is triggered in this module, FAA design methodologies [5] are used to estimate the required overlay thickness.

Budget Analysis Module - used to estimate project costs for all activities selected in the M&R analysis module and to rank projects according to user-specified prioritization factors. Budget analyses can be performed in either an unconstrained or constrained (i.e., limited budget) mode. In a constrained budget analysis, the M&R project prioritization factors are used to rank projects and select those which

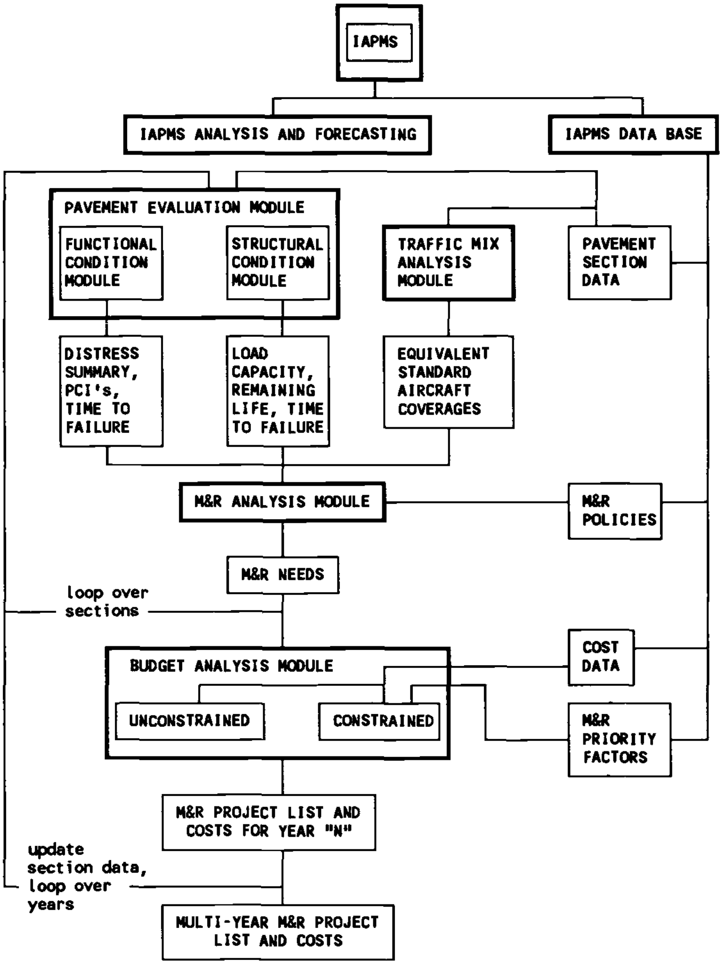

FIG. 4 -- IAPMS Analysis and Forecasting Modules

will be performed within a given year; low priority projects may be postponed to subsequent years.

GIS Features

A wide variety of general-purpose full-function GIS software packages currently exist, and many either have been or can be adapted to transportation engineering applications [9]. Several states are currently developing GIS-based applications for highway pavement management [10]. However, very little attention has been devoted to GIS-oriented applications for airfield pavement management. Airfield and highway pavement management share many features: both deal with a

TABLE 1 -- PANY/NJ M&R Policies.

Pavement Rank	Pavement Condition Index (PCI)	Structural Remaining Life (years)	M&R Policies
Primary[a]	71 - 100	All	No Action Required
	0 - 70	All	AC Overlay[c]
Secondary[b]	71 - 100	All	No Action Required
	56 - 70	< 5	No Action Required
	56 - 70	≥ 5	Seal Coat
	0 - 51	All	AC Overlay

[a] All runway and major taxiway pavement sections.
[b] Other taxiway and apron pavement sections.
[c] Includes grooving of runway pavement sections.

spatial network of pavement sections having extensive attributes of geometry (length, width, shape), structure, condition, traffic, and construction history. The pavement engineering analyses are only slightly different for the two types of pavements due to the different traffic characteristics, performance requirements, and design standards.

For GIS applications, however, the more significant difference between airfield and highway pavement networks is the nature of the networks themselves. Airfield pavement networks contain many fewer pavement sections than do highway networks, and they are geographically clustered. The data attributes associated with the airfield pavement network also tend to be more complete and less diverse in terms of content and format than those for highways, reducing the importance of the data integration benefits of GIS.

Airfield pavement management does not require many of the spatial analysis capabilities found in a full GIS, such as map overlay/dissolve, buffer analysis, and contouring/slope calculations. The subset of GIS features most relevant to airfield pavement management deal primarily with data access and interpretation. The interactive geographic displays of a GIS are a very effective interface for selecting sets of pavement sections for data queries and analyses. More important, the display of pavement existing conditions and performance predictions as color coded thematic maps greatly assists the interpretation and synthesis of data that are distributed in both space and time. This is an important tool not only for the engineering staff responsible for maintaining the pavements but also for the management personnel responsible for setting policies and priorities and for developing multi-year budgets and plans.

Given these considerations, the specific GIS features incorporated in IAPMS deal principally with selection (for query or analysis purposes) of pavement sections by geographic location and the geographic display of the database contents and the analysis and forecasting results. Both of these operations require detailed map data for the pavement sections in the network.

Map data for Kennedy, LaGuardia, and Newark airports were developed by manually digitizing engineering drawings of the pavement network layout. Digitizing was performed after the pavement network had been delineated into homogeneous sections for pavement management purposes, so the map data could be referred directly to individual sections as Level II data in the database. Since no consistent reference coordinate grid had been established at the airports and the map data were intended only for internal use in IAPMS, the map data was stored in arbitrary digitizer x-y coordinates. An interactive graphics editor is built into IAPMS to enable modifications of the map data and to enter geographic data for new pavement sections added to the network.

All data in the system can be displayed for a single section, for a group of sections, or for all sections in the network. Groups of sections can be selected according to feature, pavement rank, usage, construction type, or other parameters as requested by the user. For more complicated groupings, sections can be selected graphically using a mouse to pick individual sections from a map display of the pavement network. These pick operations are made easier by the "zoom" and labeling options in the IAPMS geographic display routines.

The thematic map display of pavement data and analysis and forecasting results is the most valuable GIS feature incorporated in IAPMS. These displays provide a concise and visually clear summary of the overall condition of the pavement network as well as a powerful tool for interpretation and synthesis of analysis results. As an example, Figure 5 illustrates the projected overall pavement condition in terms of PCI for Newark Airport in 1995 assuming a high budget level for pavement maintenance and repair; this projection implicitly reflects all benefits resulting from the IAPMS-recommended M&R projects during the intervening period of 1990 through 1994.

IMPLEMENTATION EXPERIENCE

In 1980, the work to develop and implement a pavement management system began with the collection of approximately 1,000 non-destructive deflection (NDT) readings. Although useful, the NDT data collection was premature because the pavement network as yet had not been broken into sections of similar construction and traffic loading. After a five year hiatus, a structural condition and remaining life study was performed. Under this study, all current construction, traffic and NDT data were organized under one report and used to determine current structural condition and predict remaining life. This report provided a good "snap shot" of the PANY/NJ's pavement network, but it became apparent that updating this study would prove difficult and expensive. At the same time, a visual inspection of functional pavement condition was performed in accordance with FAA circular 150/5300-6 "Guidelines and Procedures for Maintenance of Airport Pavement". By 1987, all information required for management of the PANY/NJ airfield pavement network was gathered, but a convenient method of utilizing the information had not yet been realized. This need led to the development and pilot implementation of IAPMS at John F. Kennedy International airport in 1988 [11]. Implementation of IAPMS at LaGuardia and Newark International began in 1989 and was recently completed [12]. The implementation at all three airports focused only on taxiways and runways. However, the system

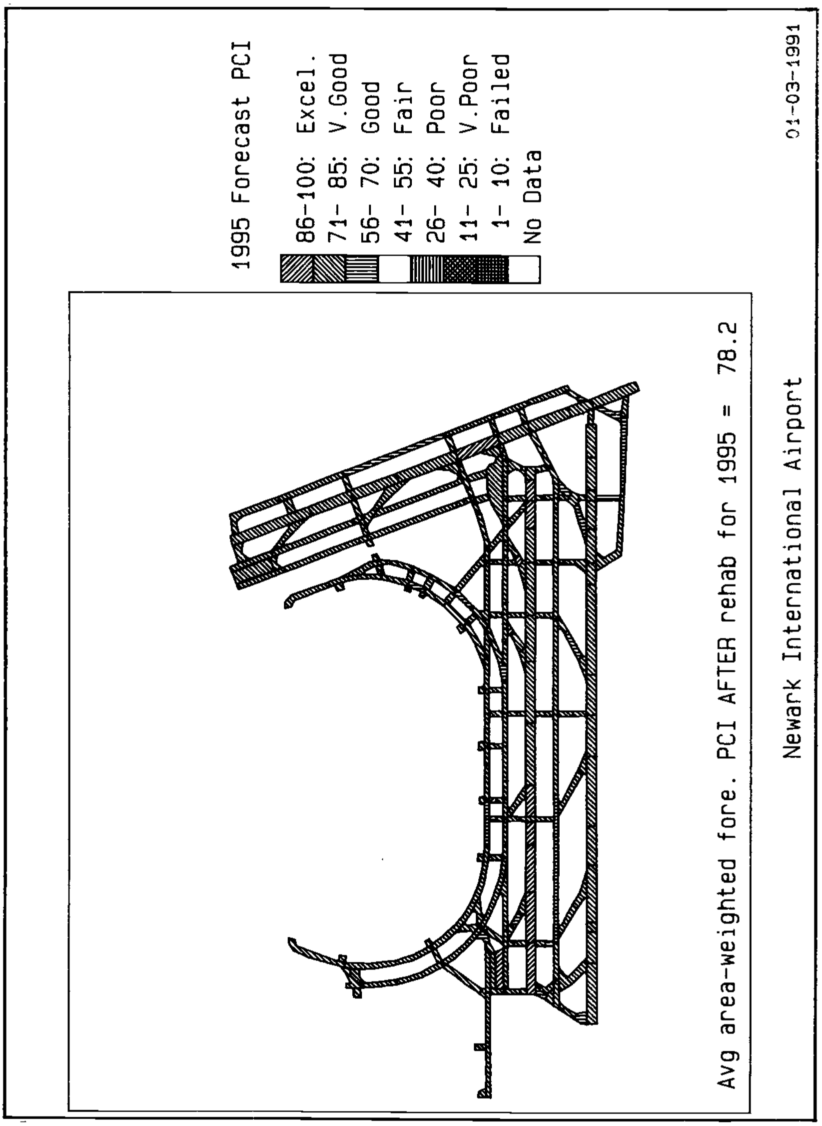

FIG. 5 -- Projected 1995 PCI Values for Newark International Airport: High Budget Assumption

framework is flexible enough to permit extensions to apron areas and to other land side pavement assets (access roads and parking facilities).

The development and implementation of IAPMS required considerable coordination and interaction through an extensive series of meetings, presentations, demonstrations, and reviews. However, the early meetings were the most crucial ones for ensuring success, as clear project objectives were defined during these initial meetings: the system should not be designed to simply automate the current pavement management methods in place but rather to provide a framework for incorporating improved pavement management methodologies both initially and in the future. Additional comments on the implementation of IAPMS at the three airports can be divided into the following categories:

Data Availability and Quality

Historical data for any pavement network is always difficult and time consuming to gather. Through several earlier studies (e.g., remaining life study), the PANY/NJ had already compiled much of this historical data and was quite familiar with the pavement networks. However, although pavement layer thickness data were often available from the construction records, data on the engineering properties (e.g., modulus, CBR) for the layers and subgrade were often sketchy; in many instances, only very rough estimates of the required properties could be made, to be confirmed or modified later through nondestructive pavement testing. Traffic data were even more sketchy than the layer property data. Because of this, the criteria for M&R activity selection and project prioritization relied heavily on the functional condition of the pavement (i.e., PCI).

The collection of PCI data requires inspection of over 1,000 sample units. This work is labor intensive and pavement sections must be closed to aircraft operations during inspections. In the future, automated inspection equipment may simplify collection of these data.

The project team received invaluable assistance from the "vintage engineers" on the PANY/NJ pavement engineering staff. These "walking databases" provided much experience-based information on pavement history and conditions that would have been unavailable otherwise. Their experience was also essential when defining the structure and intervention levels for the M&R activity decision trees and the project prioritization factors. The interaction with these vintage engineers was in broad terms similar to the "knowledge engineering" approach in expert systems development.

Pavement Engineering Algorithms

The very first step in implementing the IAPMS database was the manual delineation of homogeneous pavement sections. This was very laborious and needs to be automated within the IAPMS system itself in the future.

Because of the expected quantity and quality of the data for each section, the algorithms in the system were formulated on the assumption of "complete" data. This assumption was not entirely justified here and will likely be even less so elsewhere. Consequently, any new algorithms should be designed with "fall back" positions in the event that certain key data items are missing from the database.

The PCI prediction models were handicapped by limited site-specific visual distress survey data. At the time of the initial implementation, only one complete set of PCI data had been collected for all three airports. To overcome this handicap, three prediction models were included in the IAPMS:

- o Default deterioration rates based on pavement type. These rates were developed by review of the last date of construction and the single PCI measurement for similar pavement sections.
- o Deterioration curve formulae with user defined coefficients.
- o Deterioration curves calculated by the program once multiple PCI readings are available.

Visual distress surveys are now planned on a regular schedule, permitting the development of a time series of PCI data and correspondingly sharper PCI prediction models.

The PCI values which trigger M&R activity were based on the experience of PANY/NJ engineers. After years of using the IAPMS, it is anticipated that these values will be adjusted and more accurate budgets will result.

Project grouping is another difficult problem for any pavement management system. Pavement sections recommended for M&R activities are distributed both in space and time. Neighboring pavement sections that require some type of M&R treatment over a specified time interval should be clustered and treated as a group at the same time, either with the same or different M&R procedures. Project clustering requires a generous amount of engineering experience and is thus difficult to automate. However, maps illustrating forecast M&R activities, when generated for a series of years in a budget forecast, can greatly aid the pavement engineer in developing project groupings.

Besides project grouping, other pavement engineering issues that will be considered in future enhancements of IAPMS include: incorporation of data variability and pavement reliability concepts; consideration of more pavement performance parameters, specifically roughness and friction (although roughness data are currently collected, they are not presently used in the M&R activity selection algorithms); incorporation of additional rehabilitation options budgeted based on the type of distresses predicted, such as roughness and friction; development of a traffic flow model for automating the determination of section traffic volumes across the network; and inclusion of optimization routines to complement or supersede the project prioritization subsystem.

Database Aspects

IAPMS does not at present contain the capability to process arbitrary complex queries of the database in the style commonly found in general purpose relational database systems. However, a more comprehensive data query facility is planned for future implementations.

Some of the features that were sacrificed by not using the more "conventional" relational data model (e.g., as implemented in dBase III+/IV) include: a more rigorous theoretical underpinning of the database design; the ability to use more third-party development tools such as database browsers/editors, subroutine libraries for database indexing and access, etc.; and a formalized *ad hoc* query capabilities--e.g., query by example (QBE), structured query language (SQL). Fortunately, these sacrifices were not overwhelming, in large part because of the relatively well-defined nature of the airfield pavement management problem.

Only pavement related data are included at present in the IAPMS database. The database could be easily expanded, however, to encompass additional items such as pavement markings, signs, and lighting systems.

GIS Aspects

The incorporation of GIS features has been quite straightforward, in part because only a limited set of GIS capabilities were considered relevant and in part because the software was implemented in a computer environment that was very familiar to the PANY/NJ. It was a conscious strategy during the IAPMS development to consider relevant GIS capabilities as a natural extension of other pavement management functions, rather than to implement pavement management as an "add on" to a primarily GIS application.

At a more detailed level, the decision not to adopt a physically meaningful common coordinate reference system for the map data was a mistake; it is now somewhat difficult to reference field test locations (falling weight deflectometer, roughness, etc.) within an individual section. This problem can be easily remedied in the future, however. Future planned enhancements to the IAPMS software include improved digitizing and graphics editing routines, with provision of direct import of map data from computer-aided drafting systems.

Storage Requirements and Performance Aspects

The implementation of IAPMS at each PANY/NJ airport included all inventory, structural, traffic, geographic, M&R policy, and cost data and a single set of condition measurements (visual PCI survey) for all runway and taxiway pavement sections. The master database for each implementation consisted of 18 database files requiring approximately 0.5 Mbytes of storage. These storage requirements will increase over time as additional condition assessments are performed and the results added to the database. For example, each visual PCI survey generates approximately 125 kbytes of summary information that must be maintained in the database; archivable sample unit PCI data require another 0.3 Mbytes of storage per complete condition survey. Roughness profile surveys generate between 10 and 100 kbytes of data per 1000 feet of pavement for each survey line. If apron pavement areas are also included in the database, the total storage requirements increase by 50 to 100%.

The performance of IAPMS in developing multi-year M&R forecasts and budget estimates--the primary objective of the system--has been acceptable and is improving with use. A full 10 year budget forecast for all runway and taxiway pavement sections at Kennedy International (largest PANY/NJ airport) consumes approximately 20 minutes of processing time (on a 25 MHz 80386 w/ 80387 co-processor) for the case of the working database residing on the hard disk. If the working database is moved to a virtual disk in memory, processing time for the same budget forecast drops to approximately 2 minutes. These times correspond to a "worst case" budget request (in terms of duration and number of pavement sections) and include all processing for traffic mix analysis, pavement structural evaluation, condition forecasts, M&R alternative evaluations, structural design of overlay M&R options, and M&R project ranking and selection. This performance is more than adequate for the types of budget calculations and "what if?" scenario investigations for which IAPMS was developed.

CONCLUSIONS

The critical nature of airfield pavements requires that sections be closely monitored and efficiently managed. Accepted pavement analysis techniques have been coupled to powerful information management technology to provide an extremely versatile and cost effective analysis tool for the efficient monitoring and management of the PANY/NJ airfield pavement network. The resulting system, IAPMS, brings to the working desk of the PANY/NJ engineer or manager easy access and use of archived pavement data in combination with advanced pavement technology.

Some of the specific benefits that IAPMS provides to the PANY/NY engineer or planner include:

- Easy access to all pavement data--inventory, construction history, geometric, structure, traffic, condition;
- Replacement of the earlier approach of ad hoc experience-based maintenance by rational and systematized evaluation of pavement condition and performance and the associated required M&R;
- Codification of knowledge possessed by experienced senior engineers prior to their retirement;
- Reduced manpower requirements for performing routine engineering studies, multi-year capital budget forecasts, etc.;
- Quick response to typical questions such as the effects on pavement performance of new aircraft types;
- Permits easy study of a variety of "what if?" scenarios to evaluate possible impacts on pavement condition caused by changes in capital expenditures, M&R policies, project ranking criteria, and traffic volumes/mix/patterns, etc.

In summary, the IAPMS database and analysis capabilities enable the PANY/NJ engineer or planner to make the kinds of rational predictions of future pavement conditions and performance that are essential for accurate budget forecasting and sound management. To date the system has met PANY/NJ expectations and continues to evolve as additional data are collected and advances are made in pavement evaluation and rehabilitation. The net effect of implementation is the preservation of investment in the airfield pavement infrastructure through improved pavement performance and reduced M&R cost.

ACKNOWLEDGMENTS

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M.Y. Shahin

20 YEARS EXPERIENCE IN THE PAVER PAVEMENT MANAGEMENT SYSTEM: DEVELOPMENT AND IMPLEMENTATION

REFERENCE: Shahin, M. Y., "20 Years Experience in the Paver Pavement Management System: Development and Implementation," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: The development of a pavement management system for the US Army began in 1968. Since that time there have been many successes, but the road to development and implementation has been full of obstacles and can generally be described as "rough. This paper discusses the Army's PAVER pavement management system in terms of its history, development challenges, implementation obstacles, and solutions.

The Development issues that proved to be significant included:

*Engineering technology as it relates to pavement mechanistic behavior, pavement distress, condition prediction modeling, and optimization.

*A sponsor who understands the importance of pavement management and is willing to defend its development.

*A user group that is progressive and willing to give constructive direction and feedback.

*A research team that is not discouraged by tough challenges or initially disappointing results.

The Implementation issues that proved to be significant included:

*Availability of manpower and monetary resources.

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*The pavement management system's ability to provide for field needs such as annual planning, long-range work planning, and project justification.

*Availability of credential training.

*Endorsement by nationally respected organizations such as APWA, FAA, and FHWA.

*Obtaining system approval by the head organization.

*Finding the right branch and the right responsible person within the implementing agency.

This paper discusses all the above issues and includes a description of PAVER'S evolution from 1968 to 1990, from both a development and an implementation point of view.

KEYWORDS: pavement management, development, implementation, PAVER.

INTRODUCTION

The development of the U. S. Army Corps of Engineers PAVER pavement management system (PMS) began in 1968. The concept of pavement management used in PAVER has not changed much from the 1970s to the 1990s, but there is now a much higher level of acceptance of the concepts by managing engineers and officials. Another significant change during this time has been the improvement in PMS technology, including engineering models, computer software and hardware, and pavement evaluation devices. This paper presents the issues that have proven to be significant in the development and implementation of the PAVER PMS.

Background

The development of the PAVER system began as a result of a visit to Fort Eustis, Virginia, by a research Technical Monitor from the Corps of Engineers. The Technical Monitor became very impressed by how the pavement installation's maintenance chief managed his pavements. The maintenance chief at Fort Eustis had been working there for more than 20 years. His system consisted of dividing the installation's pavement network into uniform sections based on construction history and pavement usage. He also established a card file system where he kept the maintenance history of each section on a separate card. He used the card file information and his knowledge of the conditions of the pavement to establish 5-year maintenance plans. He hand-colored one map for each year, showing the pavement sections scheduled for major maintenance and repair (M&R).

After examination of the card file system, the Technical Monitor felt that every Army installation should have such a system. In 1968 the U.S. Army Construction Engineering Research Laboratory (CERL) began the development of a system similar to that used at Fort Eustis. The Principal Investigator (PI) leading the development of the system possessed a strong background in operation research. He also retained as a consultant, a professor of operation research from a major university. The research team visited the Fort Eustis maintenance chief to study his card file system and to improve and automate the system for operation on a mainframe computer.

This effort continued from 1968 to 1972. The preliminary product was a system called PAVER, which consisted primarily of a data structure designed for use with the System 2000 data base manager. The data structure contained a large list of data elements, including pavement layer information, traffic data, and climatic data. In 1973 the system was tested at Fort Eustis and was found to be unacceptable. This early version of PAVER was too detailed, very time-consuming, difficult to use, and, above all, did not add any pavement technology to the existing card file system. This last reason was identified as PAVER's major drawback. It was concluded that a pavement management system must be more than simply an information data base--it should include state-of-the-art pavement management technology.

SYSTEM DEVELOPMENT

Based on the lessons learned from 1968 to 1974, it was decided to first develop a manual system that could be field tested prior to automation. The guiding principle was "customize before you computerize." Figure 1 [1] shows a flow chart of the manual system that was developed. It consisted of procedures for conducting a pavement distress survey, dividing the pavement network into uniform management sections, storing pavement and traffic information on a manual card format, and developing M&R work plans.

Also in 1974, the U.S. Air Force funded CERL to develop a condition index for rating airfield pavements. Through the participation of a large number of experienced Air Force pavement engineers, the Pavement Condition Index (PCI) was developed in 1976. The PCI [2]&[3] (CERL Tech Reports) is determined based

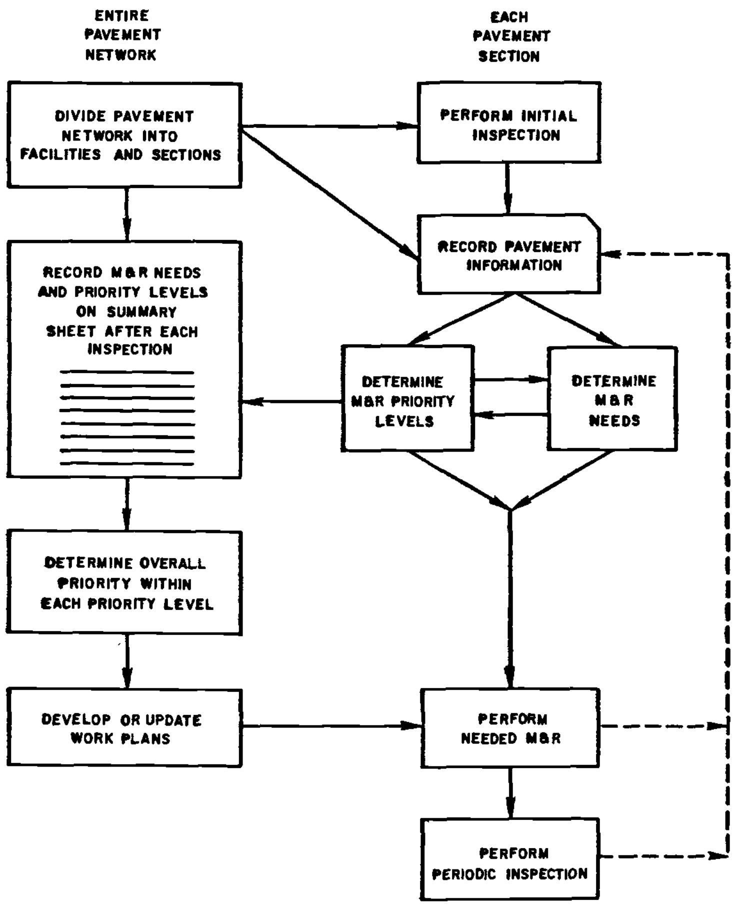

FIG. 1 -- Summary Flow Chart for the Manual System for Maintenance Management Developed in 1975 (Ref 1)

on measured distress and is measured on a numerical scale from 0 to 100, with 100 representing "excellent" and 0 representing "total pavement failure" (Figure 2).

In 1976, the Army decided to fund the development of a PCI for roads and parking lots similar to the one developed for airfields. This development was completed in 1978 [4]&[5] (CERL Tech Reports).

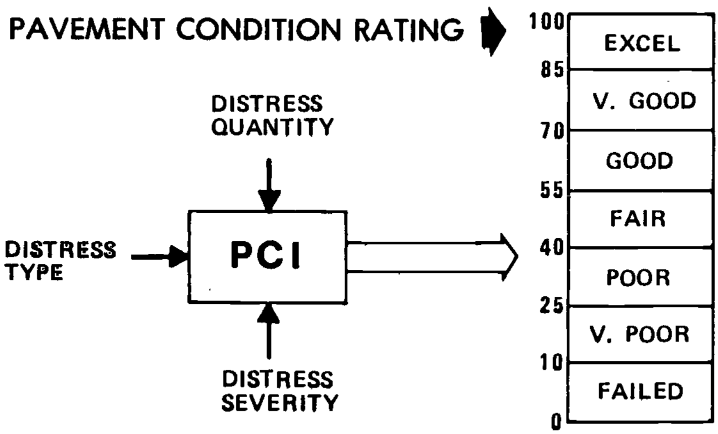

FIG. 2 -- The Pavement Condition Index (PCI) Concept Developed for Airfields and Roads

In 1978 the Army and Air Force agreed to combine all pavement management technology developed by that time (for airfields, roads, and streets) into a single pavement management system. It was also decided that the system be computerized for use on a mainframe and to retain the name PAVER. The system was computerized by designing a data structure using the System 2000 data base manager (Figure 3). Automated reports utilizing the information in the data base included inventory, PCI, distress, and localized M&R requirements based on a user-predefined distress maintenance policy. The system also included other analysis programs for performing life-cycle costing and statistical distress prediction independent of the data base.

In 1979, a formal evaluation of PAVER was conducted by test-implementing it at Fort Eustis. The pavement maintenance chief at Fort Eustis participated by comparing the developed M&R plan based on PAVER to his existing card file system. The test implementation results were supervised and evaluated by a committee of more than 20 Army engineers. Based on the results of the test, PAVER was adopted as the standard Army pavement management system. The system was approved as a voluntary system (as opposed to being mandatory). This was the beginning of the mainframe PAVER PMS as it exists today.

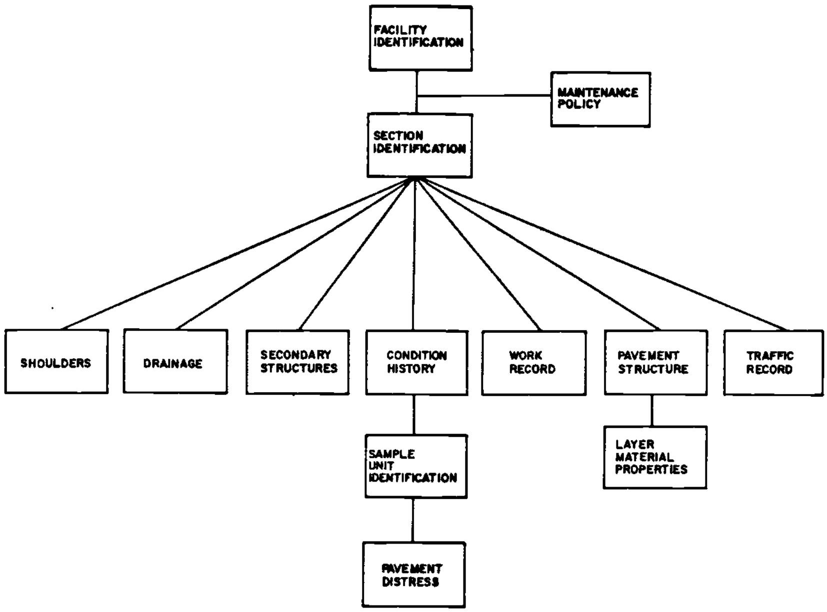

FIG. # -- Mainframe PAVER Data Structure
Developed in 1978

From 1980 through 1985, mainframe PAVER's pavement technology was enhanced and reporting capabilities were added. The pavement technology research was conducted primarily in the area of pavement condition prediction modeling. Considerable research and development was funded by the Air Force for the development of PCI prediction models for airfield pavements. Two models were developed, one for asphalt and one for concrete pavements that predict the PCI based on pavement structure, load, and climate [6]. Evaluation of the models showed that their usefulness was limited to predicting average conditions. This is caused by considerable variation in conditions among sites used to develop the models. The reality is that it is nearly impossible to accurately account for all the variation with known variables such as traffic, climate, and subgrade properties. The use of the models to predict the PCI for a specific pavement section provided questionable results. A straight-line PCI projection on a section-by-section basis resulted in a more reliable prediction, but with limitations. Accuracy decreased rapidly for predictions far in the future. Therefore, it was decided to limit all projections to 5 years until better prediction models were developed. The reporting capabilities added to PAVER included projecting annual budget needs to maintain the PCI above a specified level, and projecting the frequency distribution of the pavement network condition assuming no major M&R is performed.

In 1985 the Federal Aviation Administration (FAA) funded CERL to develop a PAVER system for use on IBM-compatible microcomputers. The development of the first version of this system was completed in 1987; the system was called "Micro PAVER." Micro PAVER V1.0 included most of the technology and capabilities of mainframe PAVER. Additionally, Micro PAVER was user-friendly and required no computer time charges.

Since 1985, the majority of CERL's pavement management R&D was directed toward the development of better PCI prediction models and enhancement of Micro PAVER rather than mainframe PAVER. The prediction modeling R&D was funded by the Army, and resulted in the highly successful Family Analysis technique [7]. Also, significant R&D effort was funded by the Army for developing optimized M&R programs for various budget scenarios. Two techniques were developed, based on dynamic programming [8] and the Critical PCI concept [9]. The Critical PCI is defined as the PCI value beyond which the rate of deterioration increases significantly. This concept recommends that pavements should be maintained above Critical PCI. The Family Analysis modeling technique and the optimized M&R program development based on the critical PCI were incorporated into Micro PAVER V3.0 in 1991.

System Development Issues

This section presents the major issues encountered during system development. The issues have been grouped into two categories: pavement technology and funding.

Pavement Technology

The first significant pavement technology issue in developing PAVER was the development of the PCI. The PCI is to be used for pavement performance prediction, budget estimation, and other PMS functions. An important characteristic of the PCI is that it should be reproducible. It should also provide a meaningful measure of M&R needs and acceptable user service levels. The PCI was specifically developed for the PAVER system to meet the above objectives. It is based on measured distress type, severity, and amount. The PCI was developed to indicate a pavement's overall structural integrity and surface operational condition.

It is also related directly to the amount of maintenance and repair needed since it is based on the quantification of pavement distress. The PCI took 3 years to develop, and its success represented a major milestone in the development of PAVER. In fact, the PCI can be considered the foundation for the PAVER system.

An equally important pavement technology issue is the development of accurate condition prediction models. There are a variety of techniques with which pavement condition prediction models may be developed. These include experience, regression analysis of condition against variables such as age and traffic, pure mechanistic analysis, and a combination of all the above. All of these techniques were investigated over a number of years in developing models for use in PAVER. The resulting models were disappointing for predicting pavement condition on a section-by-section basis. This problem is to be expected when trying to explain the complex behavior of pavement with one model to be used in different climates, for different subgrade conditions, and with materials from different sources. Therefore, for the PAVER system, it was decided that a modeling technique be built into the system rather than developing or adopting a specific model. The resulting modeling technique is called Family Analysis. This technique allows the user to identify pavements with similar performance characteristics and then develop a constrained, least-square fourth-degree curve between the PCI and pavement age. There are several advantages to this technique:

(1) There can be as many models as needed for each pavement network. For example, there can be one model for primary asphalt roads and another model for primary asphalt roads that have received one or more overlays.

(2) The models are easily developed and assigned to the appropriate pavement sections.

(3) The models can be easily and continuously updated as new PCI inspection data are added to the database.

(4) The different pavement family models can be used to conduct life-cycle cost comparisons among M&R alternatives.

Accurate condition prediction is extremely important to a PMS because this impacts future M&R budget requirement forecasting. If condition prediction is not accurate, life-cycle costing at the project-analysis level will be erroneous. It should also be emphasized that when determining M&R needs, the PCI is only one of the variables considered. Other variables include distress and whether or not the distress is load related.

Funding

There are several potentially serious problems related to the funding issue. These problems are discussed below and possible solutions are presented.

(1) It takes several years to complete the initial development of a meaningful PMS. Most agencies, however, will not (or cannot) commit funding for more than a few years, and many times for only one year at a time. To work around this problem, the PMS should be divided into separately deliverable components, such as inventory procedure, condition rating procedure, data base design and data entry methodology, condition prediction modeling, and design of different PMS reports. The delivery of each product can be such that if funding is interrupted, development can continue once the funding is resumed without a serious loss of effort. It is also recommended that the research team seek different funding sources, thus reducing the chance of losing all funds at the same time.

(2) Once initial development of the system has been completed, it is difficult to continue to secure R&D-marked funds for system enhancements. In reality, however, a PMS is a "living" system. Without technology updates and continuous enhancement, the system is likely to stagnate and die. The research team should continue to seek R&D funds for technology development, but should seek other sources (such as operations and maintenance-marked funds) for system enhancements. A PMS user group should also be formed to include the funding agencies as well as field-user representatives. System enhancements should be discussed during user group meetings, and agencies willing to participate in funding these enhancements should be identified.

A variety of other problems can have a fatal impact on system development if they occur simultaneously. Such problems include the assignment of a problematic Technical Monitor by the funding agency to oversee development and recommend future funding, and loss of key R&D staff. There are several ways to overcome such problems, but they are based on dedication and a strong belief in the importance of pavement management by the research team and senior management of the research organization.

SYSTEM IMPLEMENTATION

The first test implementation of mainframe PAVER was conducted in 1979 at Fort Eustis. Implementation was monitored by a committee of more than 20 Army pavement engineers and managers. The purpose of the test implementation was to validate the system and analyze the economics of its utilization as compared to the card file system on which it was partially based. The data collection and PCI survey were conducted by a local engineering firm at a cost of approximately $91,000. The total pavement area involved was equivalent to 343 lane-kilometers and was divided into 425 uniform pavement sections. The implementation included:

(1) Dividing the pavement network into manageable sections.

(2) Performing the PCI survey on all paved areas at a 51% sampling rate.

(3) Collecting pavement structure data from as-built drawings and coring.

(4) Collecting data on drainage, secondary structures, and shoulders.

(5) Inputting data into the mainframe PAVER data base, and verifying the input.

Based on the test implementation, the following conclusions were reached:

(1) The PCI sampling rate was too high for inspection at the network level. A 15% sampling rate would have been adequate. This would have reduced the cost of implementation by over 50%.

(2) The use of PAVER could result in annual cost avoidance of 50% to 70% as compared to the existing management system.

(3) PAVER offers other tangible benefits, including immediate access to pavement information and the establishing of a rational and consistent procedure for project identification and budget justification.

Based on the results of the test implementation, the system was approved as a standard optional Army computer system. This was a major milestone in the PAVER implementation process. In 1983, U.S. Army Forces Command (FORSCOM) decided to allocate $5 million to the implementation of PAVER at all its installations. Many other military installations, including Air Force and Navy bases, began to implement the system.

In 1981, the American Public Works Association (APWA) decided to evaluate PAVER for use by cities and counties. The evaluation was conducted through test implementation in 6 cities and lasted for 2 years. Based on the results of the test, APWA decided to adopt the PAVER system. This was another important milestone in the PAVER implementation process.

In 1982, the Federal Aviation Administration (FAA) approved the PCI procedure and published a PCI Advisory Circular [10]. In 1985, FAA funded CERL to rewrite mainframe PAVER to operate on IBM-compatible micro-computers. In 1988, the FAA published another Advisory Circular on pavement management and Micro PAVER [11].

Implementation Issues

System implementation is a major concern because without it the system is worthless no matter how good it is. The significant implementation issues encountered with the PAVER system can be classified as system-related or implementing-agency-related.

System-Related Issues

(1) System Credibility: This pertains to system acceptance or endorsement by large organizations and associations. For PAVER, this has provided the much-needed boost to overcome implementation problems. PAVER has been accepted by the Army, Air Force, Navy, APWA, and FAA. Also, the Federal Highway Administration (FHWA) has funded the development of a PCI for unsurfaced roads and its programming into Micro PAVER. PAVER has also been implemented by several international organizations further adding to the credibility of the system.

(2) System Updating: One of the important items a user looks for is assurance that the system will continue to be updated with state-of-the-art technology. This includes pavement technology as well as computer software and hardware technology. An example of pavement technology is the development of the Family Analysis pavement condition prediction technique, which replaces the simple straight-line technique originally used in PAVER. An example of updating for hardware technology was the rewrite of PAVER for operation on microcomputers. Micro PAVER has been recognized to be more user-friendly than main-frame PAVER. User confidence in system updates is important. It is reasonable for the user to expect

meaningful updates given the high initial implementation and system setup costs.

(3) System Support: This includes system distribution, answering system-related questions, and providing training. Two support centers were established for PAVER through APWA and the University of Illinois. Both organizations provide the support functions listed above.

(4) System Implementation Resource Requirements: This includes both money and manpower resource requirements for the initial implementation and continuous use of the system. The cost for initial implementation is usually much higher than the cost for data update. Most inventory and pavement structure data remain the same, but condition data should be continually updated. The implementation cost can be reduced considerably by limiting the initial data collection to the absolute minimum required to operate the system; additional data can be added later as resources allow. The minimum data required for PAVER include pavement section definition, PCI survey, and date of last construction for each pavement section. Furthermore, the PCI survey should be done through the recommended PAVER network-level sampling technique. Intensive R&D is currently being funded by the Army to automate the PCI survey with image-processing technology. The resource requirements for future condition updates can be reduced by performing a partial survey every year so each pavement section is inspected every 2 to 4 years based on its projected condition.

(5) System Output: The system should be user-friendly and should provide useful output. The value of the output is evaluated against the implementation efforts described in item 4 above. If the value of the output cannot justify the implementation and update costs, the system implementation is likely to fail. Feedback from the PAVER implementation showed that reporting inventory data and the latest inspection results are not enough. The ability to project future conditions is extremely important. This information is used to estimate future budget needs to keep the pavement above a selected minimum standard. Another reporting capability the user looks for is the ability to analyze the consequences of different budget scenarios on the condition of the pavement network. Figure 4 is an example output from the PAVER system showing the change in the network average PCI for three different budget scenarios. The System also identifies the unfunded requirements resulting from each of the three budget scenarios.

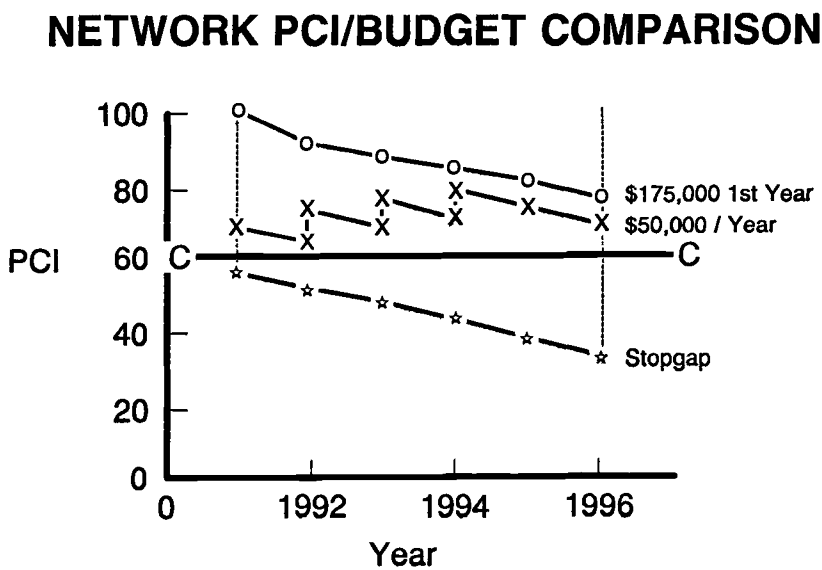

FIG. 4 -- Example Output from Micro PAVER V3.0 Showing Effect of Difference Budget Scenarios on Network PCI

Agency-Related Issues

(1) **Top Management Support:** Regardless of how good the system is, if top management opposes its implementation or update, it will have no chance. An example is illustrated by the change in top management at one PAVER implementation site. The new management opposed the concept of pavement management and, in turn, did not allocate money or manpower resources to perform reinspection in order to update the database. Also, there was no recognition given to any staff member for work done on the pavement management system. As a result, the staff lost its motivation and the system was not used.

(2) **Implementation Method:** The needed manpower for implementation can come from a contractor, from in-house labor, or a combination of the two. One disadvantage of contracting is that it may take several months to get a contract prepared, advertised, negotiated, and awarded. A second disadvantage is that contractor implementation is usually more costly than in-house implementation. However, some of the contractor capabilities may not be available in-house.

For contractor implementations, it is strongly recommended that a representative of the agency be thoroughly involved. If the agency is not involved with the contractor, the entire contracted effort could be wasted. In-house implementations can be very successful, especially if the amount of pavement to be implemented is very small. If enough personnel are available, knowledgeable, adequately trained, and well supervised, the implementation will probably be successful. For in-house implementation of the PAVER system, temporary personnel can be used to collect much of the data. For instance, summer-hire college students can provide an excellent workforce. A combination implementation may be best for ensuring a relatively trouble-free implementation. In this method, contractor personnel collect, prepare, and load certain data elements, and in-house personnel do the rest. Deciding who does specific activities is subject to local planning. Pavement condition survey work is the most labor-intensive activity of the implementation and is easily contracted.

(3) Establishment of Management Responsibility Location Within the Agency: An individual within the organization should be designated as the PMS manager. This individual is responsible for the maintenance of the system database and the coordination among the various departments in the agency who share in the planning, design, and execution of pavement maintenance and repair. In many agencies the designated individual is in the planning department. The most successful implementation and effective use of the PAVER occurred in agencies where the individual is a strong believer in maintenance management.

SUMMARY

This paper has presented the history and significant issues in the development and implementation of the Army's PAVER pavement management system. It is likely that the development and implementation of other pavement management systems will involve very similar issues.

The most significant development issues for PAVER were related to pavement technology and funding. Major pavement technology issues include the development of a meaningful and repeatable pavement condition index, and the development of accurate pavement condition prediction models. Both the index and the models are essential for the primary management functions of network condition forecasting and preparation of optimum annual and long-range work plans. Important funding issues include the ability to continue to obtain development funds over the many years necessary to develop a meaningful system, and the ability to continue to obtain funds for system update and enhancement.

The most significant implementation issues for PAVER were related to the system characteristics and the implementing agency. Important system-related issues include system endorsement by recognized organizations, commitment to system update and enhancement, good system support, resource requirements for system implementation, and the usefulness of the system outputs. Important agency-related issues include top management support, method of implementation, and the establishment of a management responsibility within the agency.

It is also very important to recognize the interaction between development and implementation. The ability to continue to obtain funding for development is very much a function of the success of the system implementation. Yet successful implementation depends on the implementing agency's confidence that the system is well supported, and that it will continue to be developed and enhanced.

NOTE

The views of the author do not purport to reflect the position of the Department of the Army or the Department of the Defense.

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Y. Richard Kim and D. Lawrence Eaddy

*STATUS OF PAVER IMPLEMENTATION WITHIN THE U.S. AIR FORCE

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ABSTRACT: This paper describes a survey designed to estimate the present status of implementation of the pavement management system, PAVER, within the U.S. Air Force. The research described in this paper is based on a 100 percent population survey of over 100 USAF civil engineering organizations, located throughout the U.S., Europe, and the Pacific, as potential users of PAVER. This work estimates and validates not only the present extent of several pre-identified problem areas in PAVER implementation, namely, training, manpower, equipment, and top management support, but also the current extent of PAVER's use and application. In addition, multiple regression is used to determine the existence of relationships between those variables which may influence the acceptance and active use of PAVER, such as training, manpower, equipment and diffusion-of-innovation variables, and those variables which may indicate PAVER's degree of use and acceptance, such as accuracy of data input into PAVER and the extent of a pavements network input into the system.

KEYWORDS: PAVER, pavement management system, implementation, training, manpower, equipment, top management support, data gathering, diffusion of innovation

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NEED FOR RESEARCH

Pavement management systems (PMS) have emerged as a means of effectively allocating funds for pavement maintenance and rehabilitation. The 1986 edition of the AASHTO Guide defines a PMS as "a set of tools that assist decision-makers in finding optimum strategies for providing, evaluating, and maintaining pavements in a serviceable condition over a given period of time" [1]. Finn et al. [2] state that a PMS "will make cost-effective decisions relative to what, where, and when. What treatment is most cost-effective, where treatments are needed, and when is the best time (condition) to program a treatment." While much has been written on the subject of pavement management systems in general as well as on specific systems that have been developed, the subject of PMS implementation has yet to be fully investigated.

To state the obvious, regardless of how well conceived a PMS is, unless it is well implemented and accepted by the end user its benefits cannot be realized. In order to enjoy these benefits, the U.S. Air Force (and other organizations) have expended considerable effort in not only developing, but also implementing PAVER. Thus, the objective of this investigation was to determine the present extent of PAVER's use and application within one of its largest users, the U.S. Air Force, as well as the presence and impact of various problem areas which may impede PAVER implementation.

IMPLEMENTATION OF PAVER WITHIN THE U.S. AIR FORCE

Pre-Identified Problem Areas

The whole issue of implementation of PAVER by the U.S. Air Force was first investigated and reported in 1984 by McLean [3]. Using a survey to gather data on problem areas and recommendations for improvement from the active and potential users of PAVER within the U.S. Air Force, he identified several significant implementation problems being faced at that time [3]: training, manpower, equipment, top management support, and user commitment.

Training: McLean [3] stated the problems with training as follows: "Bases with PAVER have not been adequately trained. Two factors have caused this problem: MAJCOM's (major commands, an Air Force organizational element directly above the base level) have not put enough emphasis on receiving formal training and base level managers have failed to support formal training. ... Bases without PAVER have not been properly educated by MAJCOM as to what PAVER is, consists of, or can do for the pavement engineer. ... Many training-related problems or concerns are due to the user being forced to 'train-as-he-goes.' As the user gains knowledge of and experience with PAVER, these problems tend to diminish."

Manpower: It was also noted that the implementation of PAVER required manpower beyond the pavement engineers themselves and has relatively low priority, primarily due to supervisors' emphasis on project design.

Equipment: McLean stated that the basic equipment support problem would be solved by the installation of the Work Information Management System (WIMS) microcomputers. Also, it was claimed that an understandable PAVER users' guide was desperately needed.

Top management support: Top management support of PAVER from base level supervisors was reported severely lacking although top management direct support from MAJCOM was perceived very favorably at base level. That is, bases felt that they got good support and assistance when they dealt directly with MAJCOM. However, indirect support from MAJCOM, such as 'encouraging' base level managers to support PAVER, was inadequate.

User Commitment: McLean stated that user commitment was somewhat favorable at that time at bases with and without PAVER; however many still were hesitant to use the system.

Exactly because McLean [3] concludes that user commitment is a direct function of PAVER training and experience, the current research does not consider this to be a separate implementation problem category. It is assumed that if other implementation problems are abated or eliminated, good user commitment will most likely follow.

Recommendations to Address Pre-Identified Problem Areas

McLean [3] made a number of common sense recommendations to address these key problem areas. Concerning training, he suggested that the Air Force Institute of Technology (AFIT) develop an Air Force sponsored PAVER short course to address problems peculiar to the Air Force and to management of airfield pavements. In addition, it was recommended that MAJCOM's and the Air Force Engineering and Services Center (AFESC) stress the importance of attending formal training as early in the implementation process as possible. Base level supervisors had to support this training if it was to be successful. Finally, he suggested that any and all information regarding PAVER implementation be disseminated to the field as soon as possible to permit the base level pavement engineer access to all available information.

Concerning manpower, it was recognized that the pavement engineer could not gather the massive volume of information (condition surveys, historical data, etc.) necessary for implementation by himself. Other manpower sources such as site developers, pavements and grounds specialists, A&E firms, etc., would have to be used, and the pavement engineer would act as a team leader during implementation. Further, implementation could proceed gradually, beginning with key features (such as runways and taxiways) and adding other pavements on a predefined schedule. The pavement engineer would need an organized plan, approved by base level supervisors, for conducting surveys, inputing data, and incorporating all key features. As a final suggestion, the pavement engineer might seek to have position descriptions for clerical staff and technicians changed to include various aspects of PAVER implementation and operation.

Equipment recommendations included the continued purchase of necessary computer equipment and support items for all bases, including modems, connections, supplies, etc. Although not strictly an equipment item, a complete user's manual for PAVER was seen as a critically needed resource. The computer system, WIMS, was in the process of implementation in 1984 for USAF civil engineering organizations. Micro Paver was not available at that time; hence, modem access to mainframe PAVER was the available means of operating the computerized PAVER system.

Top management support recommendations included ensuring that a PAVER course was instituted at AFIT, assigning an individual at AFESC who would be directly responsible for PAVER implementation, disseminating information in the form of a PAVER Newsletter, and instilling an appreciation of PAVER benefits in base level supervisors during management level courses offered at AFIT.

Concerning user commitment, MAJCOM's and AFESC were urged to actively encourage bases to use and experiment with PAVER and communicate new ideas and solutions to problems. Hands-on experience and direct education of pavement engineers would generate voluntary, enthusiastic users.

Implementation Efforts to the Present

In a policy statement issued in the same year as McLean's research was published, the Air Force signaled its commitment to implementation by making it mandatory to implement PAVER for a minimum of one base per major command during fiscal year 86 and for all bases by December, 1988. This policy was established based on Mainframe PAVER availability and was effective for all bases which had the required WIMS computer support. In a switching of emphasis to Micro PAVER, a new policy issued in July, 1989, recommended that all bases implement Micro PAVER for their primary pavements (primary runway, taxiway, and cargo aprons) by December of 1990. In part, the policy states: "Air Force wide implementation of Micro-PAVER will be an important step forward in our coordinated efforts to ensure the safety and reliability of airfield and other pavements." Where equipment was a concern, bases were recommended to upgrade existing WIMS personal computers to the required RAM and hard disk space for operating Micro PAVER. Implementation of non-primary pavements (for example, all roads) is left to the bases' discretion.

Implementation efforts since McLean's 1984 work [3] are described based in part on conversations with the Air Force's manager for PAVER implementation, Mr. Stewart Millard, who is based at Headquarters Air Force Engineering and

Services Center (HQ AFESC).

Training: Since 1984, the efforts of training Air Force pavement engineers have been continuously increased. For example, HQ AFESC conducts approximately monthly regional seminars, and AFIT and the University of Illinois at Urbana-Champaign offer PAVER short courses. Each of these training avenues offers PAVER instructional materials.

Manpower: The manpower issue remains a tough--but not impossible--problem. At least one MAJCOM has enhanced implementation (and training) by organizing five or six of the command's pavement engineers into an implementation team which rotates between each of the team members' bases and performs the initial implementation for that base. Use of other manpower resources such as A&E firms, site developers, pavements and grounds specialists, etc., remains an option.

Equipment: Unfortunately, the implementation of WIMS for civil engineering organizations did not solve the computer hardware problems, since the use of Micro PAVER requires micro computers of a capacity not provided by WIMS. Using a strong equipment purchase justification provided by HQ AFESC, individual bases have used normal acquisition channels and base level funding to purchase the required computer hardware. Although the acquisition process is not immediate, purchases have in general proceeded without difficulty. As an alternative to new equipment purchase, those bases which have AUTOCAD have used this equipment for PAVER operation. With some exceptions, distribution of the PAVER software has proceeded from AFESC to the MAJCOM's and then from the MAJCOM's to the their individual bases.

Top management support: Although HQ AFESC has maintained a PAVER consulting function for MAJCOM's and bases for the last ten years, an internal reorganization in January, 1989, enabled it to provide a greater emphasis on implementation. Through the regional seminars and increased exposure of consulting help to bases, AFESC now provides more direct help than in the past. As a means for AFESC to communicate directly with the base users, new PAVER information is now being disseminated through the Engineering and Services quarterly magazine. MAJCOM's, while generally providing good support to their bases, are not uniform in their quick dissemination of new PAVER information, however.

Finally, in an effort to instill an appreciation for PAVER in base level supervisors, AFIT provides an orientation on PAVER in its management level courses. Still, a good deal of top management support at the base level must depend on the pavement engineer's ability to "sell" the benefits of PAVER to his superiors, and this can best be accomplished with the effective training of base pavement engineers.

METHODOLOGY

Computerized methods were used to gather and analyze survey data relative to the research objective. The use of a mail-in questionnaire was selected as the most expedient means of gathering a large amount of data from numerous geographically dispersed civil engineering organizations located throughout the U.S., the Pacific, Europe, and elsewhere. Although the previous research conducted by McLean helped significantly in isolating potential problem areas, and although Air Force managers can and do have a good "feel" for implementation problems and successes, only an objective survey can estimate the present extent of PAVER's use and application as well as the presence and impact of various problem areas.

Survey Development

Sixty-six two-way and multiple choice, categorical questions were selected for the questionnaire. Although somewhat lengthy, the questionnaire was thought to be an appropriate length considering the interest in the subject of the population surveyed. Choices were designed to be mutually exclusive, well balanced, and to offer all reasonable alternatives. Because significant potential problem areas were already known from McLean's previous work, open-ended responses were kept to a minimum. The questionnaire was designed with a single skip question to permit distinguishing between those bases which have and have not at least partially implemented PAVER. As a means of logically organizing the questionnaire for the benefit of respondents, easily answered factual type questions were listed first followed by more thought-provoking opinion and perception type questions. Background information was solicited last, and space was allotted for general comments on PAVER and the survey.

The initial population for the survey included all active duty base-level civil engineering organizations listed in Air Force Regulation 4-16, Air Force Address Directory, which was assumed to contain a complete listing of Air Force organizations. A 100 percent sample was selected for a total of 125 organizations surveyed. Prior to sending the questionnaires, however, it was known that at least some of the organizations within the initial population estimate were not good candidates for using PAVER (due to a limited maintenance mission, for example) and the final population estimate would have to be adjusted downward based on respondents' survey comments. The final overall population estimate was 116.

Questionnaire Topic Areas

Although the questionnaire topic areas are easily discerned from an examination of the questionnaire in the Appendix, the purpose behind including questions 54-59 bears some explanation. This section addresses perceptions of PAVER as an innovation which have been identified in various literature as factors influencing the diffusion of innovation [4-6]. As a group, these factors (which include, for example, an innovation's perceived complexity, adaptability, and credibility) are thought to comprise an internal set which may influence PAVER's degree of implementation. According to Smith [4], "To increase the likelihood of adoption, the innovation (PMS) can be structured to maximize the advantages and minimize the disadvantages. The characteristics of the innovation have a major impact on the likelihood of them being adopted. Several characteristics which influence the rate of adoption have been identified." It follows then that if PAVER as an innovation is perceived positively by respondents, the external factors of manpower, equipment, training, and top management support may then be better isolated as factors influencing PAVER's degree of implementation.

SURVEY ANALYSIS

Survey responses were read from optical scan sheets and the resulting data base analyzed using SAS, a software system for statistical data analysis. Sixty eight out of 116 responses were received for a response rate of 59%. Two levels of analysis are presented including the presentation of summary statistics and multiple regression analysis. Finally, possible biases in the population are considered.

Summary Statistics

The population was subdivided into two major groupings: bases reporting having partially or fully implemented PAVER (completing questions 1-41 and 54-66) and bases reporting not having implemented PAVER (completing questions 1-2 and 42-66). Results show that 40 out of 68 bases responding (59%) have partially or fully implemented PAVER. Summary statistics can be found after each question in the Appendix based on these groupings (sub-population category). In the remainder of the paper, the following symbols are used to represent various sub-population categories:

A	=	All bases
I	=	Bases partially or fully implementing PAVER regardless of PAVER system (micro, mainframe, or manual)
NI	=	Bases which have not implemented PAVER
M	=	Bases using Micro PAVER only
MF	=	Bases using mainframe PAVER only
MA	=	Bases using manual PAVER only

Values of 1, 2, 3, 4, and 5 are assigned to answers A, B, C, D, and E, respectively. All respondents were to answer questions 1-2 and 54-66, regardless of their major grouping. For questions identified as dependent variables estimating the state of PAVER implementation for the sub-population of PAVER implementers (questions 3-9, 38), SAS was used to determine the presence of any significant differences between micro, mainframe, and manual PAVER users. Questions 3-5 and 7 were found to show significant differences based on PAVER system in use. In addition, to illustrate varying responses based on sub-population category, statistics for question 2 are shown according to this method.

Multiple Regression Analysis

Multiple regression analyses with a general linear model (GLM) were conducted on the sub-population categories A, I, and NI. The results from the multiple regression procedure provide two types of information; an analysis of variance (ANOVA) table and results describing the general linear model.

The general linear model is one of multiple regression models in which a response is related to a set of quantitative independent variables, and for models that relate a response to a set of qualitative independent variables. This model has the following form:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon \tag{1}$$

where x_i = independent variables,
β_i = regression constants, and
ε = random error term.

The ANOVA test procedure employs the F-value as the test statistic to test the null hypothesis that the coefficients of independent variables are zero, i.e., $\beta_i = 0$. The level of significance for this test is the probability of having F-value larger than the calculated F-value from a data set for the factor in question. Smaller value of this probability implies the heavier weight of the sample evidence for rejecting the null hypothesis. For example, a statistical test with a level of significance of $p = 0.03$ shows more evidence for the rejection of the null hypothesis than does another statistical test with $p = 0.50$. Thus, in relation to the general linear model, a lower p-value for a certain independent variable, say x_k, means that the probability of having the coefficient of the variable x_k equal to zero is lower, and therefore, the significance of the variable x_k in the model is greater.

Once the variables which are significant to the model have been identified, the direction of influence between independent and dependent variables can be determined by checking the signs of coefficient values for independent variables. An increase in an independent variable with a positive coefficient implies the increase in the value of a dependent variable.

The multiple regression analysis proceeded in four stages. In the first, the independent variables consisting of the major organizational element of the base (MAJCOM) (questions 60-63) and the level of engineering experience of the respondent (question 64, labeled ENGEXP) were tested to determine if they influenced the bases' implementation of PAVER (the dependent variable for question 1, labeled IMPL). Neither independent variable was found to be significant for the criterion of p-values less than or equal to 0.05 (see Table 1). This first stage in the analysis considered the entire population of potential PAVER users, and included only those independent variables representing conditions which existed prior to the presence of PAVER. This distinction was necessary because the dependent variable was PAVER's initial implementation, not its stage of implementation, and inclusion of independent variables representing conditions after PAVER's presence would not have been appropriate.

Analysis then shifted to the sub-population of PAVER implementers. Before looking for causal relationships between the independent variables (manpower, training, etc.) potentially influencing PAVER's state of implementation and dependent variables such as accuracy of data, extent of pavements network input into the system, etc., factor analysis was employed to reduce the number of variables input into the multiple regression model. As Comrey [7] explains, "with a large number of variables and many substantial correlations among the variables, it becomes very difficult to keep in mind or even to contemplate all the intricacies of the various interrelationships. ... One common objective of factor analysis is to provide a relatively small number of factor constructs that will serve as satisfactory substitutes for a much larger number of variables. These factor constructs themselves are variables that may prove to be more useful than the original variables from which they were derived."

For the dependent variables (questions 3-9, 38) the factor analysis yielded two readily distinguishable factors. The first, which for convenience is referred to as extent-of-implementation 1 (EXTIMPL1) combines into a mean score the variables for questions 3-5, which in turn are related to the extent of the airfield pavements network input into PAVER. The second, which was called extent-of-implementation 2 (EXTIMPL2) combines into a mean score the variables for questions 7-8, which are related to the active use of PAVER as estimated by the accuracy of data used. The variable for question 6 (EXTROAD) is related to the extent of roads/streets input into the PAVER data base and was not aggregated into a factor. The variable for question 9 (PROJPROG) also was left unfactored and estimates the active use of PAVER by its use in project programming.

TABLE 1 -- Multiple regression analysis for sub-population category A

	Level of Significance (p-value)	
	Independent Variable	
Dependent Variable	MAJCOM	ENGEXP
IMPL	0.290	0.131

Finally, the variable for question 38 (OTHERAREA) is related to the respondents' interest in adding other areas into the PAVER data base in the future, and was not aggregated into a factor.

Factors for the independent variables (questions 10-37, 39-40, and 54-66) were determined as follows: The factor EQUIP (equipment) became a variable for the mean of questions 20, 21, 25, and 26; the factor MANPWR (manpower) was a variable for the mean of questions 22 and 24; TRAIN (training) became a variable for the mean of questions 13-15, 19, and 23; BENEFITS was a variable for the mean of questions 30-37, and FAVORBL (favorableness score) became a factor for the mean of questions 54-59. DATAGATG became a factor for the mean of questions 39 and 40. Questions 60-63 were rescored to represent one variable for the base's MAJCOM, and questions 64 (engineering experience, labeled ENGEXP), 66 (PAVER experience, labeled PAVEREXP), and 27 (top management support, labeled MGTSPT) were left as unfactored variables.

The final model statement for the multiple regression was entered into SAS so that the independent variables were analyzed in their causal order. The background variables (MAJCOM, questions 60-63; engineering experience (ENGEXP), question 64; and PAVER experience (PAVEREXP), question 66) were listed first followed by the mechanical variables (EQUIP, MANPWR, MGTSPT, TRAIN, and DATAGATG). Attitudinal variables (BENEFITS and FAVORBL) were listed last.

From the multiple regression analysis, Table 2 was generated for sub-population category I using all independent variables. A culling process was then

TABLE 2 -- Multiple regression analysis for sub-population category I

Indep. Variable	Level of Significance (p-value) Dependent Variable				
	EXTIMPL1	EXTIMPL2	EXTROAD	PROJPROG	OTHERAREA
MAJCOM	0.482	0.184	0.081	0.070	0.368
ENGEXP	0.448	0.481	0.445	0.340	0.412
PAVEREXP	0.021	0.307	0.307	0.362	0.094
EQUIP	0.158	0.018	0.293	0.250	0.148
MANPWR	0.459	0.414	0.330	0.141	0.023
MGTSPT	0.360	0.134	0.168	0.026	0.233
TRAIN	0.410	0.051	0.146	0.057	0.075
DATAGATG	0.085	0.081	0.315	0.097	0.237
BENEFITS	0.030	0.146	0.040	0.245	0.093
FAVORBL	0.364	0.431	0.349	0.188	0.075

TABLE 3 -- Multiple regression analysis for sub-population category I

Indep. Variable	Level of Significance (p-value) Dependent Variable				
	EXTIMPL1	EXTIMPL2	EXTROAD	PROJPROG	OTHERAREA
MAJCOM	...	...	...	...	...
ENGEXP	...	...	...	...	...
PAVEREXP	0.016	...	...	...	...
EQUIP	...	0.005	...	...	...
MANPWR	...	...	...	...	0.009
MGTSPT	...	...	...	0.006	...
TRAIN	...	0.007	...	...	...
DATAGATG	...	...	...	0.040	...
BENEFITS	0.047	...	0.017	...	...
FAVORBL	...	...	...	...	...

Note: A (...) in a dependent variable column indicates that the independent variable was not found to be significant.

used to determine insignificant independent variables. Namely, once the significant independent variables (those with p-values less than or equal to 0.10) were identified, the multiple regression was run again with the significant independent variables only to refine the p-values. The final multiple regression analysis was performed only with the variables yielding p-values less than or equal to 0.05 from the second multiple regression analysis. The results from the final multiple regression analysis were tabulated in Table 3.

PAVEREXP and BENEFITS were found to significantly influence EXTIMPL1 with p-values of 0.016 and 0.047, respectively. In each case the β_i value indicates that with the increasing presence/availability of PAVER experience and perceived benefits of using PAVER, the state of implementation of PAVER also increases. EQUIP and TRAIN were found to significantly influence EXTIMPL2 with p-values of 0.005 and 0.007, respectively. The β_i values show that with the increasing presence of these independent variables, the state of PAVER implementation (EXTIMPL2) likewise increases. BENEFITS was the only variable found to influence EXTROAD with a P-value of 0.017, with the same direction of influence as for EXTIMPL1. MGTSPT and DATAGATG significantly influenced PROJPROG (application of PAVER in project programming) with p-values of 0.006 and 0.040, respectively. In this case, the β_i values indicate that with the increasing presence of management support (MGTSPT) and decreasing presence of data gathering (DATAGATG) as a perceived problem area, the state of PAVER implementation as estimated by PROJPROG also increases. MANPWR significantly influenced OTHERAREA (future intent for adding other pavements into PAVER) with a p-value of 0.009. Here, the β_i value shows that with the decreasing presence of manpower problems (MANPWR), the state of PAVER implementation as estimated by the OTHERAREA increases as well.

The third step in the analysis looked at the sub-population group of PAVER non-implementers. The dependent variable for this group came from question 53, which asks if the respondent plans to implement PAVER in the future (next 1-2 years). For convenience, this variable was labeled FUTINT (future intent). Factor analysis was applied to the independent variables (questions 42-52 and 54-66). From this analysis the factor MANPWR became a variable for the mean of questions 45, 46, and 47, representing bases' availability of manpower to implement PAVER. The factor RESOUR (resources) was a variable for the mean of questions 43-45, representing bases' availability of resources (funds, manpower) to implement PAVER. EQUIP became a variable for the mean of questions 48 and 49 (availability of the Micro PAVER computer program and the hardware for PAVER). Question 42 (a variable for availability of training, labeled TRAIN) was left unfactored. Responses to questions 50 and 51 did not indicate that an awareness of benefits of using PAVER was a problem area (in other words, there was little variability in responses), and hence they were not included in the analysis. FAVORBL and background variables for the MAJCOM, engineering experience (ENGEXP), and PAVER experience (PAVEREXP) were included as they were for the group of PAVER implementers.

Again as in the population group of PAVER implementers, the multiple regression model statement listed variables in their causal order. Background variables (including the base's MAJCOM, ENGEXP, and PAVEREXP) were listed first followed by mechanical variables (TRAIN, RESOUR, MANPWR, and EQUIP). The attitudinal variable FAVORBL was listed last. The p-values from this analysis are in Table 4 (for all independent variables), and the same culling process as in the population group of PAVER implementers results in Table 5 for significant independent variables only. Only the bases' MAJCOM's and FAVORBL were found to significantly influence the bases' intention of implementing PAVER in the future with p-values of 0.007 and 0.038, respectively. The β_i value for FAVORBL shows that as the perception of PAVER as an innovation becomes more favorable, a base is more likely to report that it intends to implement PAVER in the future. Since the responses for MAJCOM are categorical (a base is in only one MAJCOM), the β_i value for this variable is not useful.

These results showed that FAVORBL (representing how favorably the respondent perceives the PAVER system) influences the non-implementers but not the implementers. This indicated a need to add a fourth and final step in the analysis. The frequency of responses to 54-59 (comprising FAVORBL) for the non-implementers were examined. Not surprisingly, for each question 70% or more of the respondents held consistent attitudes; that is, if they indicated that they planned to implement PAVER in the future, they likewise held a favorable opinion of PAVER. On the other hand, if they indicated that they did not plan

TABLE 4 -- Multiple regression analysis for sub-population category NI

	Level of Significance (p-value)
	Dependent Variable
Independent Variable	FUTINT
MAJCOM	0.011
ENGEXP	0.498
PAVEREXP	0.498
TRAIN	0.331
RESOUR	0.064
MANPWR	0.424
EQUIP	0.499
FAVORBL	0.041

TABLE 5 -- Multiple regression analysis for sub-population category NI

	Level of Significance (p-value)
	Dependent Variable
Independent Variable	FUTINT
MAJCOM	0.007
ENGEXP	...
PAVEREXP	...
TRAIN	...
RESOUR	...
MANPWR	...
EQUIP	...
FAVORBL	0.038

Note: A (...) in a dependent variable column indicates that the independent variable was not found to be significant.

to implement PAVER in the future, they also indicated an unfavorable opinion of PAVER. Significantly, for each question (regardless of intent to implement) no less than 86% of respondents held a favorable attitude of PAVER.

According to Smith [5], "To increase the likelihood of adoption, the innovation

(PMS) can be structured to maximize the advantages and minimize the disadvantages. The characteristics of the innovation have a major impact of the likelihood of them being adopted." For this investigation, FAVORBL is considered to aggregate PAVER's diffusion of innovation characteristics such as its perceived complexity, adaptability, and credibility.

Potential Biases

As with any mail-in survey, respondents are self-selected (as opposed to randomly selected), and bias may result. In one approach to examining the presence of bias, the researcher randomly selects a group from the non respondents and obtains (through strong persuasion, or as in the case of the national census, by force of law) their responses. The non-respondent group may then be analyzed for bias. In another approach, at least two successive attempts are made (other than the initial mailing) to obtain completed questionnaires from the non respondents, and again, this group is analyzed for the presence of bias. The second approach requires roughly fifteen responses per additional solicitation for analysis of this survey. For this survey, the researchers did not have at their disposal the power to force a response as for the first approach. Although the second solicitation was attempted and yielded 11 responses, the chances for sufficient replies to a third solicitation appeared slim. In addition, time constraints prevented a third solicitation.

As a final, weaker approach to examining bias, the researcher must apply his own knowledge of the population to hypothesize on the presence of bias. One consideration is the difference in responses based on organizational affiliation (the bases' MAJCOM's) and geographic location (particularly, overseas vs. stateside). However, response rates do not differ significantly for these groups. Furthermore, although bases have varying missions and MAJCOM's may have varying command emphases, overall policy guidance on PAVER is provided Air Force wide by HQ AFESC. Therefore, it is not unreasonable to assume that the group of non respondents are operating under similar constraints and conditions as the group of respondents. While the possibility of bias cannot be ruled out, its presence and impact, if any, is assumed to be minimal.

DISCUSSION OF RESULTS

The data generated by responses to sixty-six questions leave many possible avenues and approaches to analysis. However, in keeping with the approach laid out previously, summary statistics for questions dealing with the original issues: training, manpower, equipment, and top management support, are considered first followed by the implications from the multiple regression analysis. PAVER implementers and non implementers are discussed separately.

Summary Statistics

For the PAVER implementers, the heaviest response for training from the various sources listed in questions 10-18 came from the AFIT pavements engineering course (and somewhat less from the PAVER short course). For those who use the pavements course (28 respondents) approximately 71% rate their training as good or better. Only 11% rate their training as poor. For the PAVER short course, 79% rate it as good or better, and 0% rate it as poor. These results suggest that AFIT remains the Air Force's main source for PAVER training, and that it is doing an effective job. Results for other sources of training are shown in the Appendix.

Overall, about 49% of respondents rate the adequacy of their training from all sources combined as good or better, 33% as fair, 13% as poor, and 5% as very poor. From these results it is apparent that training has improved significantly since McLean's work in 1984. However, a reasonable goal would be to move more of the percentage points out of the fair category and into the good and excellent categories. With a continued availability of the AFIT courses and emphasis on the regional seminars, this goal should be attainable.

The manpower issue is raised in questions 22 and 24. Signifying that this remains a crucial issue in PAVER implementation, approximately 78% of respondents rate the lack of adequate manpower as a major or minor impediment to implementing and using PAVER. Also enlightening, 47% of respondents state that they have sufficient manpower to maintain and use PAVER but have higher priority uses for their manpower. "Doing more with less" (often, with less people) is a time-worn phrase in the Air Force. Greater automation (i.e., more computer equipment, and application of more automation in data gathering) has its place as one way to address this problem. As always, applying resourcefulness in using the people we do have (i.e., A&E contracts, broadening technicians' job experience to include PAVER, etc.) has its place as well. However, each base must weigh its manpower priorities. PAVER has proven long-range benefits, but unless the pavement engineer is allowed the time to operate it, those benefits will never come to fruition.

Equipment-related questions included 20, 21, 25, and 26. Seventy-two percent of respondents report operating all portions of PAVER on the computer, whereas 28% report not having the equipment and are therefore operating PAVER manually. For those who have the computer equipment, 79% use Micro PAVER, followed by 21% who are still using mainframe PAVER, suggesting, not unexpectedly, Micro PAVER's greater user friendliness and continuing dominance over mainframe PAVER. Significantly, only 28% of respondents state that lack of the Micro PAVER computer program is a major or minor problem, although the researchers feel that dissemination of such a readily attainable resource should be even better. Concerning hardware, the problem becomes more severe. Fifty percent of respondents state that lack of computer hardware to run PAVER is a minor or major problem. As stated previously, bases have had to pursue their equipment purchases individually, and this process can be somewhat time consuming. As more and more bases obtain the needed equipment, one might reasonably expect the percentage of PAVER implementers to rise, given that the incentive to operate PAVER manually is not that great when the hardware is "on the way."

Thirty-three percent of respondents rate a lack of top management support as a major contributing factor (impediment) to implementing and using PAVER. Twenty-eight percent rate it as a minor contributing factor, and 39% as not a contributing factor. This issue is related to the manpower issue, in that top management at the base level must perceive PAVER as useful and beneficial and then permit the dedication of manhours for it to be implemented and actively used. These results suggest that more in the way of educating top management on the benefits of PAVER may be necessary.

Significantly, approximately 82% of respondents believe that PAVER's data collection process either takes too long, is too manpower intensive, or both (question 39). In addition, approximately 82% of respondents favor the introduction of more automation in the data gathering process (question 40). These results enhance the argument for greater application of automation in the data collection process.

For the nonimplementers of PAVER, a lack of manhours (72% rating as a major or minor contributing reason) and equipment problems (50% rating lack of hardware as a major or minor contributing reason, 57% rating lack of the Micro PAVER computer program as a major or minor contributing reason) appear to be the most significant problems. Sixty-two or more percent of respondents do not rate training (from questions 42-44) as a problem area. As discussed already, the training and equipment issues can be readily addressed with time and effort; the manpower issue is more intractable.

Multiple Regression Analysis

As discussed in the analysis section, PAVEREXP and BENEFITS were found to significantly influence EXTIMPL1, the first dependent variable for extent of implementation. EQUIP and TRAIN were found to significantly influence EXTIMPL2, the second dependent variable for extent of implementation. BENEFITS significantly influenced EXTROAD; MGTSPT and DATAGATG significantly influenced PROJPROG; and finally, MANPWR significantly influenced OTHERAREA. Not surprisingly, then, each of the originally postulated problem areas in implementing PAVER--in addition to the new variables of data gathering (DATAGATG) and BENEFITS--are found to be significant in influencing its state of implementation: equipment, training, top management support, and manpower. Finally, as one instructor of PAVER stated, "PAVER sells itself", perhaps explaining why the degree of PAVER experience the respondent has influences its state of implementation.

For the nonimplementers of PAVER, FAVORBL (representing how favorably the respondent perceives the PAVER system itself based on the characteristics of an innovation in questions 54-59) and the bases' MAJCOM influenced the dependent variable FUTINT (intent to implement PAVER in the future). Thus, the results appear to support the idea of diffusion of innovation, that various characteristics of an innovation (adaptability, credibility, etc.) enhance its probability of acceptance.

CONCLUSIONS

1. From the results of this survey, the following factors have been found to influence the state of PAVER implementation: training, manpower, equipment, and top management support. Two new factors, data gathering and benefits, have been found to influence the state of PAVER implementation as well.

2. The majority of respondents rate overall PAVER training as at least fair or better. Although this result appears to be a significant improvement since McLean identified training as a key problem area, the emphasis on improving the quality and availability of training must continue.

3. An overwhelming majority of respondents rate the lack of adequate manpower as a major or minor impediment to implementing and using PAVER. Bases must continue to use resourcefulness in finding people to do the job, and automation in data gathering should be explored as a means of reducing the manpower requirement.

4. A minority of respondents state that lack of the Micro PAVER computer program is a major or minor problem; however, since disseminating the program is cheaply and easily done, this problem should be eliminated altogether.

5. Half of the respondents state that lack of computer hardware to run PAVER is a minor or major problem. In time, the continued emphasis on purchasing the required hardware should remedy this problem as well.

6. A majority of respondents rate a lack of top management support as a major or minor contributing impediment to implementing and using PAVER. More in the way of educating top management on the benefits of PAVER may be necessary for them to perceive it as beneficial and therefore dedicate the manpower resources necessary for its implementation and operation.

7. A majority of respondents believe that PAVER's data collection process either takes too long, is too manpower intensive, or both. Consequently, more automation in data collection may be needed.

8. The results of the survey indicate that the factor, FAVORBL, representing PAVER's aggregate rating in diffusion of innovation characteristics, influences

non-implementers' intentions of implementing PAVER some time in the future. This result supports the idea of diffusion of innovation, that various characteristics of an innovation enhance its probability of acceptance.

9. The overwhelming majority of respondents have a favorable perception of PAVER as an innovation.

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DISCLAIMER

The contents of this document are technically accurate, and no sensitive items, detrimental ideas, or deleterious information are contained therein. Furthermore, the views in this document are those of the authors and do not necessarily reflect the views of the Air Force Institute of Technology, the Air Force Engineering and Services Center, the United States Air Force, or the Department of Defense.

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APPENDIX
QUESTIONNAIRE ON STATUS OF PAVER IMPLEMENTATION

1. Has your base either partially or fully implemented PAVER?
   A. Yes B. No
   •(A \1.41 \0.06 \58.8 \41.2 \0.0 \0.0 \0.0)
2. How familiar are you with the PAVER pavement management system?
   A. I have never heard of PAVER.
   B. I have heard of PAVER but am not familiar with it.
   C. I understand the basic components of PAVER.
   D. I am able to use my understanding of PAVER to ensure that proper data are input into the system.
   E. I am able to manipulate data, generate outputs, and use these outputs to assist in decision-making.
   (M \4.31 \0.18 \0.0 \4.5 \9.1 \36.4 \50.0)
   (MF \4.00 \0.45 \0.0 \0.0 \50.0 \0.0 \50.0)
   (MA \3.36 \0.36 \0.0 \27.3 \36.3 \9.1 \27.3)

If you answered **no** to question 1, please **skip** to question 42 and complete all remaining questions. If you answered yes to question 1, please continue on to the next question. For questions 3 - 9, we would like to know the present extent and currency of PAVER implementation at your base as well as your future plans for implementation.

3. Have you implemented PAVER for your runway(s)?
   A. No, and we have no plans to in the future (next 1-2 years).
   B. No, but we plan to in the future (next 1-2 years).
   C. Yes, some. D. Yes, all.
   (M \3.61 \0.13 \0.0 \4.8 \28.6 \66.6 \0.0)
   (MF \3.33 \0.33 \0.0 \16.7 \33.3 \50.0 \0.0)
   (MA \2.91 \0.28 \9.1 \18.2 \45.4 \27.3 \0.0)
4. Have you implemented PAVER for your taxiways?
   A. No, and we have no plans to in the future (next 1-2 years).
   B. No, but we plan to in the future (next 1-2 years).
   C. Yes, some. D. Yes, all.
   (I \3.30 \0.13 \2.5 \15.0 \32.5 \50.0 \0.0)
5. Have you implemented PAVER for your cargo aprons?
   A. No, and we have no plans to in the future (next 1-2 years).
   B. No, but we plan to in the future (next 1-2 years).
   C. Yes, some. D. Yes, all.
   (M \3.41 \0.14 \0.0 \9.1 \40.9 \50.0 \0.0)
   (MF \3.67 \0.22 \0.0 \0.0 \33.3 \66.7 \0.0)
   (MA \2.72 \0.33 \18.2 \18.2 \36.3 \27.3 \0.0)
6. Have you implemented PAVER for your roads\streets?
   A. No, and we have no plans to in the future (next 1-2 years).
   B. No, but we plan to in the future (next 1-2 years).
   C. Yes, a third or less. D. Yes, 1/3 to 2/3. E. Yes, 2/3 or more.
   (I \1.90 \0.19 \50.0 \27.5 \12.5 \2.5 \7.5)

7. How accurate is the pavement distress data that is entered into your PAVER system?
   A. Very little (less than 35%) of the data is accurate.
   B. Some (35 - 65%) of the data is accurate.
   C. Most (65 - 90%) of the data is accurate.
   D. Almost all (90 - 100%) of the data is accurate.
   (M \3.57 \0.18 \4.8 \4.8 \19.0 \71.4 \0.0)
   (MF \2.83 \0.48 \16.7 \16.7 \33.3 \33.3 \0.0)
   (MA \2.64 \0.24 \9.1 \27.3 \54.5 \9.1 \0.0)
8. How accurate is the inventory data that is entered into your PAVER system (including surface type, pavement structure, traffic, etc.)
   A. Very little (less than 35%) of the data is accurate.
   B. Some (35 - 65%) of the data is accurate.
   C. Most (65 - 90%) of the data is accurate.
   D. Almost all (90 - 100%) of the data is accurate.
   (I \3.18 \0.15 \7.7 \15.4 \28.2 \48.7 \0.0)
9. Which of the following statements best describes the active use of PAVER in programming pavements projects?
   "Pavements projects are programmed:"
   A. Entirely through the application of PAVER.
   B. Entirely through the application engineering judgement.
   C. Entirely through the application of command priorities.
   D. Through the combined application of PAVER and engineering judgement.
   E. Through the combined application PAVER, engineering judgement, and command priorities.
   (I \4.07 \0.21 \0.0 \23.1 \10.3 \2.6 \64.0)

For questions 10 - 22, we would like to know the status of training, equipment, and manpower as pertaining to your implementation of the PAVER system.

The following code is for answering questions 10 - 18:
A. Excellent B. Good C. Fair D. Poor E. Not Used/Not Applicable
(Please mark the appropriate letter for each blank)

During the implementation and use of PAVER at your base, how would you rate the training, assistance, or guidance received from:

10. HQ/AFESC: ______
    (I \3.50 \0.24 \10.5 \23.7 \15.8 \5.3 \44.7)
11. Your MAJCOM: ______
    (I \3.18 \0.24 \15.8 \21.0 \23.7 \7.9 \31.6)
12. Other bases: ______
    (I \4.76 \0.12 \0.0 \5.4 \0.0 \8.1 \86.5)
13. AFIT (Pavements Engineering short course): ______
    (I \2.92 \0.25 \20.5 \30.8 \12.8 \7.7 \28.2)
14. AFIT (PAVER short course): ______
    (I \3.58 \0.27 \15.8 \21.1 \7.9 \0.0 \55.2)

15. Univ. of Illinois (3-day short course, "The PAVER System: An Intensive Short Course"): ______
(I \4.42 \0.21 \7.9 \7.9 \0.0 \2.6 \81.6)
16. Construction Engineering Research Lab.: ______
(I \4.63 \0.17 \2.6 \7.9 \0.0 \2.6 \86.9)
17. Command-Sponsored Workshops: ______
(I \4.28 \0.21 \5.1 \10.3 \10.3 \0.0 \74.3)
18. PAVER publications: ______
(I \3.43 \0.21 \0.0 \35.8 \23.1 \2.6 \38.5)
19. How would you rate the adequacy of your training from all sources combined (questions 10 - 18) in preparing you to implement and use PAVER?
A. Excellent B. Good C. Fair D. Poor E. Very Poor
(I \2.69 \0.15 \5.1 \43.7 \33.3 \12.8 \5.1)
20. Which of the following statements best describes the status of computer use for PAVER at your base?
A. We do not have the required computer equipment (hardware and/or software) and therefore must rely totally on manual analysis procedures.
B. We have the required computer equipment (hardware and software), but still prefer to operate PAVER manually.
C. We operate portions of PAVER manually, and operate other portions by computer.
D. We operate all applicable portions of PAVER on the computer.
(I \2.73 \0.21 \30.0 \10.0 \17.5 \42.5 \0.0)
21. If you operate all or portions of PAVER on the computer, please indicate which computer system you are using.
A. Mainframe PAVER B. Micro PAVER
C. Not Applicable; we use manual analysis procedures.
(I \2.13 \0.11 \15.4 \56.4 \28.2 \0.0 \0.0)
22. Which of the following statements best describes the status of available manpower to maintain the data base and use PAVER.
A. We lack sufficient manpower to maintain and use PAVER.
B. We have sufficient manpower to maintain and use PAVER but have higher priority uses for our manpower.
C. We have sufficient manpower to maintain and use PAVER but are required to spend it satisfying the requirements of higher levels of management.
D. We have sufficient manpower and use it to maintain and use PAVER.
E. Other; please specify:
(I \2.20 \0.19 \30.0 \42.5 \15.0 \2.5 \10.0)

Questions 23 - 37 solicit your opinion on both problems with PAVER implementation and its usefulness as an engineering tool and aid to decision-making.

For questions 23 - 29, rate each of the listed factors as impediments to implementing and using PAVER on your base (A = major contributing factor; B = minor contributing factor; C = not a contributing factor). Please mark the appropriate letter for each blank.

23. Lack of adequate training. ___
(I \2.30 \0.13 \20.0 \30.0 \50.0 \0.0 \0.0)
24. Lack of adequate manpower. ___
(I \1.75 \0.13 \47.5 \30.0 \22.5 \0.0 \0.0)
25. Lack of Micro PAVER computer program. ___
(I \2.53 \0.13 \20.0 \7.5 \72.5 \0.0 \0.0)
26. Lack of PAVER hardware. ___
(I \2.18 \0.14 \32.5 \17.5 \50.0 \0.0 \0.0)
27. Lack of top management support. ___
(I \2.05 \0.14 \33.3 \28.2 \38.5 \0.0 \0.0)
28. Difficulty of gathering pavement distress data. ___
(I \1.92 \0.13 \35.9 \35.9 \28.2 \0.0 \0.0)
29. Other; please specify: ___
(I \2.35 \0.22 \29.4 \5.9 \64.7 \0.0 \0.0)

For question 30 - 37, rate each of the listed factors as benefits from the active use of PAVER at your base (A = major benefit; B = minor benefit; C = not a benefit). Please mark the appropriate letter for each blank.

30. Reduction in manhours required to perform pavement management. ___
(I \1.77 \0.14 \48.6 \25.7 \25.7 \0.0 \0.0)
31. Project cost reduction. ___
(I \2.27 \0.12 \16.7 \38.9 \44.4 \0.0 \0.0)
32. Improved project justification. ___
(I \1.36 \0.10 \69.4 \25.0 \5.6 \0.0 \0.0)
33. Elevation of project priority. ___
(I \1.64 \0.13 \55.6 \25.0 \19.4 \0.0 \0.0)
34. Increased funding for pavement projects. ___
(I \2.05 \0.13 \25.0 \44.4 \30.6 \0.0 \0.0)
35. Elimination of projects due to improved preventive maintenance. ___
(I \2.08 \0.12 \22.2 \47.2 \30.6 \0.0 \0.0)
36. Improved decision making. ___
(I \1.75 \0.13 \44.4 \36.1 \19.5 \0.0 \0.0)
37. Better communication among various levels in your organization. ___
(I \2.03 \0.15 \38.9 \19.4 \41.7 \0.0 \0.0)

Questions 38 - 41 relate to future considerations for PAVER.

38. Do you intend to add other pavement areas into your PAVER data base in the future (next 1-2 years)?
A. Yes. B. No.
C. Not applicable; we have fully implemented PAVER for all of our pavements.
(I \1.40 \0.11 \70.0 \20.0 \10.0 \0.0 \0.0)
39. Which of the following statements best describes your opinion of PAVER's pavement distress data gathering process?
A. The data gathering process takes too long and is too manpower intensive.
B. The data gathering process does not take too long and is not too

manpower intensive.
C. The data gathering process takes too long but is not too manpower intensive.
D. The data gathering process does not take too long but is too manpower intensive.
(I \2.00 \0.18 \48.8 \17.9 \17.9 \15.4 \0.0)

40. Would you favor the introduction of more automation in the data gathering process?
A. Yes. B. No.
(I \1.18 \0.06 \82.1 \17.9 \0.0 \0.0 \0.0)

41. A soon-to-be-released version of Micro PAVER will include certain changes, some of which are as follows:
(1) A graphics summary capability to produce histogram summaries of existing data.
(2) An automated annual work plan that will permit the quicker development of the pavements improvements plan as well as enable the user to determine changes to the work plan and consequences to network condition based on changing funding levels.
(3) Large data bases may be automatically broken down into smaller, more manageable data bases for quicker report generation. Individual data bases may also be combined into one large database for overall planning.
(4) Tables with default values that can be modified to meet local costs and conditions will be included.
(5) The family curve concept will be made an integral part of reports.

Please select the response which best reflects your opinion of these changes.

A. These changes will enhance the usefulness of PAVER greatly.
B. These changes will enhance the usefulness of PAVER somewhat.
C. These changes will enhance the usefulness of PAVER a little.
D. These changes will not enhance the usefulness of PAVER.
E. These changes will detract from the usefulness of PAVER.
(I \1.74 \0.15 \51.2 \30.8 \12.8 \2.6 \2.6)

If you answered **no** to question 1, please complete questions 42 through the end of the questionnaire. If you answered **yes** to questions 1, please **skip** to question 54 and complete all remaining questions.

For items 42 - 52, please rate each item as a contributing reason explaining why your base has not implemented PAVER (A = major contributing reason; B = minor contributing reason; C = not a contributing reason).

42. Training in PAVER has not been made available. ___
(NI \2.41 \0.15 \20.7 \17.2 \62.1 \0.0 \0.0)

43. Training in PAVER has been made available but we cannot afford the manpower loss to participate in training. ___
(NI \2.64 \0.11 \3.6 \28.6 \67.8 \0.0 \0.0)

44. Training in PAVER has been made available but we do not

have the funds to participate in training. ___
(NI \2.53 \0.14 \14.3 \17.9 \67.8 \0.0 \0.0)

45. We lack sufficient manhours to implement PAVER. ___
(NI \1.86 \0.16 \42.8 \28.6 \28.6 \0.0 \0.0)

46. We have sufficient manhours but have higher priority uses for these manhours. ___
(NI \2.32 \0.15 \17.9 \32.1 \50.0 \0.0 \0.0)

47. We have sufficient manhours but are required to spend them satisfying the requirements of higher levels of management. ___
(NI \2.50 \0.13 \10.7 \28.6 \60.7 \0.0 \0.0)

48. We lack the Micro PAVER computer program. ___
(NI \2.04 \0.17 \39.3 \17.9 \42.8 \0.0 \0.0)

49. We lack the hardware for PAVER. ___
(NI \2.11 \0.18 \39.3 \10.7 \50.0 \0.0 \0.0)

50. We are not aware of the benefits of using PAVER. ___
(NI \2.71 \0.11 \7.1 \14.3 \78.6 \0.0 \0.0)

51. We do not think PAVER can solve our pavement management problems. ___
(NI \2.75 \0.12 \10.7 \3.6 \85.7 \0.0 \0.0)

52. Other; please specify: ___
(NI \2.21 \0.26 \35.8 \7.1 \57.1 \0.0 \0.0)

53. Do you plan to implement PAVER in the future (next 1-2 years)?
A. Yes B. No
(NI \1.36 \0.09 \64.3 \35.7 \0.0 \0.0 \0.0)

Questions 54 - 59 ask about certain perceptions you may have concerning the PAVER system.

54. Do you perceive PAVER as an innovation to be an improvement over previously used methods of pavement management?
A. Yes. B. No. C. Not applicable; I am insufficiently familiar with PAVER or previous pavement mgt. methods.
(A \1.37 \0.09 \79.1 \4.5 \16.4 \0.0 \0.0)

55. Do you perceive PAVER to be compatible with existing management methods in your organization?
A. Yes. B. No. C. Not applicable; I am insufficiently familiar with PAVER to judge.
(A \1.38 \0.09 \75.0 \11.8 \13.2 \0.0 \0.0)

56. Do you perceive PAVER to be too complex, that is, too difficult to understand and use?
A. Yes. B. No. C. Not applicable; I am insufficiently familiar with PAVER to judge.
(A \2.00 \0.05 \8.8 \82.4 \8.8 \0.0 \0.0)

57. Do you perceive PAVER to provide you with results which you can relate to peers and higher management?
A. Yes. B. No. C. Not applicable; I am insufficiently familiar with PAVER to judge.
(A \1.23 \0.07 \85.3 \5.9 \8.8 \0.0 \0.0)

58. Do you perceive PAVER to be adaptable, that is, able to be modified to be useful for your base's particular needs?
    A. Yes. B. No. C. Not applicable; I am insufficiently familiar with PAVER to judge.
    (A \1.35 \0.08 \79.4 \5.9 \14.7 \0.0 \0.0)
59. Do you perceive PAVER to be credible, that is, soundly based on technical content?
    A. Yes. B. No. C. Not applicable; I am insufficiently familiar with PAVER to judge.
    (A \1.26 \0.08 \86.8 \0.0 \13.2 \0.0 \0.0)

Questions 60 - 66 request general, background information.

60. What is your MAJCOM or SOA?
    A. TAC B. SAC C. PACAF D. USAFE E. None of the above.
    [b]*(A \... \... \19.1 \25.0 \8.8 \11.8 \0.0)*
61. What is your MAJCOM or SOA?
    A. ATC B. AAC C. MAC D. AFSPACECOM E. None of the above.
    [b]*(A \... \... \8.8 \1.5 \13.2 \0.0 \0.0)*
62. What is your MAJCOM or SOA?
    A. AFDW B. AFLC C. AFSC D. None of the above.
    [b]*(A \... \... \0.0 \7.4 \2.9 \0.0 \0.0)*
63. What is your MAJCOM or SOA?
    A. AU B. USAFA C. None of the above.
    [b]*(A \... \... \0.0 \1.5 \0.0 \0.0 \0.0)*
64. How many years have you been engaged in the engineering profession?
    A. 0-2 B. 3-5 C. 6-10 D. 11-20 E. More than 20
    (A \3.60 \0.14 \4.5 \13.4 \22.4 \37.3 \22.4)
65. What is your engineering discipline?
    A. Civil B. Mechanical C. Electrical D. Architectural
    E. Other; please specify:
    (A \1.10 \0.07 \97.0 \0.0 \0.0 \1.5 \1.5)
66. How much experience have you had in using PAVER?
    A. Less than 6 mths B. 6 mths. - 1 year C. 1 - 2 years
    D. 2 - 5 years E. More than 5 years
    (A \1.94 \0.18 \66.6 \6.1 \7.6 \6.1 \13.6)

[a] Summary statistics are presented after each question in the following order: *(Sub-population category \Mean response \Standard error \% response to answer A \% response to answer B \% response to answer C \% response to answer D \% response to answer E)*

[b] Percentage response reflects the aggregate response to questions 60-63.

Jim W. Hall, Robert W. Grau, William P. Grogan, Yoshita Hachiya

PERFORMANCE INDICATIONS FROM ARMY AIRFIELD PAVEMENT MANAGEMENT PROGRAM

REFERENCE: Hall, J. W., Grau, R. W., Grogan, W. P., and Hachiya, Y., "Performance Indications From Army Airfield Pavement Management Program," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: Data from a pavement evaluation program implemented on U. S. Army airfields are presented to indicate both the predominant surface distresses and the structural adequacy of the pavements. Comparison of deterioration rates in terms of the pavement condition index (PCI) is presented by relating PCI to service age. An assessment of construction quality of both PCC and AC surfaces is made by comparing tests on core samples to design requirements. The method for selection of alternatives for routine maintenance, major maintenance, rehabilitation, and reconstruction is presented.

KEYWORDS: pavement evaluation, pavement condition index (PCI), nondestructive testing (NDT), PAVER

INTRODUCTION

A pavement management program for Army airfields was initiated in 1982 by the Office, Chief of Engineers, U. S. Army, with the program being conducted by the U. S. Army Engineer Waterways Experiment Station (WES). The program consists of field surveys using nondestructive testing (NDT) for structural evaluation and the pavement condition index (PCI) for surface distress evaluation [1 and 2]. The survey data along with other pertinent information on the pavements evaluated are input to the PAVER pavement management

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program [3]. The frequency of field surveys is every three years for PCI and every five years for repeat NDT. NDT is performed with a falling weight deflectometer (FWD), and a backcalculation method is used to provide moduli of pavement layers for structural analysis. To date, some 50 airfields have been surveyed, and the results input to the PAVER data base. Most airfields have received a follow-up condition survey. Reports have been written documenting results of each survey.

The pavement management program is beneficial to Army installation engineers and the major Army commands in planning expenditures on Army airfields and identifying maintenance and repair needs. The program relates current pavement condition in terms of PCI and structural adequacy to the requirements for extended performance in terms of routine maintenance, major maintenance, rehabilitation, and reconstruction.

EVALUATION RESULTS

Fig. 1 shows the location of the 50 Army airfields in the U. S. that have been evaluated. The evaluation results consist of both a structural rating and a condition rating. The structural evaluation tests are conducted using an FWD to measure deflection basins under the impact load, the basins are used with a layer-elastic backcalculation program to obtain moduli, and the load capacity for various aircraft are determined from the moduli and limiting stress/strain criteria. Also, overlay thickness requirements are determined for different design traffic situations and traffic projections. The condition survey involves the measurement of surface distresses in terms of distress type, distress levels (high, medium, low), and area affected by the distress (density). The use of the PCI method allows a condition rating on a scale of 0 to 100 as shown in Fig. 2.

Table 1 gives a listing of recognized distress types for airfield pavements as related to various possible causes.

A summary of the PCI results for all airfield pavement features (runways, taxiways, aprons) is shown in Fig. 3 for asphalt concrete (AC) pavements and in Fig. 4 for portland cement concrete (PCC) pavements. Note that approximately 1/3 of the AC pavements are in excellent condition while nearly 1/2 of the PCC pavements are rated as excellent. A PCI below 40 (level between good and fair rating) is generally indicative of a pavement in need of rehabilitation. Note that only 13.7 percent of AC pavements and 15.8 percent of PCC pavements are rated below a PCI of 40. The amount of pavement surveyed consisted of 7,119,327 sq yd of AC pavement and 4,228,449 sq yd of PCC pavement.

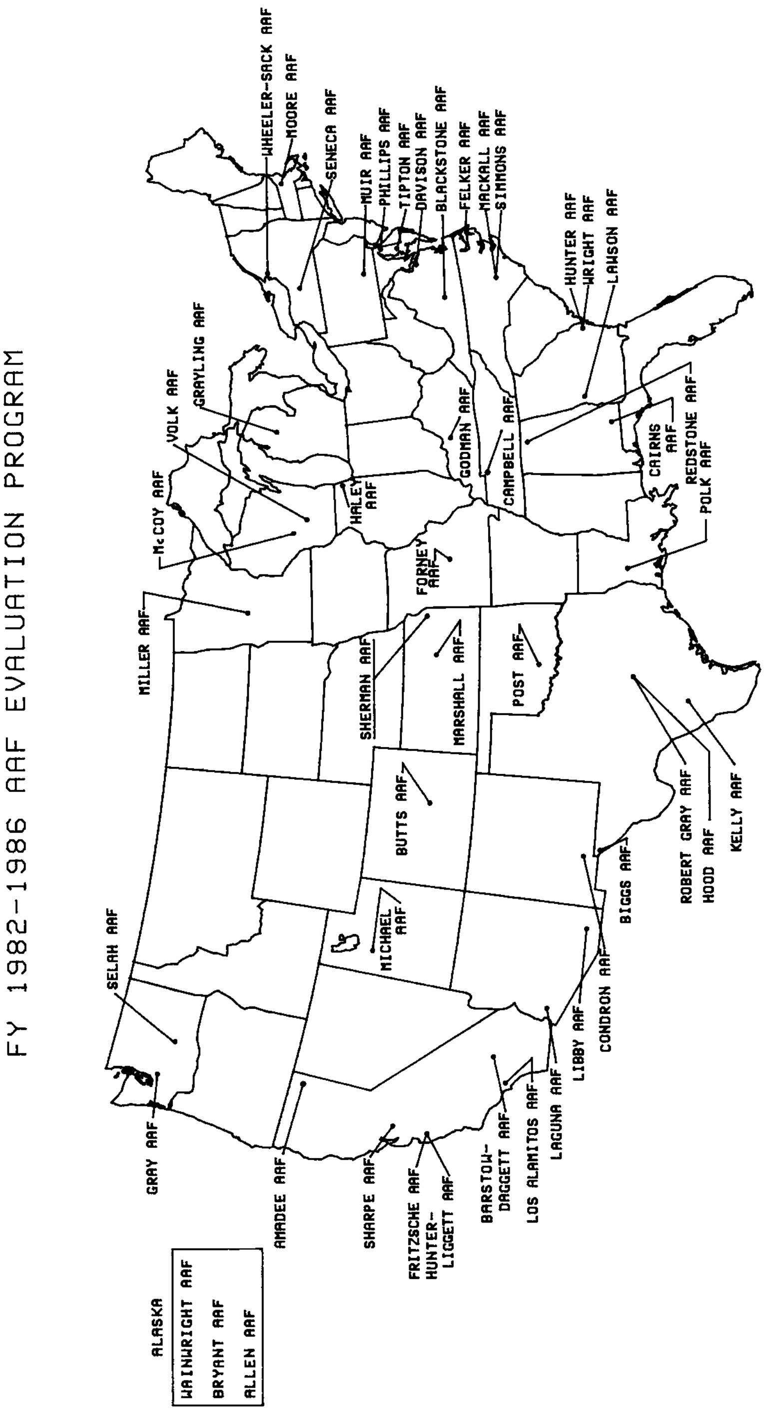

FIG. 1 -- Location of Army Airfields.

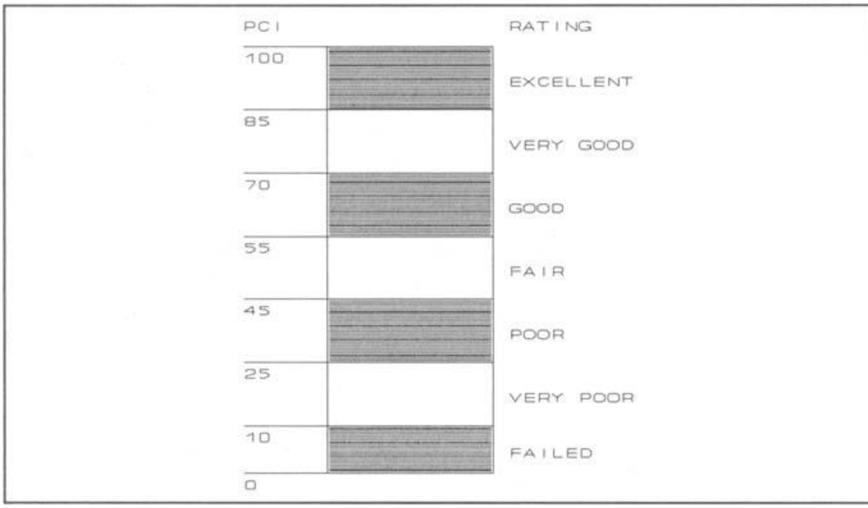

FIG. 2 -- Pavement condition index scale.

TABLE 1 -- Cause of Airfield Pavement Distress Types.

Load	Climate	Other Factors
	Asphalt Distress Types	
Alligator Cracking Rutting	Block Cracking Joint Reflection Cracking Longitudinal/ Transverse Cracking Patching Raveling and Weathering	Bleeding Corrugation Depression Jet Blast Oil Spillage Polished Aggregate Shoving from PCC Slippage Cracking Swell
	Concrete Distress Types	
Corner Break Longitudinal/ Transverse/Diagonal Cracking Shattered Slab	Blow-up "D" Cracking Joint Seal Damage	Patching Patching and Utility Cut Popouts Pumping Scaling, Map Cracking, and Crazing Settlement and Fault Shrinkage Cracking Joint Spalling Corner Spalling

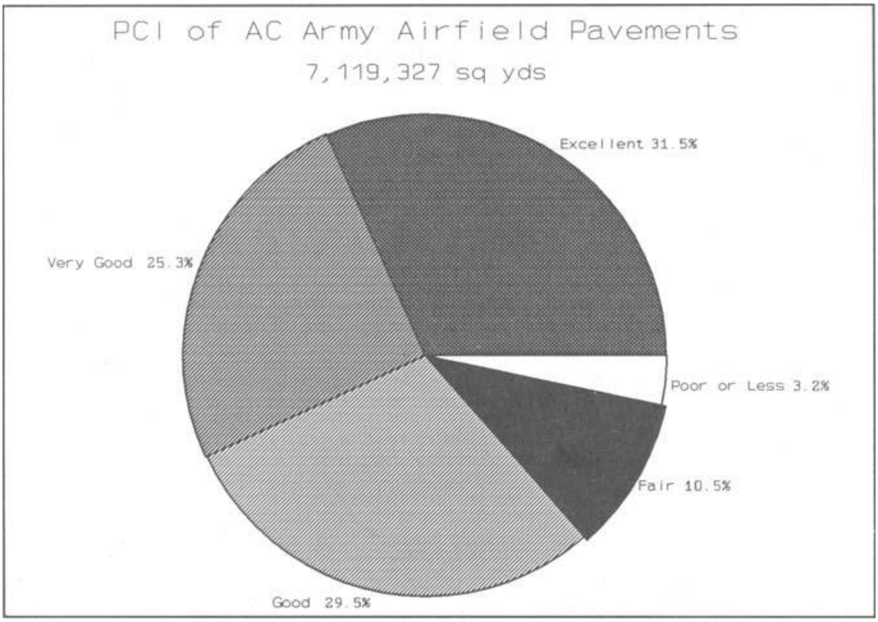

FIG. 3 -- Surface condition of AC pavements.

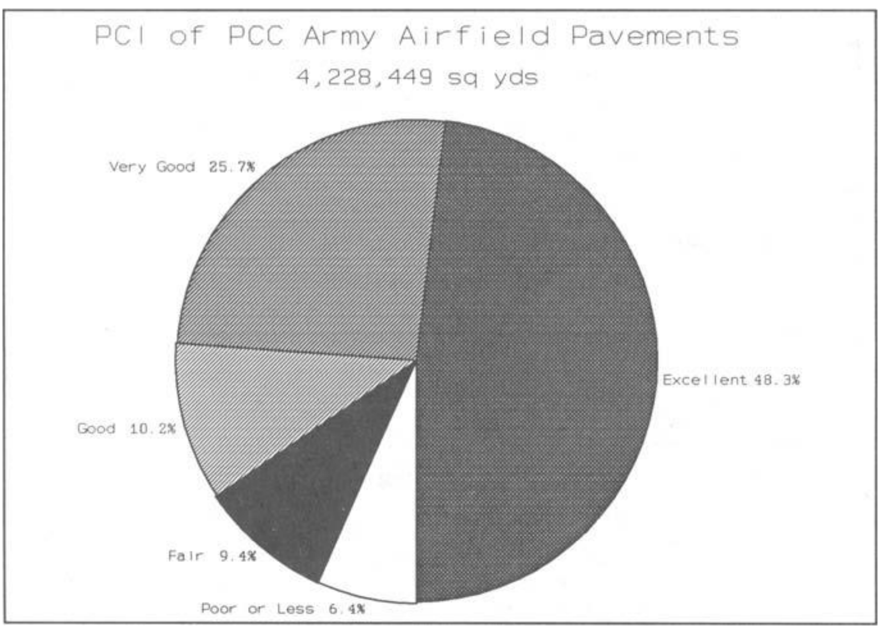

FIG. 4 -- Surface condition of PCC pavements.

PCI data were plotted against the age of the pavement surface at the time the condition survey was made. The age of the pavements surveyed ranged from a few years to over 40 years. The data were widely scattered, and regression correlations were not considered very good. The regression equations for four types of pavements--AC, PCC, AC overlay on AC, and AC overlay on PCC--are shown in Fig. 5. Regression results for the four relationships are:

PAVEMENT TYPE	NUMBER OF DATA POINTS	REGRESSION EQUATION	CORRELATION COEFFICIENT (R)
AC	343	Y = -1.412 X + 83.44	0.61
PCC	147	Y = -1.328 X + 91.76	0.67
AC overlay on AC	384	Y = -1.512 X + 89.71	0.51
AC overlay on PCC	120	Y = -3.037 X + 99.19	0.72

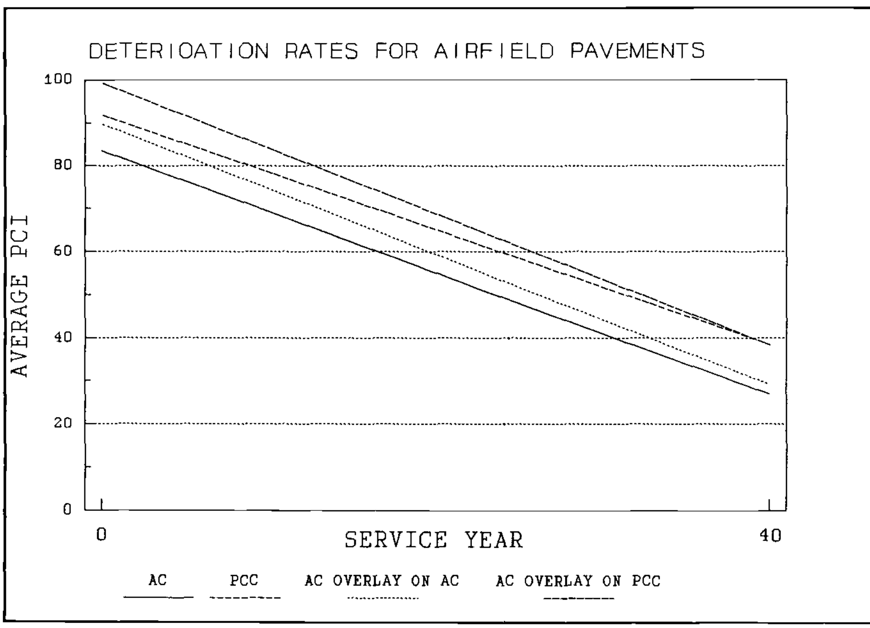

FIG. 5 -- Comparisons of PCI and pavement age.

A summary of the structural evaluation results can be expressed in terms of overlay thickness requirements. Fig. 6 gives the thickness of an AC overlay for all pavements for design traffic in terms of day-to-day operations for a 20-year life. The results show that 64 percent of the pavements are structurally adequate without the need of an overlay.

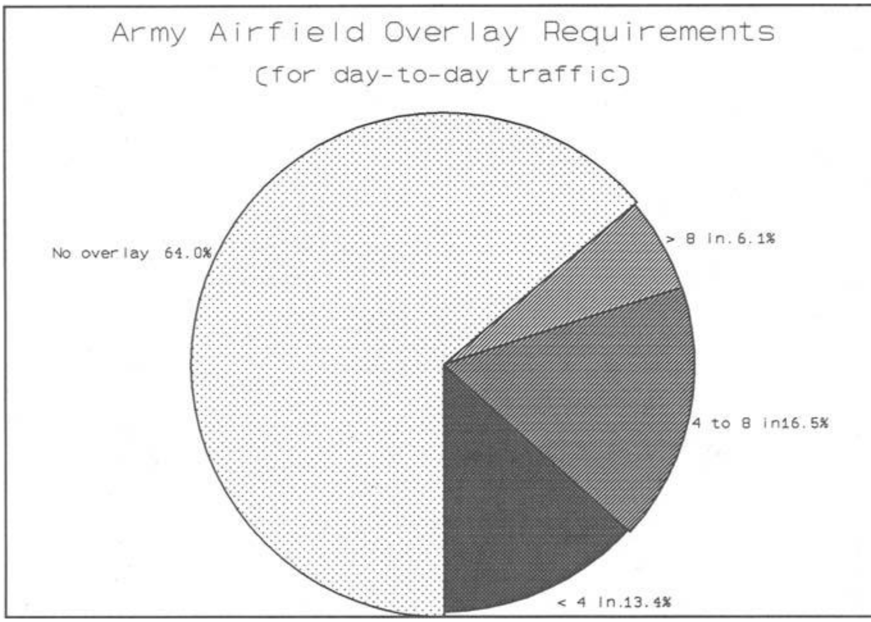

FIG. 6 -- Overlay thickness requirements for day-to-day traffic.

SURFACE DISTRESS COMPARISONS

As indicated in Table 1, the surface distresses can be categorized as related to load, climate, or other causes. Fig. 7 presents the PCI data for AC pavements in terms of these categories, breaks the data into various PCI ranges, and indicates the percentage of pavement in each category. This is the same PCI data used to develop Fig. 3. A similar relationship for PCC pavements is presented in Fig. 8. As can be seen in Fig. 7, for all levels of PCI the majority of distresses in AC pavements are climate related, as defined in Table 1. Distresses in PCC pavements are mainly a function of climate at higher levels of PCI but are fairly equally divided among load, climate, and other causes for low PCI values. In considering these comparisons, one should realize that the concrete pavements are primarily found on aprons. Most runways and taxiways are AC pavements, so the pavement usage is somewhat different.

For AC pavements, the predominant distress types found were block cracking, raveling, and longitudinal and transverse cracking. Fig. 9 shows block cracking in terms of the amount of this distress occurring on those pavements within various PCI ranges and indicates the amount of the distress at each severity level. Also shown in Fig. 9 is the average amount of block cracking for all of the pavement sample units from all 50 airfields.

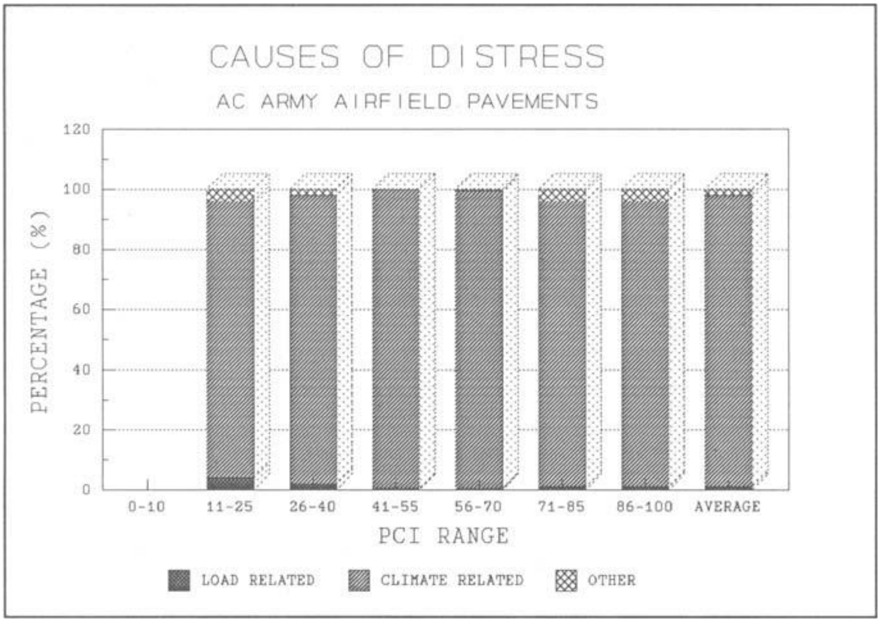

FIG. 7 -- Surface distress on AC pavements.

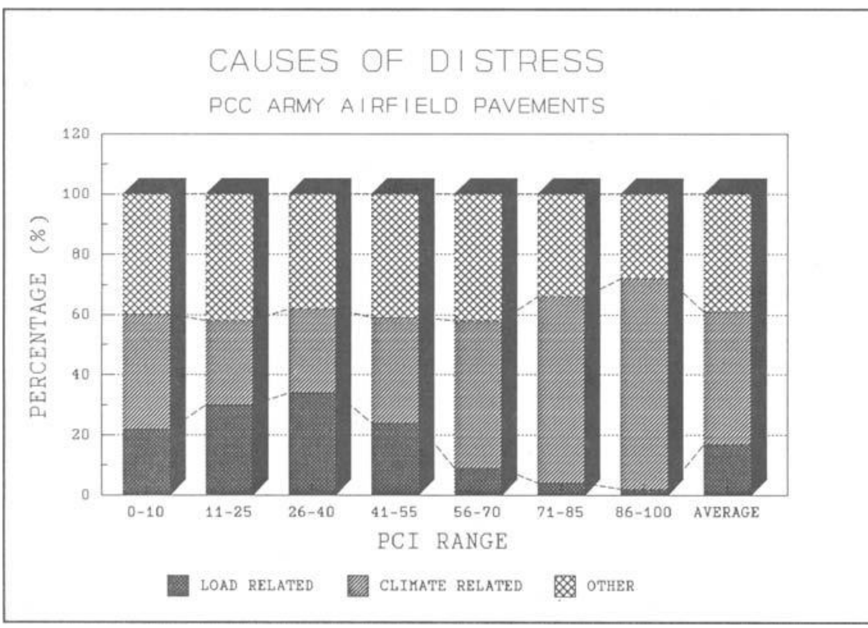

FIG. 8 -- Surface distress on PCC pavements.

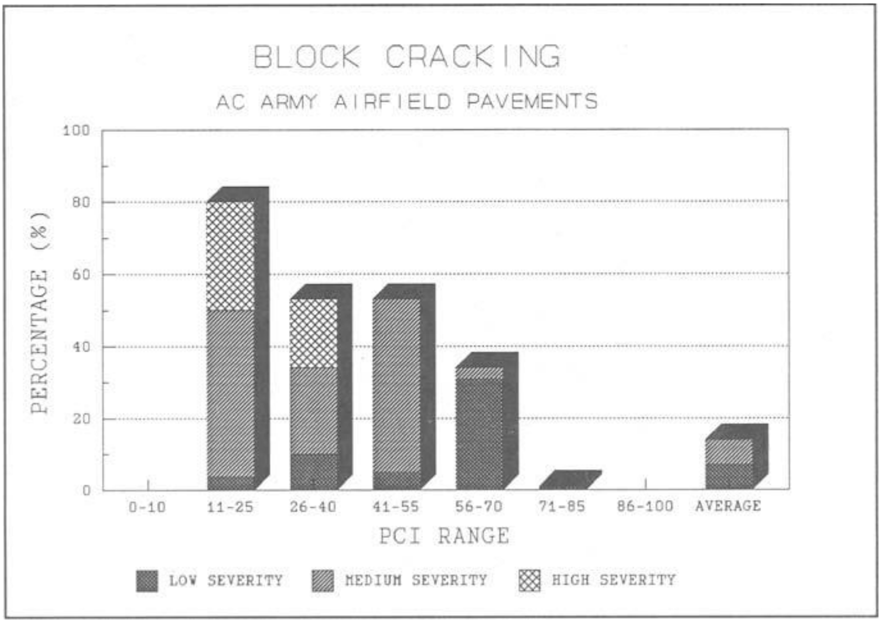

FIG. 9 -- Block cracking on AC pavements

Figs. 10 and 11 show similar presentations for raveling and for longitudinal and transverse cracking. A comparison of Figs. 9, 10, and 11 indicates that for those pavements with low PCI values, the predominant distress on the AC pavements is block cracking whereas the predominant distress for those with high PCI values is longitudinal/transverse cracking. For this investigation, longitudinal and transverse cracking were considered climate induced distresses. However, longitudinal and transverse cracking may be load associated, particularly if found in the wheel path.

For PCC pavements at Army airfields, the predominant distresses are joint spalling, scaling, cracking, and joint seal damage. Fig. 12 presents the joint spalling distress results and shows that an average of approximately 14 to 15 percent of the PCC pavements contain joint spalling. At the lower PCI ranges, the amount of high-severity joint spalling increases. As shown in Fig. 13, scaling mainly occurs at the low-severity level, and the average amount of scaling is about 12 percent. Cracking distress in PCC pavements is shown in Fig. 14. Joint seal damage appears to exist on all PCC pavements, with the average density being about 55 percent, as shown in Fig. 15.

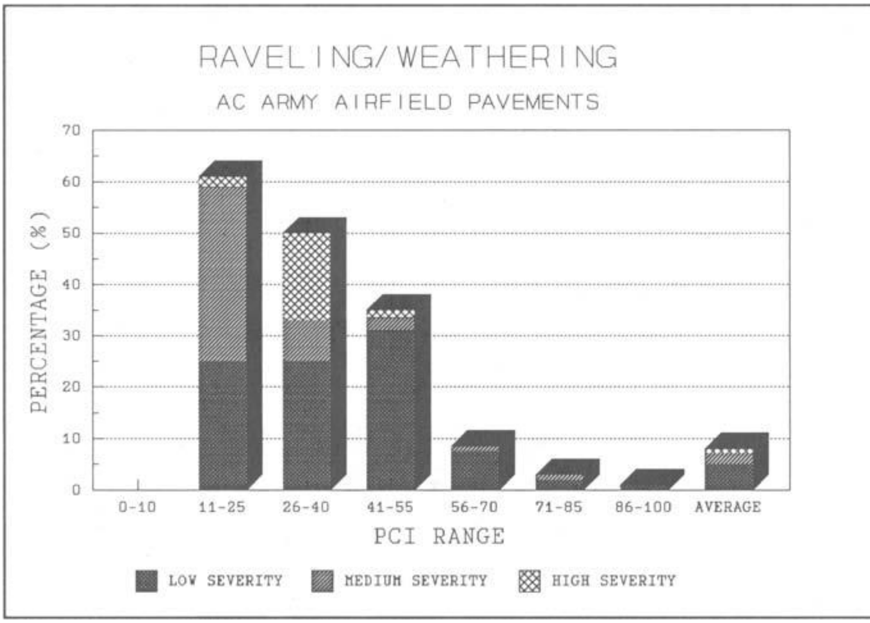

FIG. 10 -- Raveling on AC pavements.

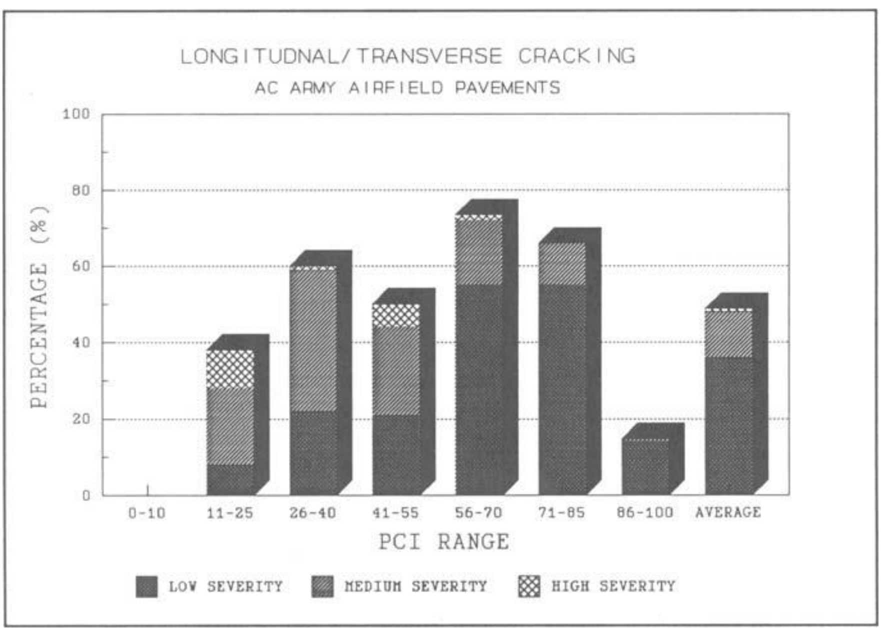

FIG. 11 -- Cracking on AC pavements.

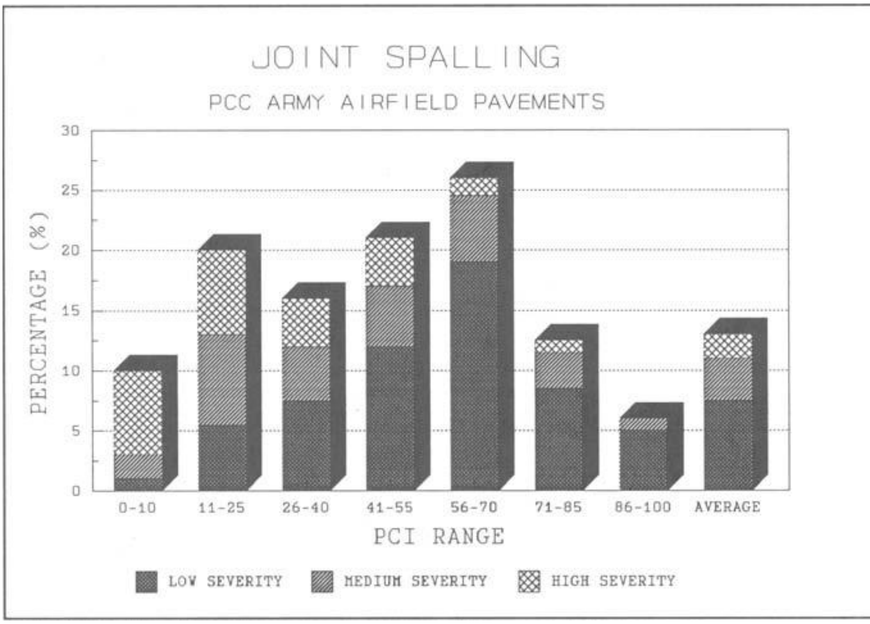

FIG. 12 -- Joint Spalling on PCC pavements.

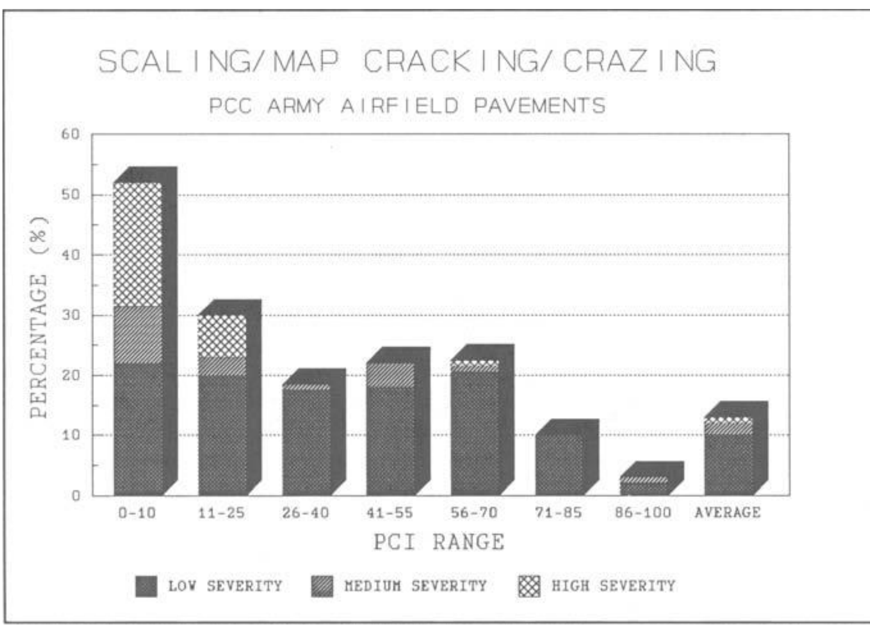

FIG. 13 -- Scaling of PCC pavements.

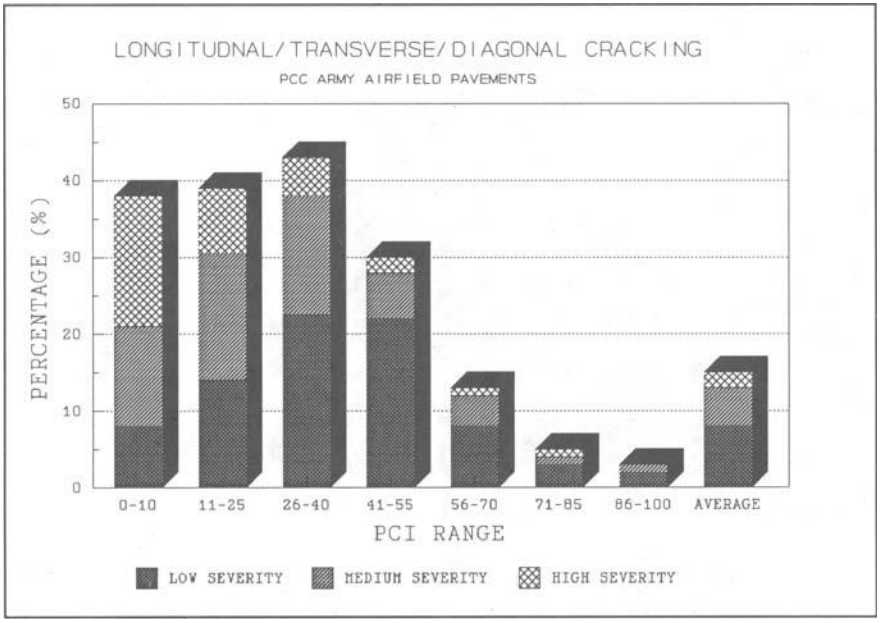

FIG. 14 -- Cracking in PCC pavements.

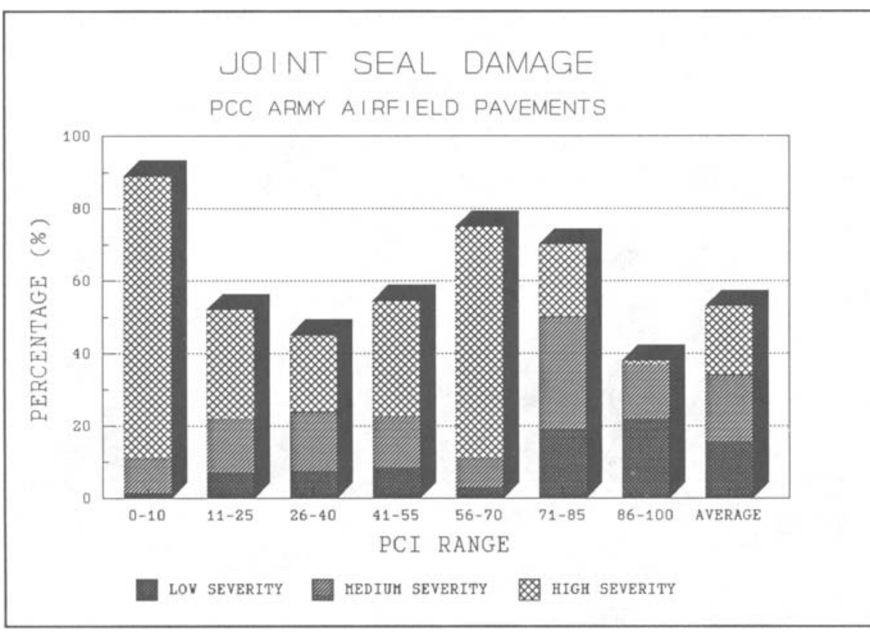

FIG. 15 -- Joint seal damage in PCC pavements.

MATERIAL PROPERTIES

As part of the evaluation program, cores are taken from the AC and PCC surfaces for laboratory testing. Flexural strength is determined for the 6-in.-diameter PCC cores through correlations with tensile-splitting strength. AC cores are used to determine in-place density and then are recompacted to obtain properties of the AC mix. Results of these tests can be used to assess the adequacy of material properties and can reflect the degree of quality control exercised.

Results from tests on the PCC cores are shown in Fig. 16. The average flexural strength is 710 psi. Normal design flexural strength is 650 to 700 psi. Only 14.7 percent of the cores show flexural strengths less than 600 psi.

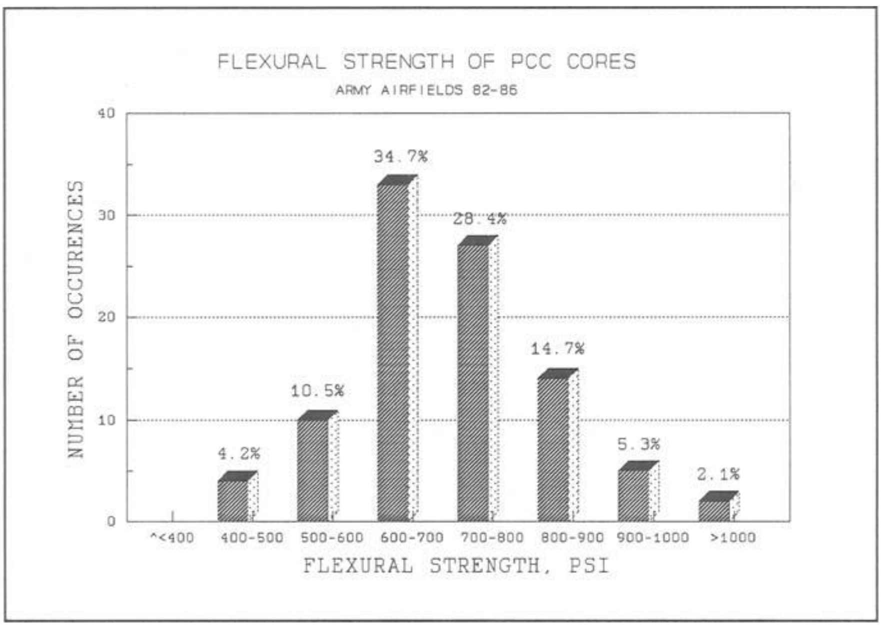

FIG. 16 -- Flexural strength of PCC pavements.

Fig. 17 shows test results on the AC cores in terms of field density as a percent of laboratory recompacted density. The laboratory compaction was the 75-blow effort required for airfield pavements. The average field density falls far below the normal specification requirements indicating poor compaction during construction. Also, the air voids in the AC pavements are quite high as shown in Fig. 18.

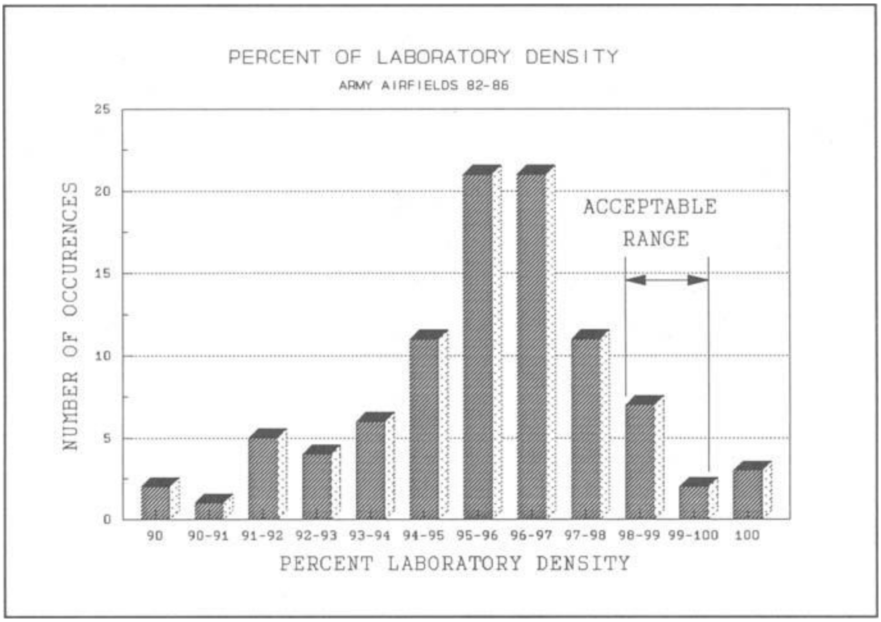

FIG. 17 -- Density of AC pavements.

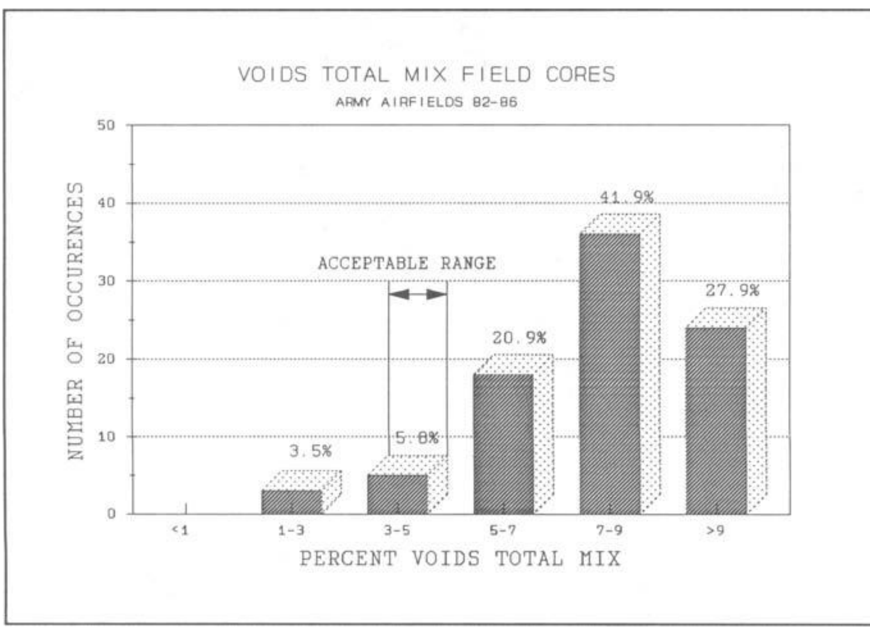

FIG. 18 -- Voids total mix in AC pavements.

MAINTENANCE ALTERNATIVES

Results from the evaluation of the Army airfields are used to recommend alternatives [4] for routine maintenance, major maintenance, rehabilitation, and reconstruction. Department of the Army guidelines [5] outline the requirements for the Army Airfield Evaluation Program, but implementation is under the direction of WES. WES evaluation procedure uses the flow chart in Fig. 19 with the condition survey and structural evaluation to select the appropriate alternative. A PCI evaluation is conducted every three years. If all of the distresses measured are nonload related, if there is no planned change in usage of the pavement (neither increased loads nor frequency), and if the same traffic has been consistent for two years or more, then there may not be a need for the NDT evaluation, particularly if such an evaluation was conducted within the last five years. An NDT evaluation should be made every five years even if the PCI does not indicate load-related distresses. If the PCI identifies significant load-related distresses, the requirement for an NDT structural evaluation is triggered.

The result from the flow chart in Fig. 19 is coupled with guidelines from Tables 2 through 5 for specific treatments as a function of the predominant distress types determined for a pavement. The guidance given is not intended to be all-inclusive, and other alternatives may be found appropriate for specific conditions. Also, consideration is not given to specific local conditions such as subgrade material type, surface roughness, or skid resistance.

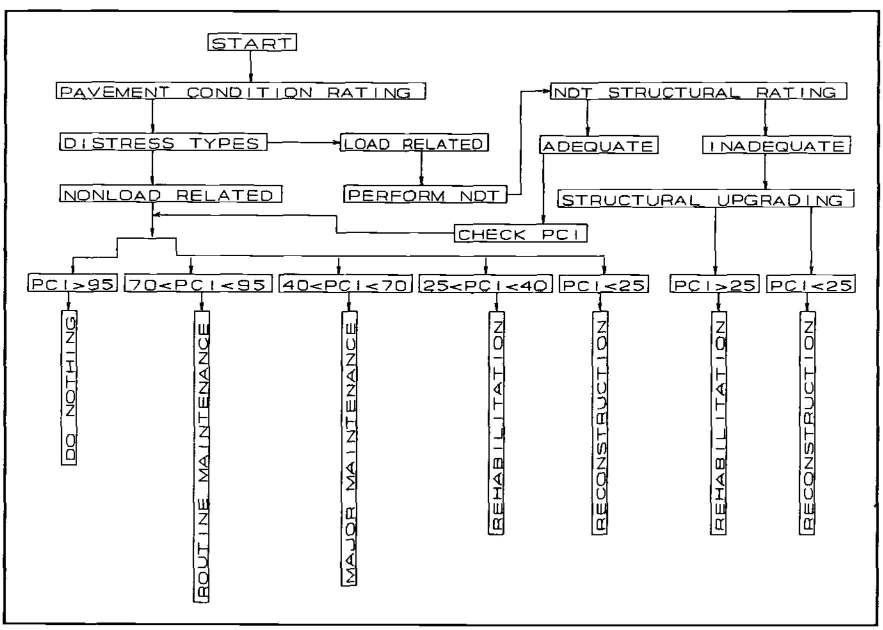

FIG. 19 -- Flow chart for pavement evaluations.

TABLE 2 -- Maintenance Alternatives for Airfield Pavements, Rigid.

Distress Type	Routine Maintenance				Major Maintenance							
	Seal Minor Cracks	Joint Seal	Partial Patch	Epoxy Repairs	Seal Major Cracks	Full-Depth Patch	Under Sealing	Slab Grinding	Surface Milling	AC Overlay	PCC Overlay	Repair Drainage Facilities*
Blowup			L,M			M,H						
Corner break	L			M,H	M,H	M,H						
Longitudinal/transverse/ diagonal cracking	L,M				M,H					H	H	L,M,H
D cracking	L		M,H		M,H	H						
Joint seal damage		M,H										
Patching (small) <5 ft^2	L,M		M	L,M	M,H	M,H						
Patching/utility cut	L,M		M	L,M	M,H	M,H						
Popouts**				A						A	A	
Pumping	A	A			A		A					A
Scaling/map cracking			M,H					M,H		M,H	M,H	
Fault/settlement		L,M					M,H	L,M	M,H			L,M,H
Shattered slab	L				L,M					M,H	M,H	L,M,H
Shrinkage crack†												
Spalling (joints)		L	L,M	L,M,H	M,H	M,H						
Spalling (corner)			L,M	L,M	M,H	M,H						

Note: L = low severity level; M = medium severity level; H = high severity level; A = no severity levels for this distress.
* Drainage facilities to be repaired as needed.
** Popouts normally do not require maintenance.
† Shrinkage cracks normally do not require maintenance.

TABLE 3 -- Rehabilitation and Reconstruction Alternatives for Airfield Pavements, Rigid.

	Rehabilitation						Reconstruction	
Distress Type	Slab Replacement	AC Structural Overlay	PCC Structural Overlay	Crack & Seat with AC Structural Overlay	AC Structural Overlay W/Geotextile	Repair/Install Surface/Subsurface Drainage System	PCC Recycling	Remove Existing PCC and Reconstruct
Blowup	H							
Corner break	H							
Longitudinal/transverse/ diagonal cracking	H	H	H	M,H	H	L,M,H	H	H
D cracking	H						H	H
Joint seal damage								
Patching (small) <5 ft^2	H							
Patching/utility cut	H							H
Popouts*								
Pumping						A		
Scaling/map cracking/crazing		M,H	M,H					
Fault/settlement						L,M,H		
Shattered slab	M,H				H	L,M,H	H	H
Shrinkage crack**								
Spalling (joints)								
Spalling (corner)								

Note: H = high severity level; M = medium severity level: L = low severity level; A = no severity levels for this distress.
* Popouts normally do not require maintenance.
** Shrinkage cracks normally do not require maintenance.

TABLE 4 -- Maintenance Alternatives for Airfield Pavements, Flexible.

	Routine Maintenance				Major Maintenance								
Distress Type	Seal Minor Cracks	Repair Potholes	Small Patching	Apply Rejuvenators*	Seal Major Cracks	Large Patching	Surface Treatment**	Slurry Seal†	Thin AC Overlays††	Surface Milling	Grooving	Porous Friction Course	Repair Drainage Facilities
Alligator cracking	L	M,H	M			M,H	L	L					L,M,H
Bleeding										L,M			
Block cracking	L,M			L	M,H		L,M	L					
Corrugation			L,M			L,M,H			M,H	L,M			
Depression			L,M,H			M,H			M,H				L,M,H
Jet blast				A		A			A				
Reflection cracking	L,M				M,H		L,M	L					
Longitudinal and transverse cracking	L,M				M,H		L,M	L					
Oil spillage			A			A			A	A			
Patching	L,M		M		M	M,H							
Polished aggregate							A	A	A	A	A	A	
Raveling/weathering		M,H		L,M		M	L,M	L	M,H	M			
Rutting			L,M			L,M,H							L,M,H
Shoving			L			L,M				L,M			
Slippage cracking	L		L,M		L,M	M,H							
Swell			L,M			M,H				L,M			L,M,H

Note: L = low severity level; M = medium severity level: H = high severity level; A = no severity levels for this distress.
* Not to be used on high speed areas due to increased skid potential.
** Not to be used on high-type airfields due to FOD potential.
† Not to be used on heavy traffic areas.
†† Patch distressed areas prior to overlay.
Drainage facilities to be repaired as needed.

TABLE 5 -- Rehabilitation and Reconstruction Alternatives for Airfield Pavements, Flexible.

Distress Type	Rehabilitation				Reconstruction			
	Surface Recycling	AC Structural Overlay*	Install/Repair Subsurface Drainage Facilities	PCC Structural Overlay	Remove Existing Surface and Reconstruct	Hot Recycle	Cold Recycle	AC Structural Overlay
Alligator cracking		M,H	L,M,H	M,H	H			H
Bleeding	M,H				H	M,H	M,H	
Block cracking	M	M,H				M,H	M,H	
Corrugation					M,H			
Depression			L,M,H		H			
Reflection cracking		M,H				H		
Longitudinal and transverse crack		M,H				H		
Oil spillage	A				A	A		
Patching		M,H			H	H		M,H
Polished aggregate	A							
Raveling	M,H			H	H	M,H		
Rutting		M,H	L,M,H	H	H	M,H		M,H
Shoving					M,H	M,H		L,H
Slippage cracking		M,H			M,H	M,H		L,M
Swell			L,M,H		H			

Note: M = medium severity level; H = high severity level; L = low severity level; A = no severity levels for this distress.
* Patch distressed areas prior to overlay.

SUMMARY AND CONCLUSIONS

The Office, Chief of Engineers, U. S. Army initiated an Army airfield evaluation pavement management program in 1982. The program included NDT of pavements, the conduct of PCI surveys, and coring of the pavements to verify layer thicknesses and obtain specimens for laboratory testing.

Results of the structural evaluation based on NDT revealed that 64 percent of all Army airfield pavements are satisfactory for sustaining day-to-day traffic. Further, 22.6 percent of the pavements require an overlay of 4 in. or greater to sustain day-to-day operations. This would indicate that the majority of Army airfield pavements are structurally adequate.

The results of the PCI surveys indicate that most of the current surface distress found on Army airfield pavements are due to climate rather than load. Also, 80 percent of all Army airfield pavements rate as good or better. This would also indicate that Army airfield pavements are sufficient structurally.

Test results on specimens obtained from the PCC surfaces indicate that the flexural strength of the great majority of PCC pavements meet design requirements. Test results on AC specimens indicate that in-place density of AC mixtures average about 96 percent with specification requirements being 98-100 percent. The low densities and corresponding high air voids may contribute to the high levels of block cracking and raveling measured from the condition surveys.

Results of the airfield evaluations are used to determine when maintenance and repair alternatives are appropriate. The Army airfield evaluation results are used by planners, airfield operators, and engineers responsible for maintaining airfields to determine and justify requirements to provide high quality pavements necessary for the operation of military aircraft.

ACKNOWLEDGEMENTS

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Waterways Experiment Station, the Department of the Army, or the Department of Defense. This paper does not constitute a standard, specification, or regulation.

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INGREDIENTS OF A THIRD GENERATION PAVEMENT MANAGEMENT SYSTEM FOR THE OHIO DEPARTMENT OF TRANSPORTATION

REFERENCE: Majidzadeh, K., Saraf, C. L., and Kennedy, J. C., Jr., "Ingredients of a Third Generation Pavement Management System for the Ohio Department of Transportation," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: The Pavement Management System described in this paper is the result of the development and implementation of a third generation pavement management system for the Ohio Department of Transportation which required slightly less than four years to complete. This is a network level system which provides optimal actions for candidate pavements, long range budget allocations, present assessment and future forecasting of the network conditions and rehabilitation need. Various modules and submodules are manipulated to achieve optimal solutions over a six year planning period by maximizing pavement performance for a given budget or minimizing cost for a given network performance level. The main components included in this system are: A pavement condition module; a maintenance and rehabilitation module; a cost module; a performance prediction module; an optimization module; and a report generation module. Additionally a scheme called "project interference" is available in this PMS which can be specified as a constraint to the optimal solution whenever the design engineer (or management) wishes to specify that a specific action (or a sequence of actions) be taken on a specific highway segment for whatever reasons.

KEYWORDS: pavement management, maintenance management, optimization, pavement rehabilitation, systems

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The Pavement Management System (PMS-III) developed and implemented for the Ohio Department of Transportation (ODOT) is a network level system which can prescribe optimal maintenance and rehabilitation actions and required budget for each roadway segment for each year of a six year planning period. Based on present network condition and pavement condition prediction models, PMS-III forecasts future network condition, rehabilitation needs, and associated budget. The optimal maintenance policies recommended by this system are based on maximizing preservation of pavement investment for a given annual budget or minimizing cost of maintaining the network condition at a given performance level.

Generally, Pavement Management Systems developed and implemented in the U.S. are quite diverse in scope, concept and analytic approach to address various management and engineering decisions [1-5]. The ODOT PMS-III described herein, however, is characterized as a system, which provides optimal actions for candidate pavements, long range budget allocations, present assessment and future forecasting of the network condition and rehabilitation needs.

The basic structure of the ODOT PMS-III is shown in Fig. 1. This system incorporates the following components:

- The pavement condition module.
- The M&R action module.
- The cost module.
- The performance-prediction module.
- The optimization module.
- Report generation module.

The operational aspects of these modules are briefly described in the following section.

DESCRIPTION OF PMS-III MODULES

Pavement Condition Module

This module includes information related to Pavement Condition Rating (PCR), Present Serviceability Index (PSI), and skid resistance (SN). PSI is currently not used in PMS and SN is used only on the project level to correct pavements with low friction values. The use of these measurements in various pavement management systems is described elsewhere in the literature [See Ref. 1-5]. PMS-III utilizes PCR, which was developed by the Ohio DOT in the 1970's and is reported in several publications [4-7].

A typical PCR form currently used by the Ohio DOT for flexible pavement is shown in Fig. 2. Inputs from PCR ratings are used to activate the Maintenance and Rehabilitation (M&R) selection process and provide the alternate six year plans for each roadway segment (See Fig. 1).

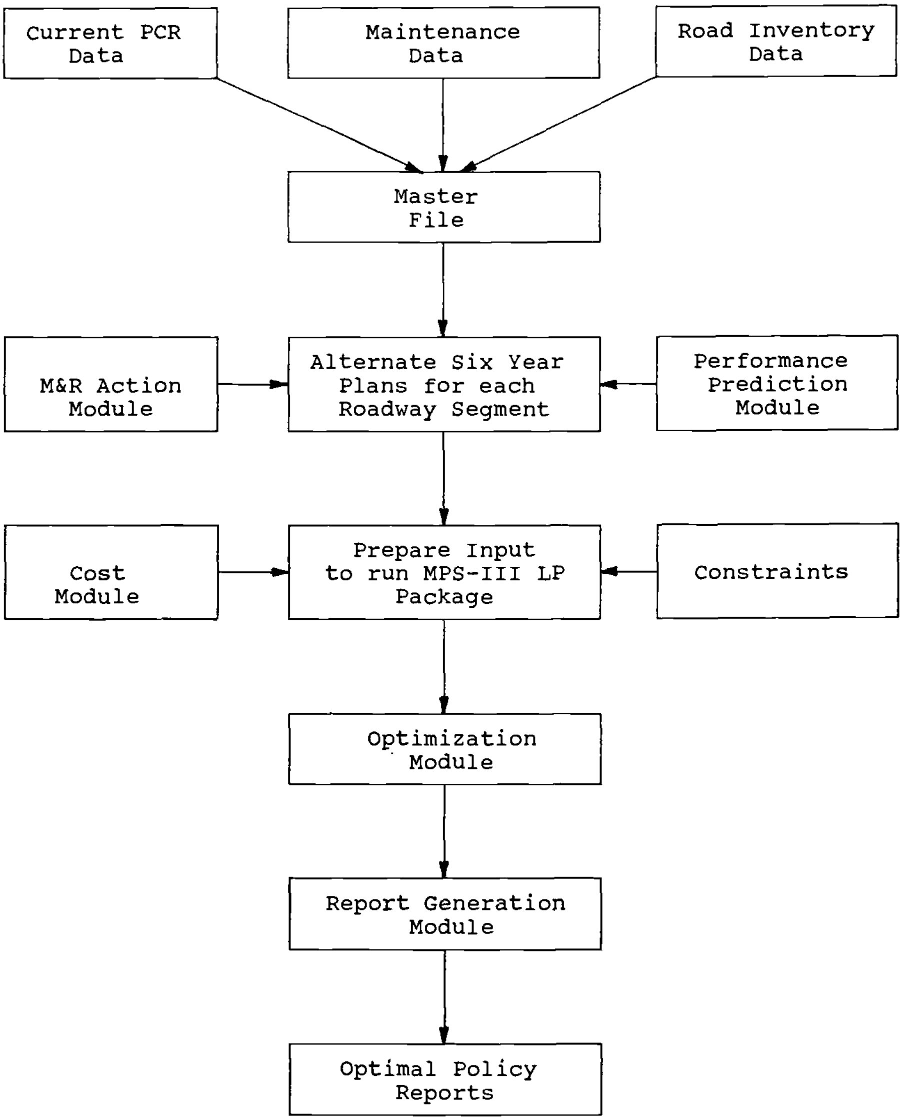

FIG. 1--Basic structure of PMS-III Program

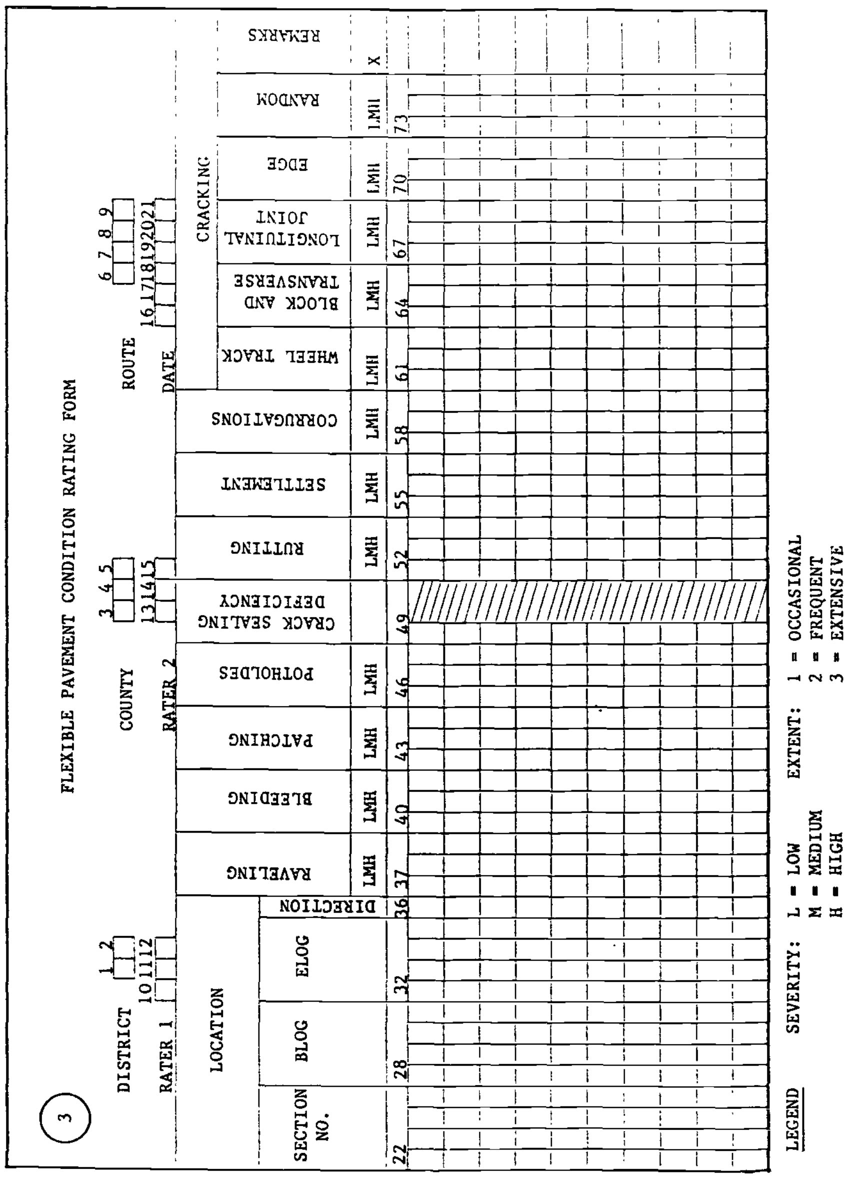

FIG. 2--Flexible Pavement Condition Rating Form

M&R Action Module

The M&R action module is concerned with the selection of the feasible M&R strategies in view of given roadway information. Roadway information includes distress type, severity and extent of distress, pavement type, and roadway functional class (or traffic level). The components of this module are as follows:

- M&R action list
- M&R selection charts
- Plan reduction rules

M&R Action List: This list contains all possible M&R actions currently used by the Ohio DOT. A total of 14 different actions are included in this list as shown in Table 1.

TABLE 1 -- List of M&R Actions used by the Ohio DOT and their Corresponding Codes.

	Description of M&R Action	Action Code
1.	Do nothing	000
2.	Routine maintenance	010
3.	Seal coat	020
4.	Joint crack underseal repair	030
5.	CPR (Concrete Pavement Restoration)	040
6.	Non-structural AC overlay with minimum repairs	050
7.	Non-structural AC overlay with repairs[b]	060
8.	Structural AC overlay with minimum repairs[b]	070
9.	Structural AC overlay with repairs[b]	080
10.	Crack and seat	090
11.	PCC structural overlay	100
12.	Reconstruction with flexible	110
13.	Reconstruction with rigid	120
14.	Reconstruction with composite	130

[a]Overlays of 3" or less are considered as non-structural
[b]Overlays of greater than 3" are considered as structural

M&R Selection Charts: M&R selection charts are used to select the most reasonable M&R action(s) which are appropriate for the given pavement segment. These charts are available for 4 different types of pavements, viz., continuously reinforced concrete pavement (CRCP), jointed reinforced concrete pavement (JRCP), flexible and composite. A typical selection chart for flexible pavements is shown in Table 2. As indicated earlier, PCR data are used to activate the M&R selection process. In-order-to begin this process, the individual distresses recorded in the PCR forms are grouped and numerical values of group severity and extent are determined by a method developed for this purpose and described in a report to the Ohio DOT [7]. Based on the distress type, severity, and extent, there are one or more M&R actions recommended for the given pavement. The list of these M&R actions is further processed by "Plan reduction rules" to arrive at the recommended list of M&R actions.

Plan reduction rules: Throughout the development of the system, attempts were made to reduce the number of six-year alternate plans for any given section. Therefore plan reduction rules were developed for this purpose. Expert opinion of consultants and the Ohio DOT engineers were used. These rules are incorporated in the M&R action module. Details of these rules are available in Reference [7].

Cost Module

Cost module provides the PMS-III one of the most important INPUT. The information from this module is used to estimate the annual and total cost of each M&R plan proposed by the system.

As indicated earlier, there are 4 different types of pavements used in Ohio. Also, there are 14 different M&R actions (Maximum) associated with each pavement type including "do nothing" action. There is no cost associated with this action, but cost for the remaining 13 actions is estimated by ODOT engineers for each pavement type. These costs are included in the cost module of the PMS-III. Currently the system contains costs related to interstate highways only. However, when the system will be expanded to other highways, the corresponding costs will also be included in this module.

Performance-Prediction Module

The performance-prediction module contains the prediction models required for forecasting deterioration of pavements with time. The general form of the performance or damage equation used in PMS-III is exponential as shown below:

$$g = \exp - [(a1H^{a2} I^{a3})/(T+1)^{a4}] \tag{1}$$

where,

g = damage at any time due to cumulative traffic, T,

TABLE 2 -- M&R Action Selection Chart for Flexible Pavement.
(See Table 1 for Description of Action Codes)

Distress Group	Severity	Extent: Occasional	Extent: Frequent	Extent: Extensive
Structural 1[a]	Low	000/010/020	000/010/020	000/010/050
	Medium	000/010/020	050/070/080	110/120/130
	High	060/070/080	110/120/130	110/120/130
Structural 2[b]	Low	000/010/020	000/010/020	000/010/050
	Medium	000/010/020	050/070/080	110/120/130
	High	060/070/080	110/120/130	110/120/130
Surface[c]	Low	000	000/010/020	050
	Medium	000/010/020	050	050
	High	050	050	050/060

[a]Structural 1 includes
- Pot holes
- Patching
- Settlement

[b]Structural 2 includes
- Rutting
- Wheel Track Cracking
- Block & Transverse Cracking
- Corrugations

[c]Surface includes
- Raveling
- Bleeding
- Random Cracking
- Crack Sealing Deficiency
- Longitudinal Cracking
- Edge Cracking

H = parameter representing the effective thickness of the given pavement and determined by the following equation:

$$H = 0.1 \sum_{m=1}^{n} Hm\ (Em/20{,}000)^{1/3} \qquad (2)$$

Hm = thickness of m th layer of pavement, in,
Em = modulus of elasticity of m th layer, psi,
n = total number of layers in the pavement excluding subgrade,
I = subgrade index defined as (Es/1,000),
Es = modulus of elasticity of subgrade soil, psi,
a1-a4 = regression constants determined from the analysis of data, and
T = cummulative traffic in 18k equivalent single axle loads since the major rehabilitation.

Performance-Prediction module contains damage function coefficients a1-a4 for all 4-types of pavements, all actions (000-130), and all distress groups associated with each pavement type. Each distress group is divided into its severity and extent as illustrated in Table 2 as well as Fig. 2.

Damage functions are used to estimate the distresses in pavements which have been treated with the selected maintenance action (see Table 1 for the list of maintenance actions). Next, the numerical values of distress group's severity and extent are converted into their discrete levels (low, medium, high, or occasional, frequent, extensive). The distress group's severity and extent levels are finally used to select maintenance alternatives as illustrated in Table 2.

The Optimization Module

The Optimization Module of PMS-III consists of a linear programming package to analyze various 6-year plans developed by the system for the highway network. Currently the ODOT network includes interstate and multi-lane highways totalling about 5000 km. The network is divided into segments based on road inventory, maintenance and design information, and pavement type.

Two methods of optimization are available in the system: performance maximization and cost minimization. Very briefly, the optimization process proceeds along the following lines: the roadway segments are obtained from the master file and mandatory actions (if any) are assigned to those segments where project interference takes place. Then feasible actions are assigned and feasible maintenance plans are prepared by M&R selection module. The performance prediction module is used to predict the consequences of an action or a series of actions over the planning period of 6-years. This data is then fed to a preprocessor that converts all input into the format required by the linear programming package used in PMS-III. The preprocessor also sets up the objective function and constraints according to optimization option selected (maximum performance or minimum cost). The optimization package solves the equations for the appropriate model and produces a solution file. In simple terms, the solution file contains the list of segments in the network and most appropriate action plan for each segment. This solution is input to the report generation module which generates a variety of user-specified reports aimed at providing information on the network as well as district or county level. Some reports are designed for management while others are meant for district and project engineers. The types of reports and their functions will be briefly described in the section on report generation module. Figure 1 illustrates the basic structure of PMS-III program as described above. The following sections briefly describe the approach used in two methods of optimization included in PMS-III.

Performance Maximization: The future performance of a pavement segment can be predicted using the performance prediction models described above. The effect of applying an action plan over the six-year planning horizon is illustrated in Figure 3. In this figure, performance can be measured either by the white area under the curve or by the shaded area which is equivalent to the loss of serviceability of the pavement. For modeling purposes the complementary (shaded) area was minimized in order to maximize performance (this also takes into account the salvage value of the pavement by considering the PCR at the end of the six year period). To be more precise, if the shaded area is called the deduct value, the performance maximization is achieved by minimizing the annual equivalent worth of the deduct value (AEWDV); this takes into account the capital recovery factors and inflation rates. The system is solved under two budget constraints: the total

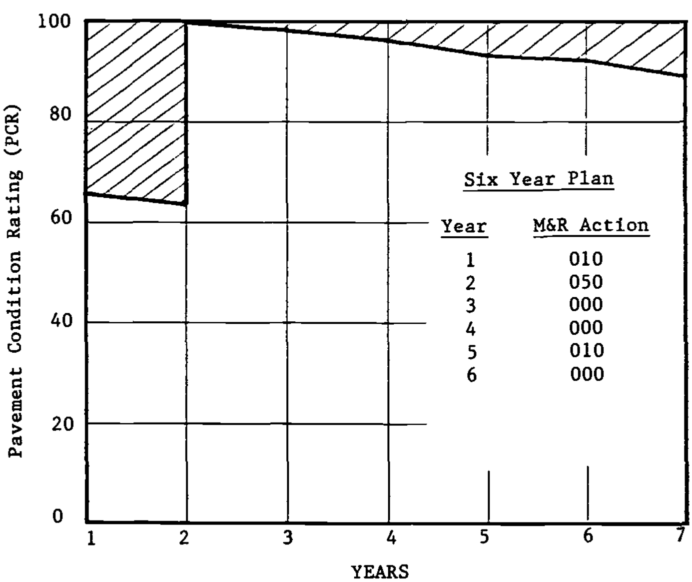

FIG. 3 -- Pavement Condition Rating PCR versus time plot of a six-year plan

on all segments in any one year must not exceed the available (allocated) budget for that year; and the expenditures for any one year expenditures must not be less the specified minimum budget for each year. The latter constraint is necessary in order to ensure an even distribution of expenditures in future years.

The system of resulting equations is solved using the MPS-III linear programming package purchased by ODOT from Ketron, Inc. By treating the system as a set of linear equations (instead of integer equations) there is a possibility of determining a "mixed mode" solution, i.e., the optimizer may select more than one action for a few segments in the network. However, this assumption greatly facilitates solution and the mixed solution can easily be implemented so that it causes no real problem. For example, the linear programming solution may assign weights of 0.60 and 0.40 to two different maintenance plans recommended for a given project. In such rare cases, the maintenance engineer can assign appropriate maintenance plans to these two road segments (one segment represented by 60% length of project and another represented by 40% length of the project).

The performance maximization model can also be used to determine the most cost-effective budget for the network. Figure 4 illustrates the network performance (average PCR for the network) at the end of the planning horizon as a function of the annual budget. It is easily seen from this figure that the returns (in terms of PCR increase per dollar) are considerably reduced when the annual expenditures increase beyond about $2 million/year (increasing the annual expenditures from $1M to $2M raises the average network PCR from 78 to 88 whereas going from $2M to $4M only increases PCR by 5 points, to 93). Thus, annual expenditures greater than about $2M/year may not be justified in this case. However, if network performance level greater than PCR = 88 is desired, there is little choice but to increase the budget.

<u>Budget Minimization:</u> Although performance maximization is easier for management to use since it is easier for an administrator to specify a maximum budget than it is to develop performance constraints. However, the option of minimizing cost is also available in PMS-III. In this option the total cost of actions taken on all pavement segments over the planning horizon is minimized, subject to two constraints. The first of these is that a minimum performance level (in terms of average network PCR) must be met or exceeded each year; the second requires that the annual budget must not be less than a minimum specified budget. The second constraint is the same as that used in the performance maximization model and is introduced for the same reason, i.e., to assure a relatively even distribution of funds from year to year.

The major disadvantage of the cost minimization model is, as was stated above, that it is difficult for an administrator to determine exactly what the minimum performance level should be or at what rate it should climb to the ultimate desired level. However, curves such as that shown in Figure 4 can be prepared with the exception that the annual budget becomes the dependent variable and the specified performance the independent variable. It is then fairly easy to determine which performance levels are cost effective and which require unreasonably large expenditures. It should, however, be pointed out

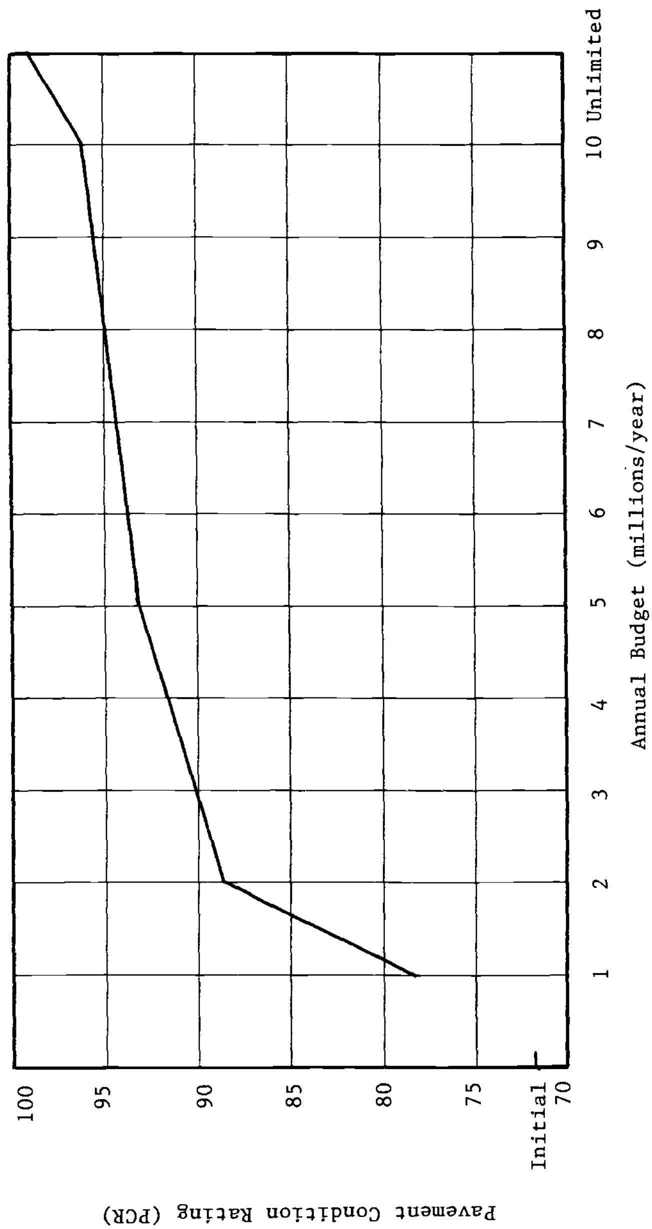

FIG. 4--Effect of yearly budget on Pavement Condition Rating (PCR) at the end of six-year planning period

that at the same expenditure level the two methods will not in general result in identical actions for all segments.

Report Generation Module

The system described in this paper generates output which can be used by management as well as district and project engineers. In order to facilitate the use of this output, the module generates several reports. These reports were designed to serve the needs of various users of the system, viz., managers and engineers of the Ohio DOT. Limitations of space will not allow a detailed description of each report produced by the module. However, a brief description of each report is as follows:

1. PM 150 Report - lists all possible M&R action plans over the 6-year planning period and the yearly cost of each plan.

2. PM 300 Report - summarizes the cost of various M&R strategies (major, minor, routine) and the resulting PCR for a particular budget or performance constraint.

3. PM 301 Report - lists the detailed M&R strategies selected for each segment and the cost by district for a given year.

4. PM 302 Report - lists the detailed M&R actions, cost, and the resulting PCR for each year in the planning period.

5. PM 305 Report - summarizes the six-year M&R costs by district and also gives the percentage of budget allocated to each district.

6. PM 306 Report - very similar to PMS 302 Report except that is includes additional details not included in PM 302.

7. PM 320 Report - summarizes M&R strategy information (action and cost) by county for a given year.

8. PM 325 Report - summarizes M&R actions and their costs by district and by action.

Together these reports display all the information applicable on the network level for all segments in the network. There are also 3 graphical output reports which display the output of some of the above reports in graphical form. These are:

1. Network Performance - this report displays the network PCR (at the end of 6 year period) as a function of annual budget and can be used to determine the most cost-effective budget.

2. PCR Distribution - this report displays the percent of network below a specific PCR value (at the end of 6 year period) as a function of annual budget.

3. Mileage in PCR Group - this report displays the percent of network mileage in each of the six PCR groups for each year in the planning period and shows how the network condition improves over time. The six PCR groups as defined by ODOT represent the condition of pavement ranging from very good (PCR between 90 and 100) to failed (PCR between 0 and 20).

A typical report (PM 300) generated by this module is shown in Figure 5.

SUMMARY AND CONCLUSIONS

This paper describes the pavement management system (PMS-III) developed for the Ohio Department of Transportation (ODOT). This system is a network-level management system, spanning a 6-year planning period and is intended to aid the management in planning network-level budgets and developing maintenance plans for the network. While one of the outputs of PMS-III is an action plan for each segment in the network, project-level analysis may at times revise the network plan due to having more detailed information on the project level. However, if there is no additional information, the network solution should be followed.

PMS-III is based on assessing the condition of pavements using the visual pavement condition rating system (PCR) developed for ODOT a decade ago. PCR components (called distress groups) and traffic level are the major inputs to PMS-III to determine an optimum action plan for each segment. The optimization can either be done under a budget constraint, in which case the optimal plans are those which maximize network condition (as measured by PCR) subject to not exceeding the specified budget or under performance constraint, in which case the optimal plans are those that minimize expenditures subject to the requirement that a minimum specified performance (network PCR) must be achieved. Both methods of optimization have some benefits although the performance maximization is generally more straight forward to use since it allows management to specify a budget and then determine the resulting network condition rather than specifying a target performance level and then determining the cost required to achieve this performance level.

Various modules and submodules are manipulated to achieve optimal solutions over a period of six years. The major modules of the system are as follows:

1. Pavement Condition Module

2. M&R Action Module

3. Cost Module

4. Performance Prediction Module

5. Optimization Module

REPORT PM300
OHIO DEPARTMENT OF TRANSPORTATION
SELECTION CRITERIA: DISTRICT: ALL
COUNTIES: , , , , , , , , ,
ALL ROADS
ROUTES: 070, , , ,
PSI LIMIT: PCR LIMIT: SKID LIMIT:

PAVEMENT MANAGEMENT SYSTEM
OPTIMIZED M&R STRATEGY COST SUMMARY
BUDGET CONSTRAINTS (IN THOUSANDS): 1986 $ 5,207
1987 $ 9,773
1988 $ 26,673
1989 $ 964
1990 $ 900
1991 $ 900

PRINTED 04-22-91
PAGE 1
TARGET PCR

BDGT YEAR	TOTAL PROJECTS	TOTAL MILES	MAJOR REHAB. COST	MAJOR REHAB. MILE	MAJOR REHAB. PRJ*	MINOR REHAB. COST	MINOR REHAB. MILE	MINOR REHAB. PRJ*	ROUTINE MAINT. COST	ROUTINE MAINT. MILE	ROUTINE MAINT. PRJ*	TOTAL COST	PCR BEGIN	PCR END
1986	11	29.6	1,341	1.04	1	3,143	9.70	3	717	18.88	7	5,201	77	77
1987	10	29.1	7,370	9.40	2	2,234	6.89	5	167	12.80	3	9,771	77	77
1988	22	65.1	8,366	8.75	5	18,305	56.32	17	0	0.00	0	26,671	77	83
1989	4	10.5	444	0.80	1	404	1.07	1	112	8.60	2	960	83	79
1990	2	2.3	0	0.00	0	900	2.28	2	0	0.00	0	900	79	77
1991	1	2.1	0	0.00	0	900	2.12	1	0	0.00	0	900	77	75
TOTAL **	50	138.7	17,521			25,886			996			44,403		

ACTION	DESCRIPTION	MAINT. CATEGORY
000	NO ACTION	
010	ROUTINE M/R	ROUTINE
020	SEAL COAT	ROUTINE
030	JOINT, CRACK, UNDERSEAL	ROUTINE
040	CPR	MINOR
050	NON-STRUC. OVERLAY	MINOR
060	NON-STRUC. OVERLAY W/REPAIR	MINOR
070	STRUCTURAL OVERLAY	MAJOR
080	STRUC. OVERLAY W/REPAIRS	MAJOR
090	CRACK AND SEAT (R&R)	MAJOR
100	PCC STRUCTURAL OVERLAY	MAJOR
110	RECONSTRUCTION W/FLEXIBLE	MAJOR
120	RECONSTRUCTION W/RIGID	MAJOR
130	RECONSTRUCTION W/COMPOSITE	MAJOR

*PRJ = No. of Projects

FIG.5--A typical report generated by Report Generation Module

6. Report Generation Module

Figure 1 shows the interaction of various modules of the system. The report generation module was designed to present the results of various analyses performed by the system to its users. Although the system was originally designed to run on mainframe computers, a PC version of the PMS-III is also available to analyze small size roadway networks. In summary, the PMS-III includes the following features:

1. Produces a list of M&R actions which should be used for the segments of the network to minimize the budget for a prescribed level of performance (PCR).

2. Identifies the projects which should be funded and determines the cost of each project.

3. Provides an estimate of the budget required to maintain the network at a given level of pavement condition.

4. Estimates the change in budget level per year over the six year period for which the greatest change in performance is achieved.

5. Estimates the useful remaining life of the roadway pavement for a significant period after the planning horizon to include salvage values of different M&R alternatives at the end of a specified period after the last major maintenance was performed on the roadway.

6. The reports generated by PMS-III can aid all levels of ODOT management and engineers in making cost effective decisions on pavement M&R actions.

7. Allows the analysis to be performed for statewide network, or district, or one single route with "project interference" capabilities.

DISCLAIMER

The contents of this paper reflect the views of the authors, who are responsible for the facts and validity of the developments presented herein. The contents do no necessarily reflect the views or policies of FHWA or ODOT. This paper does not constitute a standard, specification or regulation.

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Lucien J. E. HELEVEN, and Pierre DIRCKX

DATA COLLECTION IN BELGIUM AND THEIR USE IN THE MAINTENANCE PLANNING SYSTEM.

REFERENCE: Heleven, L. J. E. and Dirckx, P., "Data Collection in Belgium and Their Use in the Maintenance Planning System," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: A maintenance planning system is under development in Belgium. It uses the longitudinal evenness, the rut depth, the skid resistance and the bearing capacity as road qualities. Visual inspection is also carried out. The different prediction models are given, and all the individual intervention threshold values. The overlay design is based on the deflection measurement and the damage factor, derived from the visual inspection.

KEYWORDS: Longitudinal evenness, rut depth, skid resistance, visual inspection, deflection, bearing capacity, APL, SCRIM, pavement maintenance planning, intervention levels, prediction models, overlay design.

The construction and the operation of roads implies the preservation of sufficiently high levels of safety and comfort. The non-users of the road should be disturbed as little as possible.

For a new-built road there is, generally speaking, no maintenance problem, but this is not the case for roads under traffic.

The current state of the economy imposes limitations on the money available for investments in roads and their maintenance. Thus there must be more stringent control on the planning and the management of the road system.

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Such constraints are expressed in the need for high quality information about the condition of the system. This explains the desirability of establishing a Road Databank linked with a number of sub-systems.

The consequences of maintenance on the quality of the roads and the costs of that maintenance must be known in order to make an optimal choice between the different maintenance techniques.

I. GENERALITIES.

The first sub-system is an automatic data capture system for information about the state of the road, which provides the Road Data Bank (RDB) with a constant supply of values for the quality parameters of the road system.

This sub-system makes it possible to collect the following data :

1.- The longitudinal evenness

2.- The transverse evenness (or the rutting)

3.- The skid resistance

4.- The visual inspection (of defects) is based on the following five sub-parameters:

   a. Cracking
   b. Loss of materials
   c. Deformations
   d. Local repairs
   e. Various defects (according to the type of pavement)

5.- The deflection

All those parameters determine the condition of the pavement.

There are two kinds of parameters.

1. Those which concern the safety and the comfort are of interest for the road-user.

2. Those which concern the structural behaviour of the road are of interest for the road manager.

The collection of data of the road qualities is rather expensive and demands the use of high-tech apparatuses and skilled people to run them. It is not necessary to measure all the parameters every year. It is useful to look for the road sections which are near to the intervention level. This can be done by the use of apparatuses with a high capacity of at least 100 to 200 km/day. (60 - 120 miles/day)

The critical sections will be examined by means of apparatuses with a low capacity. Typical are the deflection measurements with a capacity of only 10 to 20 km/day.

The knowledge of the condition of the road network can be used on two levels:

1. Global (Network level).

The knowledge of the road condition can be used on network bases, in order to compare different regions (states) and can be used to allocate the financial means to these regions.

2. Local. (Project level).

The more detailed knowledge can be used on the project level. It is used to prepare the maintenance of that road section.

The second sub-system will use the data of the road quality and the prediction models to evaluate the future quality of the road network and thus determine what road sections will need intervention.

A third sub-system will be used on the project level and it calculates the possible overlay thickness.

II. DESCRIPTION OF THE APPARATUSES.

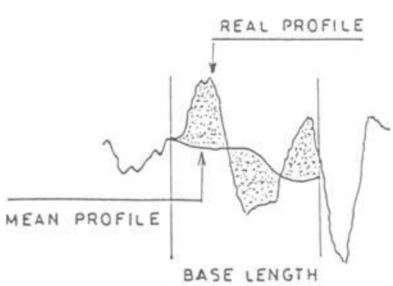
II.1. Longitudinal Evenness

The longitudinal evenness is measured in Belgium with the A.P.L. [1]

The values measured with this equipment are expressed in terms of a longitudinal evenness coefficient (EC_1)

The apparatus consists of a measuring wheel that keeps in contact with the road. The wheel is linked by the connecting arm at the frame and the balance arm. This balance arm has a very low proper frequency and is used as a reference. The measured value is the angle between the connecting arm and the balance arm.

The connection between the apparatus and the towing vehicle is constructed thus that the movement of the vehicle does not interfere with the movement of the connecting and balance arms.



The electronics used enable a digital measurement of the angle at speeds up to 144 km/h (90-mph) and a measurement step down to 50 mm (2").
For routine measurements the

test speed is set at 72 km/h (45mph) and a step of 250 mm (10") is used.

The transfer function of the APL is very flat between 0.4 and 20 Hz. This means that, at the normal test speed of 72 km/h, irregularities with a wavelength between 1m and 40m can be measured.

The Evenness Coefficient is calculated for 3 basic wavelengths. These wavelengths are 2.5, 10 and 40 m ($EC_{2.5}$, $EC_{10.}$ and $EC_{40.}$). The EC_1 is the surface between the profile and the mean profile for that wavelength. The calculation technique of the moving average is used. The units for EC_1 are 10000 mm^2/km.

II.2. Rutting

The rutting of the asphalt pavement is measured with the Dutch rutmeter. The trailer is equipped with large rubber wheels positioned 1.5m apart so as to provide a stable baseline. Seven smaller wheels connected with a measuring frame are located between the outer big wheels to follow the rut profile. The follower wheel at the deepest part of the rut guides the movement of the measuring frame. Since this apparatus can only measure the maximum rut depth we also use an ultrasonic device developed at the Queens University of Belfast. This ultrasonic device measures the cross profile of half a traffic lane (1.6 m). It is also equipped with an inclinometer to determine the cross fall. [2]

II.3. Skid resistance

In Belgium we use the SCRIM for the measurement of the skid resistance. The SCRIM was developed by the TRRL. The test apparatus consists of a freely rotating fifth wheel fitted with a smooth tire and inclined at 20° to the direction of travel. The ratio of the force, developed at the right angles to the plane of the test wheel, to the load on the wheel is the SFC (sideway-force coefficient). [2]

The test is carried out under wet road conditions. One of the important disadvantages of the SCRIM is the reduced dimension of the measuring tire. It is narrow and has a contact pressure of 3.5 bar. (51psi) As a consequence the water layer, compared to an ordinary tire of a passenger car, is more easily broken through. The SCRIM presumes a good macrotexture. To cope with this disadvantage, an

ordinary car tire can be used, but this has consequences for the autonomy of the machine, which is reduced.

II.4. Visual Inspection

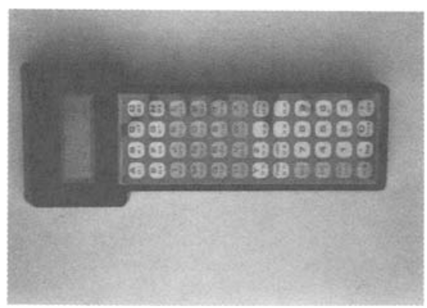
The visual inspection mentioned here describes the damages that can be observed, such as: cracks, deformations, loss of materials and repairs.
For these measurements one has to make a clear distinction between

a. the manually filling in of forms at walking speed,

b. simple machines with immediate codification,

c. making visual images, of which the codification will be done later manually under ideal circumstances, and

d. the more or less sophisticated machines that do the work automatically (image processing).



In Belgium the visual inspection is carried out by filling in forms and recently with the Informant. This is an especially programmed "hand-held" computer which enables the codification of cracks, deformations, loss of material, repairs and diverse specific characteristics of a certain kind of pavement. The Informant is programmed in such a way that it is capable of coding 20 events. Eight events are coded on two levels, this means present or not. The next four events are coded on 5 levels. The last eight events are also coded on two levels, but in contrast to the previous twelve events they are permanent and must only be coded if a change occurs. The other ones are erased every 10 meters and must be coded again before being transferred to the permanent memory of the Informant. [3]

The following events are coded:

1- Transverse crack. A transverse crack in discontinuous concrete slabs or an isolated crack in asphalt pavements.

2- Longitudinal crack. A longitudinal crack in a concrete pavement or in asphalt pavements.

3- Bridge.

4- Hectometerpoint. (100 m stone)

5- Transverse joint. A non-treated open transverse joint in concrete pavements or in asphalt pavements.

6- Longitudinal joint. A non-treated open longitudinal joint in concrete pavements or in asphalt pavements.

7- Crossroad.

8- Kilometerpoint. (1000 m stone)

9- General cracking.

10- Local repairs.

11- Ravelling.

12- Deformations.

The last 4 events are coded in 5 classes.

class 1 : nil
class 2 : less then 10% of the surface
class 3 : between 10% and 25%
class 4 : between 25% and 50%
class 5 : more than 50%.

13-14-17- : type of pavement

15-18-19- : free

16- Control

20- Annulation (used to undo a false code)

The capacity of the "hand-held" computer is 200 km (20.000 sections of 10 m) to be divided over a maximum of 15 road sections.

After the transmission of this data to a Personal Computer, the work up and the data reduction are done automatically to become the parameters of the Visual Inspection. These are cracking, repairs, ravelling and deformations.

The parameters of the Visual Inspection (failures) enable the Road Administration to calculate a global degree of damage. It is this "degree of damage" that will be used together with the bearing capacity for the structural evaluation of the pavement and for the calculation of the possible overlay.

One of the important disadvantages of the Informant is the lack of possibility of whatever control/supervision, since the data is directly coded and there is no visual image stored.

Coding is influenced by the weather condition (it is impossible on wet road surface) and the subjective codification by the operator.

The next table shows the judgments of the different road qualities.

table 1 -- Judgment of the road qualities [2]

	Evenness			Rut	Skid	Visual Inspection		Index
	EC2.5	EC10.	EC40.	depth	Res.	Concr.	Asphalt	
A very good								
limit A/B	40	80	160	4	.80	1.3%	5.2%	0.80
B good								
limit B/C	80	160	320	12	.60	7.7%	16.0%	0.60
C medium								
limit C/D	120	240	480	16	.40	20.0%	28.4%	0.40
D bad								
limit D/E	160	320	640	24	.20	35.3%	41.8%	0.20
E very bad								

The index gives the relative value for each parameter on a 0 to 1 scale (1 being the best).
The differences in the judgment for the Visual Inspection are explained by the different behaviour of rigid pavements (cement concrete) and the non-rigid pavements (bituminous pavements).

II.5. Deflection

The deflection of an asphalt pavement with an unbound foundation is measured with the Lacroix deflectograph.
The deflection is expressed in hundredths of a mm (1/100mm) and measured under a static load of 127 kN (13,000 kg). The data are recorded graphically on paper.
A manual data entry is necessary in order to be able to make the calculations. Since we have a working speed of 3 km/h and a data density of 1 measured deflection every 5 m, the manual data entry is still many times faster than the real measurements.

The deflectograph cannot evaluate the bearing capacity of the concrete roads, especially the short chassis-deflectograph we use in Belgium.

The judgment of the bearing capacity of a road is based on the measured deflection and the damage factor from the Visual Inspection.

This judgment is, in contrast to the previous 4 parameters, not possible without considering the traffic volume. Indeed, a large or a small deflection does not signify the same for different traffic conditions.

III. PREDICTION MODELS

The following equations are based on theoretical and practical considerations and experience. [4]

The value of each parameter is the physical value and is expressed versus relative lifetime or in total number of standard axles .

In Belgium we use the following formulas:

-1- **Longitudinal evenness**

$$EC = EC_0 + A*(n/N) \quad (1)$$

-2- **Rutting**

$$RUT(n) = B * (n/N)^{.5} \quad (2)$$

-3- **Skid resistance**

$$SFC(n) = SFC_0 - C * \exp(-n) \quad (3)$$

-4- **Damage factor** (visual inspection)

$$DAMbit = 100/(1+64**(-\log(n/N))) \quad (4)$$

$$DAMcrt = 100/(1+512**(-\log(n/N))) \quad (5)$$

-5- **Deflection**

$$DEF(n) = f(structure, traffic, damage) \quad (6)$$

where : n = the real traffic (on a given moment)
N = the total traffic (lifetime)
exp = the exponential function
and A,B,.. numerical constants

The index 0 refers to the starting values.

IV. INTERVENTION LEVELS.

The next table shows the different intervention levels

Table 2 -- Intervention levels

Parameter			Intervention level	Nature
Evenness	short	$EC_{2.5}$	120	safety
	medium	$EC_{10.}$	240	comfort
	long	$EC_{40.}$	480	comfort
Rut depth			16 mm	safety
Side-way force			0.40	safety
Bearing capacity, remaining life			8 years	structure
Damage asphalt pavements			28.4 %	structure
Damage concrete pavements			20.0 %	structure

In connection with these intervention levels it is important to point out a few principles:

The intervention values for the longitudinal evenness are based on the existing regulations for the row of 3 meter for short wave-lengths, and for the viagraph for the medium wavelengths. The value for the long wavelengths has been determined by analogy.

The intervention value for the transversal evenness was determined as the value of the rut depth, that with a normal cross fall of 2%, causes a water stagnation of 1 mm.

The value of the skid resistance is of course a safety value, in which the existing requirements for new roads and the differences between the measurement machines are taken into account. In Belgium the requirement for newly-built roads is a minimum of 0.45 .

The intervention levels for the bearing capacity and damage are of a completely different kind. The limits are determined in such a way, that the values are obtained, for an ideal road construction, when 60% of the expected design life is over, so a remaining life of 8 years on a 20 year lifetime basis.

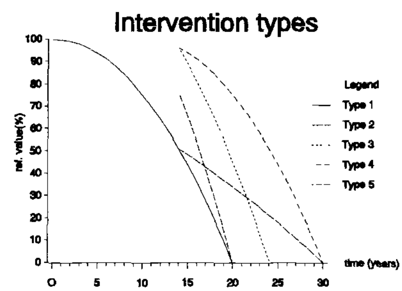
Naturally, all of the evolution values and intervention levels can be expressed as indexes. These indexes make it easier to compare values. The intervention index for each value is chosen to be 0.40

V. POSSIBLE INFLUENCES OF THE REPAIRS

In order to be able to judge the consequences of a technical intervention, a working group has studied about 25 possible interventions. For each pair (intervention, parameter) they have evaluated influence of this intervention for the measured (to be measured) parameter. After the analysis it has been shown that the influence can be classified in 6 types. This is shown in the next figure.

TYPE 1. There is no influence of the intervention on the parameter. Example: surface dressing on the rutting.

TYPE 2. There is no immediate influence, but the intervention has a delaying effect on the evolution.
Example: the treatment of crack formation has no immediate influence on the evenness, but it will delay the evolution.



TYPE 3. There is an immediate improvement of the parameter, but there is no real improvement of the road. The evolution curve is moved vertically.
Example: the local repair of a damaged pavement of a road decreases the damaged pavement without changing the future evolution of that road (outside the local repairs).

TYPE 4. There is an immediate improvement of the parameter and an improvement of the future behaviour. The evolution curve is moved horizontally. Example: An overlay immediately improves the bearing capacity of the road and its future behaviour.

TYPE 5. There is a momentary improvement, but the total lifetime does not change. Example: A surface dressing will reduce the observed cracked surface to 0%, without lengthening the lifetime (as long as the intervention is done at the beginning of the lifetime).

TYPE 6. The evolution of the considered parameter after the intervention is completely independent from the one before the intervention.
Example: The evolution of the skid resistance after a surface dressing is completely independent from the one before the surface dressing.

VI. OVERLAY DESIGN.

The overlay design is the module that determines when, where and what has to be executed. At the same time the costs will be estimated. We limit ourselves to the non-rigid pavements, this means the bituminous pavements with a non-bound road base/foundation.

Based on the experience of the B.R.R.C. (Belgian Road Research Centre) and the Ministry of Public Works, now the Department for

Environment and Infrastructure, it was possible to make a correlation between the measured deflection and the lifetime (total number of standard axles).

We have obtained the following equation: [5,6,7]

$$N_t=11.25*10^{12}/d^{(10/3)} \quad (7)$$

where : d = characteristic deflection (1/100mm)
N_t = total number of standard axles (80kN)

If we represent the different road sections in points (traffic/deflection) we can immediately see the road sections which are too weak (above the curve) and those who don't need any reinforcement (overlay) (under the curve).

It is evident that the concept of "End of lifetime" is not a rigid one. We use the lifetime as the period which gives a 50% damage. Of course other values can be used. This will change the constant value (11.25) in the equation.

VI. 1. Overlay and deflection

In order to evaluate the overlay, we use the reduction of the deflection as a criterion. [8]
For the prediction we use the following equations:

$$d_a = d_b * 10^{(-e/500)} \quad (8)$$

or , solved to e

$$e = 500 * Log(d_b/d_a) \quad (9)$$

where : e = thickness of the overlay (mm)
d_b = characteristic deflection before the overlay
d_a = characteristic deflection after the overlay

Of course, the value 500 is only a mean value and the real value depends on the qualities of the asphalt mix.

It is also necessary to know that this equation is only valid for overlay thicknesses up to 150, maximum 200 mm.

VI.2. Cracking

From the many observations, under the Belgian conditions (climate, materials, traffic), we could deduct that, for an asphalt pavement on an unbound base, the degree of cracking follows the so-called logistic curve (S-curve).

$$S=100/(1+64^{-\log(n/N_t)}) \quad (10)$$

where S = damaged part (%)
n = real traffic (up to now)
N_t = total traffic

Values of S(x) for some values of $x=(n/N_t)$

x	.20	.40	.60	.80	1.0	1.2
S	5.2	16	28.4	41.8	50	60

VI.3. Relative thickness and damage factor

The traffic deteriorates the pavement. The evenness will change and so will the dynamic behaviour. There will be some cracking and as a consequence the deflection will increase.

Experience has proven that there is a relationship between damage (cracking) and effective thickness as shown in table 3. [6]

table 3 -- equivalency factors

description	E_i (MPa)	factors $b_i=(E_i/10000)^{(1/3)}$
new pavement	10000	1.00
old pavement, without cracking	7800	0.92
old pavement, with isolated cracks	4000	0.74
old pavement, with many cracks	1700	0.55
old pavement with alligator cracks	500	0.37
unbound granular material (subbase)	200	0.27
poor material	150	0.24

VI.4. Evolution of the deflection

The equation (8) enables us to evaluate the change in deflection for a given overlay thickness. This overlay thickness can be positive (real overlay) or negative (cutting). We use the last in the model.

The effective thickness of a pavement is given by the following equations:

$$H_{eq} = b_1*H_1 + b_2*H_2 + b_3*H_3 + \dots \quad (11)$$

$$H_{real} = H_1 + H_2 + H_3 + \dots \quad (12)$$

$$\text{DELTA } H = H_{real} - H_{eq} \quad (13)$$

where H_{eq} = the equivalent thickness (mm)
H_i = the thickness of layer i (mm)
b_i = the equivalency factor of layer i
H_{real} = the total real thickness of the layers (mm)

The new condition (S=0%) gives $b_i=1$
The total damaged situation (S=70%) gives $b_i=0.37$

The combination of the values from the table 3 gives us

$$\text{DELTA H} = .63*H_{real}*(S/70)^{EX} \quad (14)$$

where DELTA H is the thickness reduction for a given damage factor.

In this evaluation of the weakening of the pavement due to the cracks, it is taken into account that less cracking (% low) also means that the cracks are less significant. This is expressed in the model in a link between S (damaged surface %) and b_i (equivalency factor). The exponent EX is commonly equal to 1, but can be used for agreement between the prediction and the reality.

In order to be able to evaluate the characteristic deflection (m+2s) of a road section, the model makes a statistical combination of the cracked and the uncracked surface. We also suppose that the probability to make a measurement near a crack is proportional to the amount of cracks.

This is given in the formulas :

$$d_a = d_b * [c*(1+a*b) + c*SQRT(F)]/(c+2) \quad (15)$$

and

$$F=b(1+a)^2 + (1-b)[1+a^2*b^2*c^2*(2-b)] \quad (16)$$

where

- a = the relative change in deflection for the completely cracked situation (S=70%), based on equations (14) and (8)
- b = the cracked surface
- c = the ratio between the mean deflection and its standard deviation of the uncracked situation (normally = 3)
- F= a function of (a,b,c)

VI.5. Overlay design

The basic principle of the overlay thickness design is the reduction of the measured deflection to the value derived from the equation 8 and made by the equation 17.

$$d=(11.25*10^{12}/N_t)^{.3} \quad (17)$$

The following data must be available to make the calculation:

1. Pavement thickness. A crack in a relatively thick pavement gives a bigger relative change of the deflection.

2. The traffic volume, and more precisely the heavy traffic. In order to determine the traffic by the number of the commercial vehicles we suppose the axle load spectrum to be known.[5]

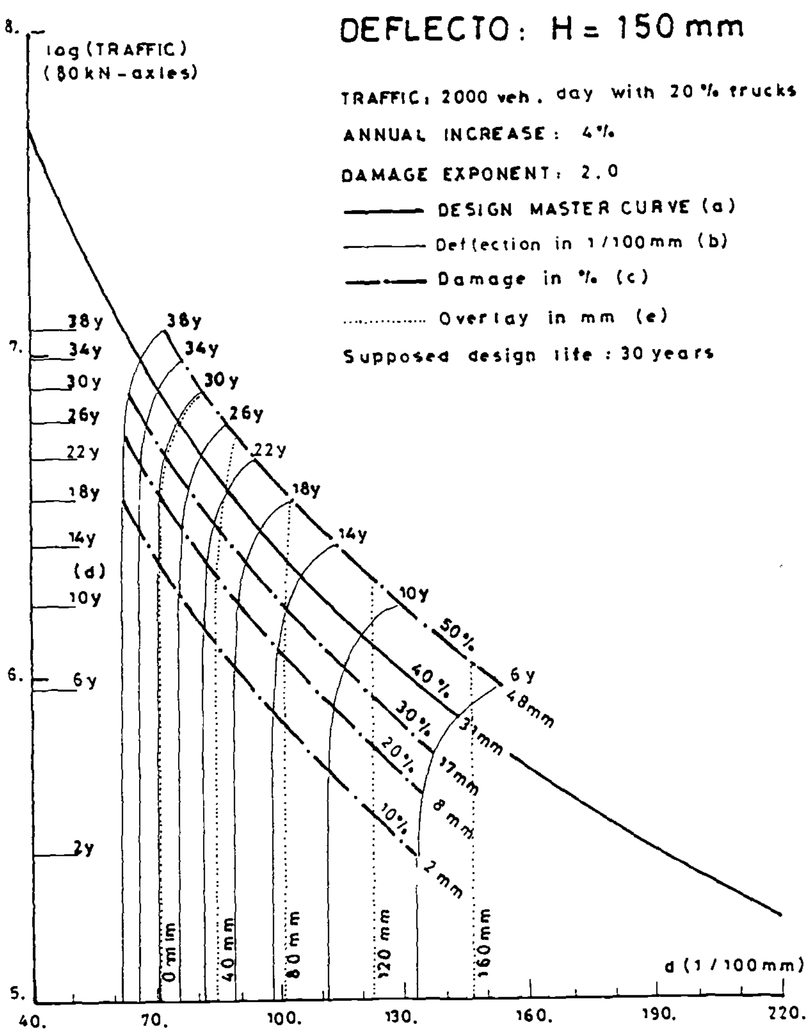
   For the Belgian condition and with the damage exponent of 4.17 we can state that 1 commercial axle means 0.61 standard axles.

One commercial truck a day means 411 standard 80 kN-axles in a year. This value is obtained for 250 working days/year and a mean of 2.7 axles for each truck or 675 commercial axles a year.

3. The age of the pavement and the cracked surface. (years)

4. The measured characteristic deflection. (1/100 mm)

All the calculations can be represented on the following drawing.



a. master curve
b. the evolution of the deflection versus time (traffic)
c. constant damage (curves of ...)
d. time (traffic)
e. constant overlay (curves of ...)

From the curves b and c we can conclude that the overlay thickness is independent of the moment of application, as long as the damage is small. If the damage is higher than 30% there must be an extra thickness to compensate for the differences between the real damage and the normally expected damage.

The values 0, 40, 80, 120 and 160 mm are the necessary overlay thicknesses. The values 2, 8, 17, 31 and 48 mm are the DELTA H values based on the equation (14).

VII. REPAIRS OF RUTTING

The examination of many cases of rutting in Belgium learned that it was almost never a design problem.

Most cases are a result of MIX design, and the only real solution is the removal of the bad material and the spreading of new layers.

Unfortunately we do not have a system that can tell us the quality of the asphalt layer without taking samples from the road. On the other hand we can determine the section where we suspect rutting problems, based on early measurements.

The Department uses the Traffic Simulator to test the different layers of the suspected road sections, and determine thus the "bad" layers.

There are two possibilities

1. The problem occurs in the top layer (depth < 10 cm).
   The top layer(s) must be replaced by new layers.

2. The problem occurs in the lower layers of the pavement (depth > 10 cm)

   This is a more complicated problem. Of course, the only real solution is the replacement of all the layers down to the depth of the bad layer, but this is not often possible for financial reasons.

   So, in most cases, there will be an inlay of a certain thickness. The risk, for a new rutting problem, depends on the traffic and the position of the bad layer and the quality of the new layer.

VIII. REPAIR ON SKID RESISTANCE

The solutions for the Skid Resistance are independent of structural problems. So all treatments, starting with cleaning, over surface dressing to an inlay or thin overlay are possible.

IX. CONCLUSIONS

The necessity of a rational system for the maintenance and the management of the road network is no longer doubted.
The disposal of valid data is a condition sine qua non for a rational maintenance system.

The global evaluation can be done by apparatuses with high capacity. The measurements are made every 2 years. This global approach makes it possible to locate the road sections which will be critical in the years ahead.

Those critical sections will be examined in a more detailed way on the project level. The detailed evaluations enable the Road Administration to make an optimal maintenance program.

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G. Norman Clark and Raymond K. Moore

A CRITICAL ASSESSMENT OF PAVEMENT MANAGEMENT STANDARDIZATION

REFERENCE: Clark, G. N. and Moore, R. K., "A Critical Assessment of Pavement Management Standardization," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: All aspects of implemented pavement management systems (PMS) cannot be standardized. However, several candidate areas for standardization related to pavement performance monitoring appear promising. These include the definitions of roughness, distress severity, and distress extent. Standardization may be useful for specification of equipment capability in measuring pavement roughness and distress. This does not imply that all agencies should use the same distresses as the critical parameters for triggering maintenance or rehabilitation actions. The KsDOT experience has clearly affirmed the necessity that a PMS be adaptable to the way a highway agency does business. A PMS may have specific standard parts or modules, but these must work within the existing agency planning and programming framework. Other generic standardization opportunities include PMS generated "products" (reports and data summaries) and PMS development and implementation steps.

KEYWORDS: Pavement management, pavement management systems, standardization, roughness measurement, distress evaluation, implementation

INTRODUCTION

The Kansas Department of Transportation (KsDOT) Pavement Management System (PMS), developed by Woodward-Clyde Consultants, uses a

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"total system approach" and is comprised of three major computerized components:

1. Pavement Management Information System (PMIS)
2. Network Optimization System (NOS)
3. Project Optimization System (POS)

Although this particular PMS is mathematically and computationally complex, it was selected because the allocation of funds over the 11,000-mile highway system for the necessary pavement preservation and rehabilitation actions can be optimized to improve the overall performance of the system. In addition, site-specific project design criteria must conform to the conditions established by the network analysis which optimizes pavement performance on a state-wide basis.

The PMIS has been used since 1982 to organize, manipulate and manage roughness and distress survey data used to define annual pavement network condition. The NOS, which models the highway network as a Markov decision process and uses large scale linear programming to optimize allocation of expenditures, assists KsDOT management in developing annual and multi-year pavement preservation and rehabilitation programs and has been fully implemented since 1986 [1-4]. The POS, which uses an integer programming approach, is currently being tested with planned implementation by 1992 [5].

Standardization is discussed herein with a perspective shaped by KsDOT experience in implementing this particular PMS. Furthermore, network level issues will be the focus of the paper since KsDOT has significant experience using the NOS. As previously stated, the POS has not been fully implemented.

PAVEMENT CONDITION SURVEYS

Three components of the pavement condition survey process have potential for standardization. These relate to (1) roughness measurement, (2) distress identification and rating, and (3) friction measurement. Although friction measurement data are not directly used in the KsDOT PMS and will not be discussed within the context of this paper, pavement surface skid resistance properties have significant potential for standardization.

Roughness Measurement

The definition of roughness and the method of measurement are prime candidates for standardization. From a historical perspective, roughness has been quantified using both subjective estimates (e.g. rating panels) and objective measures obtained from various types of roughometers and profilometers.

KsDOT measures roughness using a calibrated towed Mays ride meter, a response-type road roughness measuring system. Mays ride meter roughness is expressed as the accrued inches of vertical axle displacement per mile of vehicle travel. The displacement data are obtained from a transducer that detects small increments of axle movement relative to the vehicle body [6]. This simple single-statistic measure of pavement roughness has been correlated with present serviceability of in-service Kansas pavements using both 3-point and 5-point subjective rating scales [7]. However, the vertical displacement is not a direct function of the actual longitudinal pavement profile as would be measured by a profilometer, but is a measure of Mays ride meter response to that profile. The response is not unique but is affected by several equipment dependent factors, the speed of travel, hysteresis error, quantization error, and pavement type [6,8].

KsDOT is currently investigating equipment which provides a more direct measurement of roughness using the actual longitudinal pavement surface profile. While response type roughness instrumentation offers a relatively inexpensive means to obtain a roughness statistic, pavement profilometer devices can measure roughness using more precise data including pavement texture and surface characteristics.

The reduction of error associated with replicated measurements is also desirable, especially when evaluating pavement segments that have roughness values at or near a boundary of qualitative roughness categories (e.g., good, deteriorating, deteriorated using KsDOT terminology). For example, KsDOT classifies pavements segments with less than 60 inches per mile in the good category. Because of the replication error associated with the KsDOT Mays ride meters, a pavement section must exceed 65 inches per mile <u>to change</u> from the good category to deteriorating rather than use the 60 inches per mile boundary definition.

KsDOT also sees a definite advantage in using a standard roughness definition that would not be affected either by pavement type (e.g., flexible, rigid, composite) or by an interpretation based on extent or severity of distress. For example, flexible and rigid pavement distresses have fundamental differences which must be considered when evaluating Mays ride meter data. A standardized procedure for roughness measurement in conjunction with standard roughness statistics would allow direct comparison of roughness data associated with pavement design, construction, and maintenance practices of other states and countries. The comparison of data collected on the Federal Highway Administration HPMS (Highway Performance Monitoring System) pavement test sections in the United States would become a more valid exercise. It would also allow the influence of different maintenance and rehabilitation actions used by various states to be evaluated relative to their cost effectiveness in extending satisfactory pavement performance, assuming that roughness makes a significant contribution to present serviceability.

The International Road Index, IRI, appears to have these advantages. The IRI, developed as an outcome of the International Road Roughness Experiment in Brasilia, Brazil, is based on simulation of the roughness response of a car travelling at 80 kilometers per hour. IRI is the Reference Average Rectified Slope, which expresses a ratio of the accumulated suspension motion of the vehicle, divided by the distance travelled during the test. IRI uses a mathematical quarter-car simulation as a reference rather than a particular type of equipment. IRI can be computed from data obtained by many profilometric methods, is highly correlated with output values from various response-type road roughness measuring devices, and with subjective opinion [9]. However, if IRI were to be adopted by KsDOT in conjunction with utilization of a high-tech highway speed profilometer, research would be needed to develop the transfer function to convert the Mays ride meter data in the PMIS to estimated IRI data to preserve roughness data continuity in the historical record.

Distress Evaluation

The evaluation of distress is a critical component of pavement condition surveys. Distress can be rated in terms of severity and extent. The KsDOT distress rating system is based on the evaluation of rutting, transverse cracking, fatigue cracking, block cracking, faulting and joint distress. These distresses are caused by a combination of traffic, environmental, and materials factors and are the most prevalent observed in Kansas. The "key" distresses within a PMS can not and should not be standardized since they will differ geographically as traffic, environmental, and material factors vary. The present KsDOT system used to rate distress extent and severity does not directly correspond with other recently published systems (e.g., Appendix K, 1986 AASHTO Guide for Design of Pavement Structures [10] or the 1990 Strategic Highway Research Program Distress Identification Manual for Long-Term Pavement Performance Studies [11]). However, the rating of distress severity and extent does have the potential for standardization. At present, the SHRP LTPP Distress Identification Manual [11] appears to have promise since it was designed to be used in the ongoing nationwide long-term pavement performance study.

PMS COMPONENTS

The AASHTO Guidelines for Pavement Management Systems [12] describes a PMS as a connected system of components:

Database-at a minimum, composed of data required for PMS analysis with a direct connection to the feedback process.

Analysis Methods-algorithms to analyze pavement performance and cost data and to identify cost-effective MR&R treatments and strategies; at a minimum, the PMS should have one of the following modules: (1) a pavement condition analysis module, (2) a priority assessment model module, (3) a network optimization model module.

Feedback Process-algorithms to verify and improve the reliability of PMS by comparison of actual cost, pavement performance, and project implementation data to predicted or projected data developed using analysis methods.

This general system description is composed of the basic generic components associated with a contemporary PMS, but does not specify the exact nature of each of the modules. In essence, these 1990

AASHTO Guidelines [12] provide a framework which can be used to test a proposed PMS against a set of standard requirements, but allows a state highway agency to select the specific algorithms.

A major requirement for the analysis methods module is the ability to look ahead. Therefore, prediction models are required. For instance, the KsDOT PMS was selected on the basis of the ability of the NOS to recommend an optimized set of pavement preservation actions considering the present and projected performance condition of the entire 11,000 mile state highway system. Hence, the development, testing, and revision of prediction models are major aspects of PMS implementation and operation. Standardized prediction models do not exist. In function form, prediction models can vary from polynomial statistical regressions that estimate future specific parameters to Markov transition matrices which define probabilities of change.

The ability to optimize was also a major KsDOT criterion, although an inherent disadvantage would be the conceptual, software, and operational complexity of the PMS. However, the KsDOT PMS has all of the capabilities described in the AASHTO generic model and uses them to develop the necessary "products".

PMS PRODUCTS

The 1990 AASHTO Guidelines [12] provide an example list of "products", which in a computerized information system are reports designed for highway agency management and engineers, transportation policy and oversight boards or commissions, state legislators and executive officials, media, and other public interest groups.

1. Current condition of the highway system, subdivided by pavement segment

2. Budget requirements to meet current and future performance objectives

3. Current and projected pavement system condition as a function of various budget alternatives

4. Site specific maintenance, rehabilitation, and reconstruction (MR&R) actions

5. Analyses to illustrate the consequences of changed budget allocations, performance goals, or pavement preservation actions

6. Priorities for allocating funds for MR&R actions on a pavement segment basis

7. History of MR&R actions by pavement segment and year

8. Historical cost of MR&R actions by pavement segment and by year

9. Summary of traffic by route and location

10. Estimated MR&R costs by pavement segment

These reports are major tangible benefits associated with PMS implementation because management is able to formulate, justify, and explain network-level program and budget decisions. Of the list given above, the KsDOT PMS does not provide priorities for allocating funds on a pavement segment basis (number 6) because the available budget is optimally distributed across the system. The KsDOT does not produce the historical cost of MR&R actions (number 7) either because no record-keeping system is presently in place which can produce specific costs by pavement segment. The documentation of costs associated with routine maintenance is especially challenging if pavement segment detail is required.

The KsDOT PMS can produce each of the other report types, but the most widely distributed report is the annual NOS pavement condition survey completed during the spring and early summer and published in August of each year. This report incorporates traffic, roughness, distress condition, distress state, and performance level data for each pavement segment (typically one mile in length) on the state system sorted by each of the six KsDOT Districts. This report is an example of how some of the ten "product" categories can be merged within a single document.

The KsDOT PMS group also responds to a multitude of report requests from management in which different combinations or information are assembled and printed. Often, these requests are "one of a kind" and require new software to be written before the report can be composed and printed. Thus, neither the specific reports nor their formats can or should be standardized.

A major complexity in the KsDOT NOS highway program development phase is converting the recommended maintenance actions on a one-mile pavement segment basis into projects. At the present time, a pavement management engineer develops feasible projects from a series of sequential pavement segments using experience and professional judgment with a set of basic agency rules (e.g. minimum project length). This process is a candidate for standardization within the agency through the development of a knowledge-based expert system.

PMS FUNCTION WITHIN AGENCY ORGANIZATION

The KsDOT PMS group (headed by a pavement management system engineer) is assigned to the Geotechnical Unit, which also has responsibilities for surface and subsurface geotechnical (geology and soils) investigations, analysis and interpretation; foundation and retaining wall design; and pavement design. Although the PMS function represented a logical extension of pavement design responsibilities within the Geotechnical Unit, other important prerequisites were also in place. The pavement management function required expertise in pavement condition evaluation, equipment support, computer system software and hardware support, and applied mathematics/statistics. The Geotechnical Unit had on staff the nucleus of a team of professional engineers and engineering technicians who could handle these complex tasks.

The Geotechnical Unit reports to the Chief of Materials and Research, who in turn reports to the Director of Operations. The Director of Operations reports directly to the State Transportation Engineer. Since the Geotechnical Unit has been traditionally responsible for pavement engineering activities, the location of the PMS group within this administrative unit in the Bureau of Materials and Research has functioned relatively well because it has received the necessary budgetary and equipment support from the higher administrative levels within KsDOT. Communication with the Division of Planning and Development has also been important because of the interdependency related to the data base and the development of the annual and multi-year highway programs for management. Although this scheme has worked well for KsDOT, the standardization of the location of PMS group within state highway or transportation organizations would be unwise and imprudent. Each agency should have the flexibility to incorporate PMS within its organization on the basis of its successful historical operating practices.

PMS IMPLEMENTATION SEQUENCE

The 1990 AASHTO Guidelines [12] recommend a seven step implementation sequence.

1. Decision to develop and implement a PMS
2. Organize a steering committee
3. Appoint a PMS staff
4. PMS selection or development
5. PMS demonstration on a limited scale
6. Full scale implementation
7. Follow up and feedback

KsDOT essentially utilized this procedure with success. A steering committee was initially formed and this developed into a task force composed of individuals from both the Geotechnical Unit and the KsDOT districts. The task force completed several technical assignments (e.g., studies related to the selection of appropriate maintenance actions for specific distress states, the assignment of specific distress states to performance categories, and the utilization of rating panels to correlate Mays ride meter roughness to subjective opinion) required during the development and limited PMS demonstration phases. As previously stated, the NOS is fully operational and the POS is currently at step 5 with testing being conducted prior to full scale implementation by 1992. The follow up and feedback phase has been fully implemented.

CONCLUSIONS

The KsDOT experience nine years into an implemented PMS suggests that the potential for standardization exists for:

(1) measurement and definition of pavement roughness

(2) evaluation and rating of pavement distress

(3) generic definition of standard pavement management "modules" which define functional activities

(4) generic definition of PMS products

(5) implementation steps

It does not appear either feasible or desirable to standardize the following:

(1) selection of "key" roughness or distress parameters that trigger MR&R actions

(2) selection of specific MR&R actions for specific pavement roughness and distress conditions

(3) specific definition of algorithms or models used for pavement condition analysis, priority assessment and network optimization

(4) specific formatting or definition of PMS products

(5) specific location of the PMS function within a state highway or transportation organization

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INNOVATIONS IN PMS - STATE OF OHIO & KINGDOM OF SAUDI ARABIA

REFERENCE: Harper, W. V. and Majidzadeh, K., "Innovations in PMS - State of Ohio & Kingdom of Saudi Arabia," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: Two different Pavement Management Systems (PMS) are discussed in this paper. One developed for the Ohio Department of Transportation (ODOT) has deterministic degradation models based on historical data. The ODOT system is optimized using a 0-1 optimization. This is solved using linear programming techniques including generalized upper bounding to considerably improve the computational efficiency. The second PMS discussed is part of a Highway Maintenance Management System developed for the Kingdom of Saudi Arabia that integrates a PMS, a Bridges & Structures Management System, and a Nonpavement Management System. It is a stochastic optimization system using initial prediction models partially based on expert opinion. The Saudi Arabian system is a Markovian based optimization that uses Lagrange methods to link together the various strata within the system. The use of Lagrange methods combined with parametric programming efficiently solves very large problems. An algorithm is presented for updating degradation models for pavements. Bayesian statistical procedures are given that automatically update the degradation models with new survey data. These procedures continually self-adjust the PMS to fit the specific conditions found in the network. This results in improved prediction models and a better utilization of resources.

KEYWORDS: pavement management, optimization, statistics, Bayesian updating

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INTRODUCTION

A PMS should be able to predict the future degradation of the pavement as well as the improvement that results from a particular maintenance action. This ability to predict may depend on many parameters and may be the result of empirical, mechanistic, or empirical-mechanistic models. To provide a network level solution, the condition prediction models must depend on readily available information on every segment in the network. Test results that will be available for only a small portion of the network may be used in a project level analysis, but such information often cannot be incorporated into a network optimization model.

Condition prediction models usually are based on actual field data relevant to the network being modeled. A Pavement Management System requires a well planned database management system. Even with such a database, degradation models are not always readily available for a given network even in well developed countries.

Selected aspects of two different PMS are briefly covered in this paper. One developed for the Ohio Department of Transportation has deterministic degradation models based on detailed statistical analysis of historical data. The ODOT PMS (Reference [1]) predicts Pavement Condition Rating (PCR) deduct values for a given pavement segment strategy considered in its network optimization. The second PMS discussed is part of a Highway Maintenance Management System (Reference [2]) developed for the Kingdom of Saudi Arabia that integrates a PMS, a Bridges & Structures Management System, and a Nonpavement Management System. It is a stochastic optimization system based on minimal historical data. It predicts the probability of a pavement segment transitioning from condition state "i" to condition state "j" for the feasible Maintenance & Rehabilitation (M&R) actions.

ODOT PMS

The ODOT network level optimization model is an integer 0-1 linear program that is approximated by a standard linear programming (LP) solution using Generalized Upper Bounding (GUB) techniques. The use of the GUB in the standard LP allows very large 0-1 problems to be solved quickly. For the few non-integer solutions (theoretically there will be only a small number, Reference [3]), these require a project level choice by the decision maker.

The Pavement Condition Rating (PCR) is one of the key ODOT factors in determining both the condition of given segment as well as the condition of the entire network. The PCR is a weighted average of many distresses, e.g., ravelling, bleeding, patching, rutting, cracking, etc. Expert opinion from both ODOT and other pavement engineers was used to develop lumped distress groups. Based on the severity and extent of these lumped distress categories, feasible M&R actions were selected for the different pavement types (rigid, composite, flexible, and CRC) using a panel of experts.

The ODOT PMS develops six-year plans for each segment within the state-wide network. The plan is an ordered set of 6 M&R actions. Only a limited number of "applicable" plans can be associated with each segment while maintaining the entire highway system in "satisfactory condition". Expert opinion was used to construct an expert system (described below) that develops the potential six-year plans on a segment by segment basis. These feasible plans are then input to the optimization. Based on the available budget and desired performance goals specified, the optimization selects one of the individual segment feasible plans for each segment. The optimization will either maximize performance (in terms of PCR) subject to budgetary limitations or it will minimize cost subject to performance constraints.

It should be emphasized that the feasible six-year plans are developed independently for each highway segment and thus represent the possible plans from a project-level point of view for a given segment. The optimization then selects one plan for each segment that is optimal from a network perspective. Thus the plan chosen for a given segment was determined considering all segments in the network simultaneously. This is something that could not be done without the use of sophisticated optimization packages. An engineer can consider the possible six-year plans in isolation for a segment, but it would not be possible for that individual to perform the trade-offs necessary to arrive at a network optimal solution. This expert system also reduced the solution space considerably and has resulted in lessening the computational burden.

ODOT's Determination of Feasible M&R Action Plans

Conceptually, the PMS network optimization models could allow the possibility of assignment of any M&R action to a pavement segment. While this would not theoretically cause any difficulties, it may create problems in practice. It is often mandatory to follow agency policies which may not permit certain M&R actions for pavement segments in given conditions. Thus it is reasonable to develop an expert system for the network level selection procedures that determines the feasible M&R alternatives that will be available to the optimizer.

The PCR for a given segment is the sum of weighted deduct values representing the severity and extent of many pavement distresses. Table 1 shows how these individual distresses are lumped into categories for the four ODOT multi-lane pavement types. Jointed Concrete, for example, has 3 lumped distress categories - surface, joint 1, and joint 2. Table 2 defines the possible M&R actions that may be applied to a segment in a given year. Table 3 gives the feasible M&R actions for jointed concrete as a function of the severity and extent of these lumped distress categories. As seen in Table 3, this is further divided into interstate or non-interstate multi-lane.

Table 3 is used to select the maintenance actions that would be appropriate for each of the different distress groups. The individual distresses are combined, and based on expert opinion established limits (Reference [1]) the lumped distress categories are characterized by severity and extent.

TABLE 1 -- Composition of PCR groups for different pavement types.

FLEXIBLE	COMPOSITE*	JOINTED CONCRETE	CRC
Structural 1:	Surface 1:	Surface:	Pavement:
- potholes	- ravelling	- surface deterioration	- patching
- bleeding	- popouts	- pumping	
- settlement	- longitudinal cracking	- settlement	- settlement
Structural 2:	- crack sealing	- longitudinal cracking	- transverse cracking
- rutting	Surface 2:	Joint 1:	- longitudinal cracking
- wheel track cracking	- rutting	- pumping	- punchout
- block and transverse cracking	- debonding	- faulting	Surface:
- corrugation	- settlement	- transverse cracking	- spalling
Surface:	Joint 1:	- corner break	- pressure damage
- ravelling	- pressure damage	Joint 2:	
- bleeding	- patching	- pressure damage	
- random cracking	- pumping	- patching	
- crack sealing deficiency	- shattered slab	- joint spalling	
- longitudinal cracking	Joint 2:	- seal damage	
- edge cracking	- transverse cracking		
	- joint reflection cracking		
	- other reflection cracking		

* Either jointed concrete or CRC covered with an asphalt overlay.

TABLE 2 -- Definition of M&R actions

Description	Action Code
Do nothing	000
Routine maintenance	010
Seal coat	020
Joint crack underseal repair	030
Concrete Pavement Repair	040
Non-structural overlay with minimum repairs	050
Non-structural overlay with repairs	060
Structural overlay with minimum repairs	070
Structural overlay with repairs	080
Crack and seat	090
PCC structural overlay	100
Reconstruction with flexible	110
Reconstruction with rigid	120
Reconstruction with composite	130

TABLE 3 -- Feasible M&R actions given the Extent/Severity classification of the distress groups for jointed concrete pavement.

Distress Group	Severity	Occasional	Extent Frequent	Extensive
			Multi-Lane	
Joint 1 & 2	Low	000	000	000
	Medium	010/070	010/070	010/070
	High	030/070	030/090/100	030/090/120
Surface	Low	000	000	000/010
	Medium	000/010	000/010	060
	High	050	060	060
			Interstate	
Joint 1 & 2	Low	000	000	010
	Medium	010/070	010/070	010/040/080
	High	030/080	040/090/100	040/090/120
Surface	Low	000	000	000/010
	Medium	000/010	000/010	060
	High	050	060	060

As an example, let a given segment of jointed concrete interstate have medium severity and extensive extent for both joint 1 and joint 2. This segment also has low severity and occasional extent for surface. These values result in actions 010, 040, and 080 for joint 1 and joint 2, and 000 for surface. Thus, the possible actions for this pavement are 000, 010, 040, and 080. (The possible actions from each distress group are rank-ordered and duplicates eliminated.) Of course, only action 080 (structural overlay with repairs) would repair all problems, but the other actions cannot be ruled out as being cost-effective when considering a multi-year planning period and a finite money supply.

The above scheme has resulted in reducing the possible number of actions from 14 to 4 in the example given, although some combinations of pavement distresses may result in more actions. Only the highest 4 actions are chosen if this list also contains actions 000 or 010 (do nothing or routine maintenance); if one of these actions is not part of the list, action 010 is inserted as a fifth action - this is necessary in order to deal with budget constraints.

The same procedure is used in other years of the planning horizon. First, the condition of the pavement one year after applying a particular action is predicted using PCR performance prediction models; then the appropriate tables are used to determine the proper actions for these (new) conditions. This procedure is carried out for each year in the planning period, except that the number of actions is restricted to 3 (or 4 if action 010 has to be added) for the second year and 2 (or 3 if action 010 has to be added) for the third through the sixth years.

Although the above procedure has drastically limited the number of possible action plans for a particular pavement segment, the resulting number of plans (a maximum of 1620 plans are possible) is still too large to be practical either in real life or as far as the optimizer is concerned. Therefore, a set of heuristic rules has been developed to further reduce the number of possible plans to be considered by the optimizer. These rules given below have been developed in consultation with ODOT design and maintenance engineers.

Define:

k_n = number of actions in year n
C_n = pavement condition at the beginning of year n
A_n = action taken in year n
P_n = PCR at end of year n (after action A_n taken)

The rules used to reduce the number of action plans are presented in Table 4. The rules to reduce the possible number of actions for year n+1 are applied according to Table 5 for year n. The following considerations apply:

i. Actions A_n are selected based on pavement condition C_n as described above; note that the maximum number of actions is 5 for the first year, 4, for the second year and 3 for the subsequent years (see rule 3 of Table 4).

ii. If action $A_n \geq 050$, $P_n = 100$; otherwise only those distresses directly addressed by action A_n are eliminated.

iii. Using action A_n, the amount of distress in each distress group expected in year n + 1 is predicted from the PCR performance prediction equations. The condition C_{n+1} is obtained from the condition C_n and the predicted distresses developed during <u>one</u> year.

iv. For mandatory projects $k_1 = 1$ and the action is that specified for the mandatory project for year n = 1. Actions for years n>1 can be selected in the normal fashion or the entire action plan over the planning period can be input as mandatory.

This expert system has been extensively tested and validated. It is an important part of an efficient multi-year PMS that also provides guidance to the project level analyses that follow the completion of the optimization runs. Complete documentation of the entire system is given in reference [1].

TABLE 4 -- Rules for reducing the possible number of action plans.

Rule No.	Rule
1.	If year n action $\geq$ 020, year n+i action $\leq$ 010, i = 1,3
2.	If year n action $\geq$ 040, year n+i action $\leq$ 010, i = 1,5
3.	The maximum number of actions considered each year are k_1=4, k_2=3, k_3 to k_6=2 if either action 000 or 010 are among the feasible actions; otherwise action 010 is added to the list and the maximum number of actions is increased by one.
4.	If year n action is m$\geq$ 020, year n+i action cannot equal m; i = 1,4.

TABLE 5 -- Application of rules for year n to determine feasible actions for year n+1

Year n action	Apply rule(s)
000/010	None
020	4,1
$\geq$ 040	4,2,1

Note: If $k_{n+1} = 0$ as a result of applying the above rules, then $k_{n+1} = 2$ and actions are 000 and 010

SAUDI ARABIAN PMS

The Saudi Arabian PMS uses a different approach that is more applicable to the situation with limited historical data. The Saudi PMS uses a stochastic network level optimization based on a Markov process and automatically updates its condition prediction models using Bayesian procedures discussed later. Three network level linear programming (LP) models are used in this PMS.

The first is a long-term (or steady state) goal setting model. It determines the optimal condition states of the network so that cost is minimized subject to top management's performance objectives. In all three models (solved for each stratum) top management specifies lower and upper bound constraints for the minimum proportion and maximum proportion of the stratum that should be in desirable and undesirable condition states, respectively. Strata are used to divide the network into pavement that have similar characteristics, e.g., by functional class and climate.

The second network optimization model is the multi-year model that determines the optimal policy to move from the current network condition levels to the optimal steady-state levels determined by the long-term model mentioned in the previous paragraph. This model is also solved separately for each stratum. If the sum of the desired budget from all strata is within the amount that can be obtained, then this is the last model run in the sequence of the three optimization models. These first two models closely parallel the Arizona models (References [4,5]) that have become well known.

The third network model is a financial exigency model (Reference [6]) that ties together all the strata with a global first year budget constraint. This budget constraint links together the individual multi-year optimization models described briefly in the previous paragraph by the use of a Lagrange multiplier and parametric programming techniques.

Obviously, the computational burden of solving these three LP can be considerable. This is especially true of the latter two models that are large linear programs.

The notation for the multi-year model (briefly described above) objective function is defined as follows:

Parameter Notation:

$I = (1, 2, ..., n)$: Index set of condition states.

$M_i = (a_1, a_2, ..., a_{m_i})$: Index set of feasible maintenance actions "a" for pavement segments in condition state "i".

$C_{ia}(s)$ = Average cost of applying maintenance action "a" to one pavement segment in stratum "s" and condition state "i".

r = Discount rate for computing net present value.

Decision variable notation:

$w^t_{ia}(s)$ = Proportion of the segments in stratum "s" that is in condition state "i" and should receive maintenance action "a" in year "t".

Dependent variable notation:

$\hat{C}(s)$ = Expected net present value of cost per segment in stratum "s" of a maintenance policy.

The multi-year optimization model objective function for stratum "s" follows:

$$\text{Minimize } \hat{C}(s) = \sum_{t=1}^{T} \sum_{i \in I} \sum_{a \in M_i} (1+r)^{1-t} w^t_{ia}(s)\, C_{ia}(s) \qquad (1)$$

As seen above in Eq 1, the summation of the objective function is over time "t", condition states "i", and actions "a". However, note that instead of considering all possible actions "a", only those that are determined to be feasible (based on expert opinion) for condition state "i" are allowed as choices in the LP (as indicated by the summation over $a \in M_i$ instead of all possible actions).

Financial exigency model

The purpose of the financial exigency model is similar to that of the multi-year model, but it also incorporates a network budget constraint for the first year of the planning horizon. The financial exigency model combines all strata together through the first year budgetary constraint using Lagrange methods. It then decomposes the overall problem into individual stratum linear programming problems. The financial exigency model also allows the relaxation of the second year goals if necessary to meet the first year budget target. The following financial exigency model objective function in Eq 2 can be solved by determining the optimal value for the Lagrange multiplier α (Reference [6]). If necessary, there are three phases (Phase A, Phase B, and

Phase C) of the financial exigency model that can be used to find an optimal solution that will meet the available first year budget.

Minimize

$$\sum_{s \epsilon S} N(s) \sum_{i \epsilon I} \sum_{a \epsilon M_i} \{ \sum_{t=2}^{T-1} (1+r)^{1-t} w^t_{ia}(s)C_{ia}(s) + \alpha w^1_{ia}(s)C_{ia}(s) \} \quad (2)$$

Subject to: constraints of multi-year models for all "s" ϵ S

Let:

S = The set of all strata indices.
B = The available budget for the first year.
N(s) = Number of segments of structure in stratum "s".

Note: for $\alpha = 1$, this objective function is identical to the multi-year model.

Different values of α will yield solutions that expend different amounts in year one. If for a given α, the solution prescribes a policy that expends too much money in the first year, a new solution can be obtained for a larger value of α that will expend a smaller amount in year 1.

The value of α that produces the solution in which the total of all first year expenditures among the strata is as close to (but less than or equal to) the budget, B, results in a solution that is a globally optimal for the original financial exigency model (References [6],[7]). The first year budget is a monotonic decreasing function of α.

Parametric programming on the objective function allows the financial exigency problem to be solved with minimal computational burden. To make the financial exigency objective consistent with parametric programming features found in some LP packages the objective function in Eq 2 may be rewritten as Eq 3 below:

Minimize

$$\sum_{s \epsilon S} N(s) \sum_{i \epsilon I} \sum_{a \epsilon M_i} \{ \sum_{t=2}^{T-1} (1+r)^{1-t} w^t_{ia}(s)C_{ia}(s) + (\alpha_{min}+\theta) w^1_{ia}(s)C_{ia}(s) \} \quad (3)$$

Subject to: multi-year constraints for all "s" ϵ S

Thus α has been replaced by $(\alpha_{min}+\theta)$. For Phases A and B below, α_{min} = 1.0 while $\alpha_{min} < 1.0$ for Phase C. Then θ will range from 0.0 to θ_{max} (θ_{max} may be different for each phase) for the financial exigency runs.

Before describing the financial exigency algorithm, a brief summary of each phase is as follows:

Phase

A The year 2 goals are the same as the multi-year model.

B Relaxes the year 2 goals so that the current (based on the condition survey) percentages Desirable and Undesirable are maintained.

C Completely removes the year 2 goals and attempts to spend as much money as possible while meeting the network level budget.

The goals referred to above are the percentages Desirable and Undesirable that were set by top management for the multi-year model. One of the advantages of the three phases above is that it is not necessary to go back to top management and request revised goals. The above assumes the goals specified by top management had year 2 goals that improved on the current conditions found in the stratum. If this is not the case, then Phase B may be skipped.

The algorithm used for the financial exigency problem applies to all phases. θ_{max} is determined from initial runs of the PMS or may be set to an arbitrarily large number. Using parametric programming, the entire continuum is spanned. For any given level of θ, there is a total PMS budget, B_θ^{tot} that is calculated as follows in Eq 4:

$$B_\theta^{tot} = \sum_{s} N(s) \sum_{i \in I} \sum_{a \in M_i} w^1_{ia}(s)\, C_{ia}(s) \qquad (4)$$

All three phases use the same algorithm below to find the optimal solution (θ_{opt}, $B_{\theta opt}^{tot}$). The only difference between the three phases is in the second year performance goals as described above.

For $\theta = 0$ to θ_{max}

Compute B_θ^{tot}

If $B_\theta^{tot} \le B$ (available 1st year network budget)

Output $\theta_{opt} = \theta$, $B_{\theta opt}^{tot} = B_\theta^{tot}$
- This is the optimal solution.
Stop

Continue

It is possible that $B_{\theta max}^{tot}$ may not satisfy the desired first year budget constraint for Phase A. In this case, Phase B changes the second year performance goals to match those found from the current survey. Thus instead of endeavoring to improve the second year performance as it is anticipated will be the case for the multi-year (& Phase A), the stratum desirable and undesirable percentage goals are set to maintain the existing stratum conditions. Then the above algorithm above is used to search for an optimal solution to this modified set of year 2 goals for Phase B.

If Phase B cannot find a solution that meets the available budget, then more drastic measures are necessary. Phase C completely relaxes the second year goals, i.e., no second year goals exist in Phase C. For Phase C, $\alpha_{min} < 1.0$. An arbitrarily low value may be used for α_{min} or a reasonable value may be selected based on initial runs. The optimal solution is determined using the above algorithm.

Phase A above may not be able to reach a low enough first year budget because it has performance goals that must be met at the beginning of the second year. However, it is important to try to obtain those performance goals if possible. In the event that the goals must be relaxed, Phases B and C may be run. In Phase B, the second year goals are relaxed so that the status quo is maintained without any improvement in the network. If necessary Phase C completely removes the year 2 goals and will spend as much money as possible while still meeting the first year budget. Phase C varies the first year M&R action costs from very inexpensive [starting with α_{min} $C_{ia}(s)$] to more expensive [α_{max} $C_{ia}(s)$]. At the low end of this range, the first year expenditures will be high because of the apparent inexpensive M&R action costs. As α increases, the first year expenditures will decrease until finally the budget goal is met. Top management will have to examine the resulting performance and decide if additional funds should be requested.

Saudi Prediction Models

Expert opinion has played a major role in the development of the initial condition prediction equations for the Saudi PMS. An extensive search of the literature as well as use of mechanistic models was used to develop initial empirical regression equations. Due to the lack of historical field data, the initial regression equations could not be directly developed for actual Saudi conditions. Expert opinion from pavement engineers was used to modify published prediction models, where available, for the variables used to determine the condition state of each pavement segment in the Markovian-based network optimization models used in this PMS.

The Saudi PMS classifies a pavement segment into one of 324 possible condition states based on rutting, cracking, delta-cracking (one year change in cracking), index to first crack, and roughness. Three condition prediction equations are required for each M&R action within each stratum. Within the PMS, there are 20 possible M&R actions and various strata (based on functional class, climate, etc.). Condition prediction equations for the change in rutting, change in roughness, and change in cracking were developed. These predict the one year change in the corresponding distress for a given M&R action. The change in cracking prediction model is used to produce joint probabilities for cracking and delta-cracking. No prediction equation is required for index to first crack because it is a table look-up based on the chosen M&R action.

Past published work for a similar climate in the state of Arizona (Reference [5]) in the United States resulted in empirical linear regression models for cracking and roughness; however, the literature review could not find any similar empirical prediction equations for rutting. Stepwise regression analysis of available data combined with expert opinion was used to develop an empirical regression for rutting. A team of pavement engineers worked to modify these equations to adjust them as much as possible to conditions in Saudi Arabia.

Annual surveys will be performed for the entire pavement network in the Kingdom using the Swedish RST vehicle. This provides the field values for the variables above as well as others used at the project level, e.g., ravelling and skid resistance. These annual surveys provide the field data necessary to improve the prediction equations automatically using Bayesian statistical updating techniques.

Bayesian updating of condition prediction parameters

The condition prediction models mentioned above generate the transition probabilities that drive the Markov based linear programs. They also provide the prior distributions required for the Bayesian updating (Reference [8]). The regression parameters of the prediction models are self-adjusted using new annual survey data and result in improved transition probabilities. This automatic adaptation of the condition prediction models results in more accurate degradation estimates over time.

A general description of Bayesian updating of the regression parameters follows. The notation is generalized from the explicit equations used for the condition prediction of individual variables. The following notation is be used.

Y = Vector of dependent values, e.g., the data for the actual change in cracking.

X = Design matrix created from the independent variables, e.g., from the variables in the right hand side of a condition prediction equation.

b = Regression parameter vector to be estimated. These are the coefficients of the prediction models.

Then the least squares solution for the initial ("init") prediction equations is Eq 5:

$$\mathbf{b}_{init} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{Y} \qquad (5)$$

The prior distribution for the **b** is then a multivariate normal (MVN) as follows:

prior distribution of **b** is $MVN(\mathbf{b}_{init}, \mathbf{V}_{init})$

where:

$\mathbf{V}_{init}$ = Covariance matrix of $\mathbf{b}_{init}$

The above addresses the development of the initial prior distribution, i.e., $\mathbf{V}_{init}$ becomes the first $\mathbf{V}_{prior}$ and $\mathbf{b}_{init}$ becomes the first $\mathbf{b}_{prior}$. After each year t, the prior will be updated to develop a posterior distribution that will be used to calculate updated transition probabilities. Upon completion of that, the posterior distribution for year t becomes the prior distribution for year t+1. In the development of the posterior distribution below it is assumed that year t data has just been collected. From this, ordinary least squares parameter estimates for year t data (Eq 6) will be used to perform the Bayesian updating resulting in posterior parameter estimates.

For year t,

$b_t = (X'X)^{-1}X'Y$ (6)

V_t = Year t covariance matrix for b_t

where:

X and Y now represent the current year's data.

Then the posterior distribution for the desired regression parameter vector b_{post} (Eqs 7 and 8) is calculated.

posterior distribution of b is MVN(b_{post}, V_{post})

where

$$V_{post}^{-1} = V_{prior}^{-1} + V_t^{-1} \quad (7)$$

$$b_{post} = V_{post}(V_{prior}^{-1}b_{prior} + V_t^{-1}b_t). \quad (8)$$

This process will continue annually, and the posterior parameters will be used to develop the updated transition probabilities. A simple example follows. In this the regression is modeling only a simple straight-line relationship between the dependent variable y and a single independent variable x. The prior estimates were formed using ordinary least squares with the following results:

$y = 11.33 + 4.38x$; $b'_{prior} = (11.33, 4.38)$

$$V_{prior} = \begin{bmatrix} 69.80 & -4.56 \\ -4.56 & 0.32 \end{bmatrix}$$

The current survey data (time period t) results in the following (using ordinary least squares):

$y = 17.43 + 3.92x$; $b'_t = (17.43, 3.92)$

$$V_t = \begin{bmatrix} 31.40 & -2.16 \\ -2.16 & 0.16 \end{bmatrix}$$

Following the mathematical formulation given above, this results in the posterior parameter estimates below.

$y = 15.56 + 4.04$; $b'_{post} = (15.56, 4.04)$

V_{post} =

$$\begin{bmatrix} 21.49 & -1.45 \\ -1.45 & 0.11 \end{bmatrix}$$

From these updated parameter coefficients the desired transition probabilities are generated.

CONCLUSION

This paper highlights two PMS that have advanced but different optimization approaches. The first developed for the state of Ohio in the United States uses deterministic degradation models based on an extensive database. An expert system is employed to select the feasible 6 year plans that are created for each highway segment being modeled. This rule based expert system determines the feasible M&R actions for the current year. Then it sequentially predicts the resulting condition given each action and selects feasible actions for the next year until all the 6 year plans are generated. The network optimization is modeled as a linear integer (binary) program and solved using generalized upper bounding with a commercial linear programming package. The details of the expert system are given in this paper.

The second PMS is for the Kingdom of Saudi Arabia. The entire kingdom is divided into 9 strata based on climate and functional class. Within each stratum network optimizations are run. Each of these optimizations is a Markovian decision process that minimizes cost subject to specified performance goals. A financial exigency model globally links all the strata together to solve situations in which there is insufficient budget to meet the multi-year goals of the Kingdom. This stochastic system uses Bayesian statistical methods to automatically update the degradation models that were developed with scant empirical data and expert opinion.

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DEVELOPMENT OF THE DELAWARE PAVEMENT MANAGEMENT SYSTEM

REFERENCE: Matsen, D. W., Smith, H. A., and Rada, G. R., "Development of the Delaware Pavement Management System," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: The Delaware Department of Transportation is responsible for the operation of 4,765 miles of roadways under its jurisdiction ranging from Interstate highways to local roads. The preservation and management of these facilities is vital to the economy of the state and a key responsibility of the Department. A systematic approach to the management of pavements is needed to provide the engineering and economic analysis tools to assist decision-makers in making cost-effective selections of maintenance and rehabilitation strategies for their preservation at desired performance levels. Such an approach has come to be known as a Pavement Management System (PMS). The overall objective of the current effort is to provide the Delaware Department of Transportation with an implemented state-of-the-art set of tools for cost-effective management of the entire network of paved roads and streets under its jurisdiction. Ancillary objectives include (1) evaluations of equipment and procedures for data collection, (2) determination of pavement maintenance, rehabilitation, and reconstruction strategies applicable in Delaware, (3) selection of report types and formats required by decision makers for cost-effective management of Delaware roads & streets, and (4) preparation and demonstration of training activities for use in implementation of the Delaware PMS.

KEYWORDS: highway pavement management, databases, highway pavement engineering.

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INTRODUCTION

The Delaware Department of Transportation (DelDOT), Division of Highways, is responsible for the maintenance of 4,765 of the 5,385 total miles of public roads and streets in the state. Of this mileage, 221 are multi-lane highways. Only 1,459 miles (27%) are eligible for some type of Federal financial aid. The majority of the necessary funds for construction, reconstruction, rehabilitation, and maintenance of these roads are allocated from the Delaware Transportation Trust Fund.

This statewide roadway network represents a tremendous investment. The preservation and management of these facilities is vital to the economy of the state and a key responsibility of the Department. Increases in traffic, both in numbers of vehicles and in wheel loads, along with rising costs and reduced resources results in significant challenges to administrative and engineering personnel. Because pavement surfaces are (1) the primary link between the roadway network and the efficient movement of goods and services; (2) the portion of the network most visible to the traveling public; and (3) the most significant functional and structural components of the network; their preservation and management at performance levels appropriate for desired service is a major activity of the Department. The changing emphasis from new construction to Maintenance, Rehabilitation, and Reconstruction (MR&R) of existing pavements must be addressed.

It is acknowledged that pavement management is not a new activity. Highway agencies have been by necessity managing pavements since the acceleration of road and street paving in the 1920's. Field experience (the mental storage and analysis of information) was in the early years the pavement management process. More recently, data has been collected on paper forms, stored in voluminous files, and analyzed manually.

The Delaware DOT has been utilizing certain elements of pavement management in recent years for the annual prioritization of pavement MR&R projects. However, the process is time consuming because the required information is located in different files and the analysis requires both manual and computer efforts. It is essentially a project level activity without the ability to forecast conditions and needs for long term planning purposes.

A systematic approach to the management of pavements is needed to provide the engineering and economic analysis tools to assist decision makers in making cost-effective selections of MR&R strategies on a network basis. Such an approach has come to be known as a Pavement Management System (PMS). The overall benefits attained from implementation of a PMS include the planning and conduct of MR&R activities in a timely manner to preserve pavement surfaces and the most effective and efficient use of available highway funds. As described in the most recent FHWA "Pavement Policy for Highways," *The analysis and reporting capabilities of a PMS are directed towards identifying current and future needs, developing rehabilitation programs, priority programming of projects and funds, and providing feedback on the performance of pavement designs, materials, rehabilitation techniques, and maintenance levels.*[1]

Because of the desire to expedite the PMS development and implementation process, the Department decided to retain a consultant with PMS expertise and experience. On the basis of technical proposals submitted, Pavement Consultancy Services (PCS/LAW), a division of Law Engineering, Inc. was selected as the consultant.

The overall objective of the project is to provide the DelDOT with an implemented state-of-the-art set of tools for cost-effective management of the entire network of paved roads and streets under its jurisdiction. The primary deliverable will be the operational Delaware Pavement Management System. Ancillary objectives include (1) the evaluations and recommendations concerning equipment and procedures for collection of data on pavement characteristics to be utilized in the PMS; (2) the determination of pavement maintenance, rehabilitation, and reconstruction strategies applicable in Delaware; (3) the selection of report types and formats required by decision makers for cost-effective management of Delaware roads and streets; and (4) the preparation and demonstration of a training program (including users manuals, training aids, user-friendly computer programs, etc.) for use in implementation and operation of the PMS by Delaware DOT personnel.

An outline of the scope of work includes the following project activities:

1. Establish detailed requirements for the Delaware PMS and identify data needs.

2. Develop detailed work plan for development and implementation of the Delaware PMS.

3. Evaluate methods and equipment for collection of traffic, ride (or roughness), surface distress, structural adequacy, and surface friction data and make appropriate recommendations.

4. Evaluate PMS software to maintain the database, provide required analysis and forecasting, and generate the necessary reports for budget and policy decisions plus make recommendations for software selection and installation.

5. Prepare data collection plan.

6. Plan and conduct pilot implementation of PMS on portion of pavement network involving data collection, data input, conduct of analyses, and generation of reports.

7. Revise and refine PMS based on pilot implementation experience.

8. Prepare revised PMS implementation plan for entire network including users manuals and training aids.

9. Initiate implementation plan.

10. Provide instruction and training for DelDOT personnel.

11. Provide interaction between the PMS development and implementation and the concurrent development at the DelDOT Coordinated Departmental Database (CDD) of which the PMS

will be the first operational unit. This interaction will include population of the CDD with the roadway and bridge inventory data.

Phase I of the project, involving conduct of activities 1 and 2 has been completed. The customized DelDOT PMS software is currently being refined in preparation for pilot implementation as the next project milestone. As background for further development of a DelDOT PMS, current activities in the areas of organization, procedures, and data collection and storage were reviewed.

PMS EVOLUTION

Within the Division of Highways at DelDOT, the Pavement Management Unit is a part of the Office of Planning and Programming. The Pavement Management Engineer reports to the Assistant Director of Planning. The Pavement Management Unit has a professional staff of 4 engineers to support the PMS activities. Annual highway construction and rehabilitation programs are developed by the office of Planning and Programming with the Pavement Management Unit providing substantial input. Consequently, pavement management is currently an integral part of annual highway program development process.

Another significant aspect of DelDOT organization is that a Transportation Trust Fund has been created to provide a stable funding source to construct and maintain the transportation system within the state. Highway user fees, toll revenues, and Federal funds distributed to Delaware for use on the Federal-Aid systems are included in the Transportation Trust fund for authorization to the various items of the list of transportation projects in the Annual Legislative Authorization Bill, generally known as the "Bond Bill."

PROCEDURES

The Office of Planning and Programming (OPP), Division of Highways, is charged with the responsibility for prioritizing the entire annual highway program needs for the State of Delaware. For the development of the priority recommendations, OPP uses the following 180 point rating scale that has been approved by the Council on Transportation:

Item	Points	
Pavement Condition		60
Surface Condition	20	
Ride Quality	10	
Maintainability	10	
Skid Properties	20	
Safety		50
Accident Experience	40	
Shoulder Width	10	
Service		70
Volume to Capacity Ratio	40	
Surface Width	30	
		180

The OPP recommendations (generally referred to as the Capital Improvements Program[2] but actually including rehabilitation and resurfacing projects) are submitted to the Council on Transportation. Public meetings are scheduled and conducted, appropriate modifications incorporated, and the Council approves the recommendations for submittal to the State Development Office on or before October 15 for inclusion in the State Capital Improvement Program for the following fiscal year. The General Assembly usually passes the "Bond Bill" by June 30 authorizing the recommended expenditures.

The majority of the priority process, utilizing the 180 point rating scale and other procedures for developing the annual highway OPP recommendations, is actually conducted by the Pavement Management Unit. A thorough review has been made of the process for selecting recommended projects ranging from Interstate to subdivision roads and streets and the results are summarized in Figure 1.

It is appropriate to note that the Safety and Service considerations in the priority process are not directly pavement related. Consequently, the current prioritization procedures used for Interstate, primary, and some secondary road classes is a step toward a roadway management system. However it is the desire of the Department that these considerations be incorporated into the operational PMS because the Pavement Management Unit will continue to have primary responsibility for developing the OPP highway priority recommendations.

DATA COLLECTION AND STORAGE

Based on the extensive review of documents and information collected by interviews with headquarters and district personnel, the general perceptions are that DelDOT collects and stores all types and large volumes of data for Interstate, primary, secondary, and local roads; the majority of the data is keyed to maintenance road number segments; a substantial amount of this data is used in the current prioritization process; and time and effort consuming activities are required for its use in the process because of the lack of significant interaction of the different databases through computer analysis programs. More specific information that has been gathered and reviewed is described by individual data element and category.

Road Inventory - A road inventory was conducted in 1970 with all information recorded on paper files and retained by the Pavement Management Unit. It is in the process of being entered into the VAX computer system operated by the Information Resource Management (IRM) Unit. The information is updated as construction, rehabilitation, and resurfacing activities occur. All information is identified by Maintenance Road Number (MRN) segments of a road with specific beginning and ending features, and individual features within the segment located by hundredths of a mile from the beginning of the segment. The same MRN is used as the data identification method by virtually all units within the Department. Consequently, large amounts of information needed to populate the PMS database can be entered by MRN and subdivided into appropriate PMS sections as a family of sections within a MRN. This will facilitate both population and use of the PMS because of Department personnel familiarity with the MRN identification method, particularly at the District level. From

PROGRAM	ACTIVITY	HWY. CLASS	FACTORS	PROCESS	PREL. SELECTION	COST EST.	FINAL SELECTION
Capital Improvements Corridor/Non-Corridor	New Construction (Relief Route) Add Lanes, Widen, Major Reconstruction	Interstate Primary Secondary (Limited)	Pavement Condition Safety (Accident Ratio) Service (V/C)	Established 180 Point Priority Process	Uncompleted Projects From Previous Programs. / Others with Lowest Priority Process Scores	Use Current Preliminary Cost Estimate Program (Formal Plans Required)	Uncompleted projects from previous programs plus Lowest Scores within Allocated Funds
Capital Improvements Delaware Transportation Authority	Interstate (Toll Road) Improvements, Interchange Reconfigurations, etc.....	Interstate	Less structured at present but will be same as above in future	Will use priority process in future	Will use same process in future	Presently by Consultant. Will use above process in future (Formal Plans Required)	Will use same process in future
Rehabilitation & Reconstruction 4R	Lane Widening, Safety Improvements, Etc. associated with Resurfacing, and Reconstruction	Interstate Primary Secondary	Pavement Condition Safety Service	Established Priority Process. Consider projects not selected for capital improvements	Lowest Priority Process Scores *not in Capital* Improvement Program	Use current cost *estimate program* (Formal Plans Required)	Lowest Priority Process Scores *within* Allocated Funds
Rehabilitation & Reconstruction 2R	Similar to 4R, but less extensive. Can be improvements (moving *utilities etc.) to prepare* for future resurfacing	Primary Secondary *Local (Limited)*	Pavement Condition Safety & Service (Primary & Secondary) *Pavement Condition* & other (Local)	*Established Priority* Process (Primary & Secondary) consider projects not selected for capital improvement or 4R. Also District recommendations	Lowest *Priority Process* Scores not in Capital Improvement Plan or 4R / Also District recommendations selected by the Pavement Management Engineer	Use simplified cost estimate procedure (simplified plans often used)	Lowest remaining scores plus other selected by the Pavement Management Engineer
Paving & Rehabilitation (100% State Funds) Hot Mix resurfacing	2" - 3" Hot Mix resurfacing by contact	Primary Secondary Local (North District)	Pavement Condition (by PURD)	Ranked by PURD 0 - 8 Ratings (Primary & Secondary) / Local Road District recommendations checked by PURD	Lowest pavement condition scores not in CIP, 4R, or 2R / Also District recommendations after check by PURD	Use estimated cost per mile	Lowest Scores within allocated funds (District option to divide funds between Hot Mix & surface treatment)
Paving & Rehabilitation (100% State Funds) Surface Treatment	Surface Treatments by District Forces in Central & South District occasional on secondary roads	Secondary Local (Limited)	Pavement Condition (by District Rater)	Rated by District (0 - 8) Subjective Ratings	By District	Use estimated Cost per mile (materials only)	Lowest scores within allocated funds (District option to divide funds between Hot Mix & Surface Treatment)
Suburb Streets	Wide variety of activities - ditching, patching, clean culverts, etc...	Subdivision roads & streets built by developers			Local Legislator	Prepared by Districts	Local Legislator Discretion up to $228,000

FIG. 1 – DelDOT Annual Highway Program Development

the standpoint of populating the PMS database, the road inventory data file will provide a large portion of the required information such as identification (beginning and ending points, maintenance area, district, classification, pavement construction type, surface type, etc.) and geometry (pavement width, shoulder width, number of lanes, grade, curvature, and misc. features).

Pavement Condition - DelDOT purchased a Portable Universal Roughness Device (PURD) in 1983. The equipment is operated by personnel of the Pavement Management Unit about 3 months per year, generally in the fall season, and at other times to resolve questions and concerns during annual program development. The PURD has a keyboard for entering visual pavement surface distress information that is converted to a Surface Distress Index (SDI). Using responses from accelerometers, a Ride Comfort Index (RCI) is determined. During 1989, the International Roughness Index (IRI) was also calculated for HPMS sections. Since 1984, SDI and RCI data has been collected for all Interstate, primary, secondary, and some local roads with a hot mix asphalt surface. About half of these roads are inventoried per year. This data is currently used with the friction data to determine the pavement condition portion of the 180 point rating scale in the priority process for selecting projects to be included in annual highway improvements program.

All other local roads with an asphalt surface treatment are rated in the fall of each year by district personnel and the data submitted to the Pavement Management Unit. The rating is a 0 to 5 subjective (visual) rating that includes both surface distress and ride comfort. These ratings are used by the Pavement Management Unit to select projects for the annual surface treatment program.

Friction - DelDOT uses a conventional locked wheel skid trailer to collect FN_{40} data for all primary and secondary roads annually. Measurements are generally made at 0.5 mile intervals in both directions and recorded as distance from the beginning of a MRN. As indicated previously, the FN_{40} data is included in the priority process for determining the pavement condition rating.

Pavement Structure - The Road Design Unit maintains extensive files beginning in 1917 of all projects for which plans were prepared. They have a computer program for identifying the construction history of each road segment. Pavement layer types and thicknesses can be used from these files to populate the PMS database. The Research and Materials Unit has been the traditional collector of laboratory and field test data for construction projects. This information was originally collected and stored in paper files but is gradually being transferred to the VAX computer. Subgrade soil and pavement layer characteristics can be extracted from these files as needed for populating the PMS database. Deflection data is also available for the Interstate pavements.

Traffic - Data is collected, analyzed, and reports developed by the Bureau of Traffic. Each vehicle is counted throughout the year at 35 permanent automatic traffic recorder stations located on primary routes. Portable counters are used on other routes with location and frequency dependent on traffic volumes. These permanent stations are in the process of being upgraded to provide vehicle classification counts. There is one permanent truck weigh station on U.S. 13 near Smyrna and truck weights are sampled at 8 other locations annually with portable scales. A portable Weigh-In-Motion (WIM) device has been purchased and will be used to collect truck weight data at the 5 Strategic Highway Research Program (SHRP) sites. Also, a project has been initiated with the University of Delaware to develop a traffic data collection plan to meet the needs of the Department for PMS, SHRP, and FHWA. The Traffic Bureau produces an annual Traffic Summary report containing the following information for each MRN; Annual Average Daily Traffic (AADT), Design Hour Volume (DHV), directional split, percent trucks, and truck weight group. The AADT data is quite adequate for the PMS database. However, equivalent single axle load (ESAL) information is not available at the present time but the collection of WIM data for the SHRP sites should improve this situation.

All accident reports are reviewed and coded into an accident report file. Information from this file is used to select projects for the Highway Safety Improvement Program and in the priority process for annual program development. Because the actual number of accidents on a specific section of road may not be a realistic indication of the degree of hazard (10 accidents per year on a local road indicates a much greater hazard than 10 accidents per year on an Interstate highway), procedures have been developed for determining an annual critical accident rate ratio for each road section. Three year averages of the ratio are also used. The accident rate ratio is essentially a relationship between the number of accidents on a road section in relation to the average number of accidents that occur on road sections of similar traffic and classification.

The Bureau of Traffic also has a complete video log of DelDOT major roads that is updated every year. This information is stored on high resolution laser disks. An individual video photo can be projected on the monitor at one hundredth of a mile intervals. It is used primarily to verify accident information and inventory location and condition of signs.

Maintenance - A Maintenance Management System (MMS) has been developed and implemented for several years. It is used for both scheduling of maintenance work and recording amounts of manpower, equipment, and materials used for various maintenance functions. This information is all entered directly into computer files by maintenance area clerks at the end of each day and transferred to the Pavement Management Unit (PMU). Cost information in the PMU files is combined with the manpower, equipment, and materials units to produce an annual Maintenance Cost Summary report listing units and costs by maintenance function and district plus statewide totals. This information is not used in program development at the present time but certainly will be a valuable addition to the PMS database for computing life-cycle-costs.

In summary, it is determined that DelDOT has been in the PMS development process for several years and some elements are in stages of operation. A Pavement Management Unit operates with support of upper-level management. Pavement functional condition and traffic data are collected and used in the Priority Process for annual program development. Deficiencies include the time and effort required for manual operation of the Priority Process, the lack of network level long term planning modules, and the limited report production capability.

COMPUTERIZED PMS

The primary objective of the remaining portions of the project is to produce an operational DelDOT PMS with emphasis on expanding and improving the currently used priority process and data collection procedures. Some of the factors in support of this approach are:

1. The Department desire for an operational PMS by early 1992.

2. The currently used priority process and data collection procedures are generally accepted by headquarters and district personnel.

3. Early implementation of a PMS without drastic changes will develop headquarters and district support for further enhancements and improvements.

4. Use of existing data is necessary for development of interim forecasting models and threshold values required for multi-year budget projections.

5. The majority of required data is presently available in an electronic form and universally related to a maintenance road numbering system.

The customized DelDOT PMS computer software will consist of user-friendly database, analysis, and reporting modules with emphasis on flexibility to permit incorporation of modifications and enhancements as needs and objective levels change, data collection methodologies improve, and analysis requirements are modified. It will operate on PC computers in the Pavement Management Unit of the Department utilizing data from the CDD.

Significant features of the proposed DelDOT PMS, in addition to computerization of portions of the currently used priority process, will be:

1. All HPMS data, pavement structural data, traffic data, Equivalent 18-kip Single Axle Load (ESAL) data, MR&R cost information, and paved shoulder type and condition information will be incorporated into the PMS database.

2. Analysis modules for pavement structural evaluation and determination of ESAL's will be included in the DelDOT PMS.

3. Modules to forecast pavement condition and friction values will be included.

4. Interim threshold values to initiate various MR&R activities will be developed.

5. Software for preparation of annual HPMS transmissions from PMS database as required by FHWA will be included.

6. Procedures for segment ranking and prioritization to prepare multi-year budget projections will be included.

7. Capability to produce a variety of graphic type reports including color coded pavement condition maps will be included.

As indicated by the above list of significant features, the currently used priority process for development of annual programs will be substantially expanded and improved. A flowchart illustrating the primary elements of the current process is included as Figure 2.

The DelDOT PMS will identify current "health" of the network; trigger PMS sections for improvement of service and safety, MR&R activities, and need for friction courses; select typical remedial actions; apply typical costs; and determine current year budget needs on an unconstrained (unlimited funds) basis or prioritize activities based on budget constraints. By the use of pavement performance prediction models, multi-year budget needs based on several levels of performance will also be determined. In addition to the tracking of pavement performance as influenced by time and traffic, the PMS will document construction, rehabilitation, and maintenance activities plus the programming of these activities to avoid reprogramming of such activities. During initial stages of PMS implementation, engineering judgement, field surveys, and site specific data collection will be required to combine PMS sections into projects for rehabilitation design and construction. As data is added to the system and experience gained by PMS operation, these activities will be minimized and the PMS can be used for life-cycle cost analyses and project level optimization.

The initial activity of PMS software development is the design of the database structure to compile and store all data required for the analysis and reporting modules in a suitable format for operation of the system. The DelDOT approach is to store all data in the Coordinated Departmental Database (CDD) in the mainframe computer. The DelDOT PMS will be operated on PC workstations in the Pavement Management Unit utilizing a PMS working database containing all necessary data retrieved from the CDD. Data will be coded to pavement management segments that are essentially subsets of current data files coded as maintenance road numbers. The proposed concept is to include provisions for all data items applicable to all road classifications (Interstate to local) and both network and project level analysis activities regardless of current data availability. Flexibility will be provided for additions to or modifications of the database as future needs become apparent. All data will be updated to the current year by forecast models. Improvements over the current process include all PMS data in an operating database rather than being received from other units such as traffic and combined by the Pavement Management Unit; all data updated to current year rather than the year of collection; and data identified by PMS segment rather than larger maintenance section.

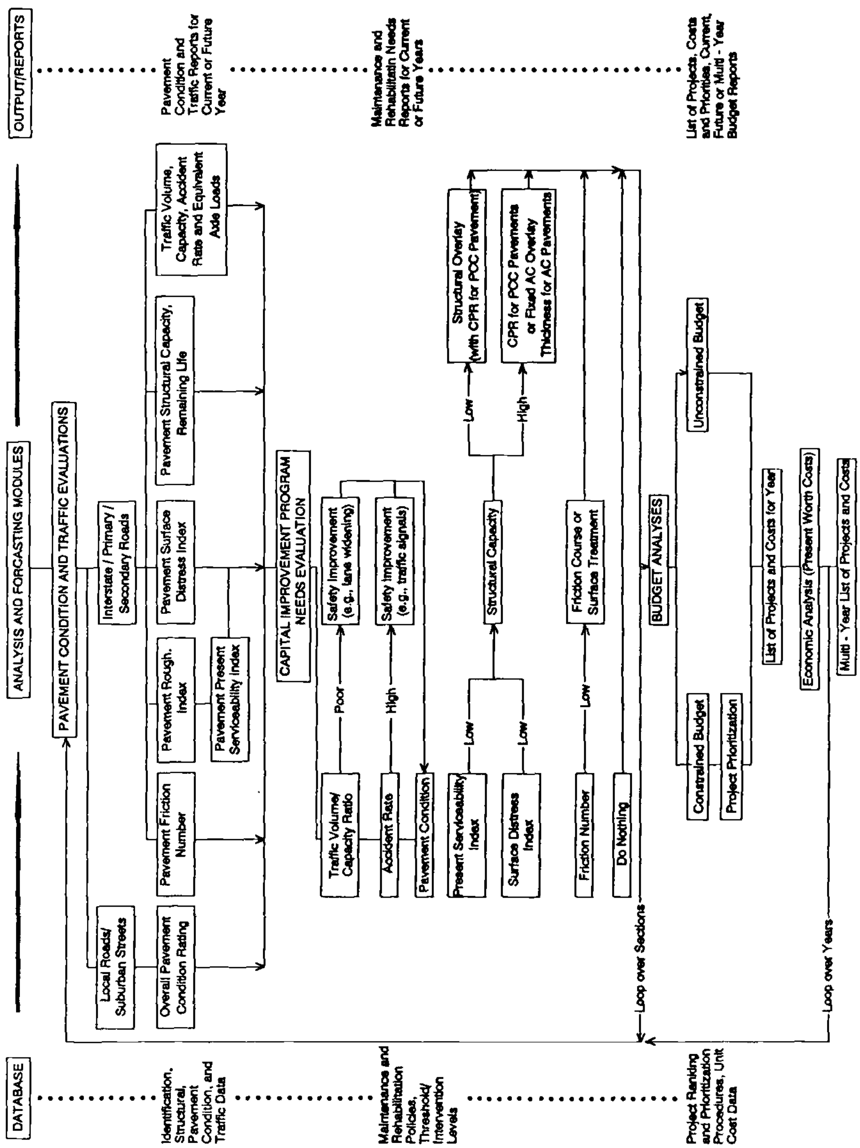

FIG. 2 -- DelDOT PMS Flow Chart

The proposed DelDOT PMS involves decision tree concepts of considering individual elements rather than combining all elements as an overall sufficiency rating. The roadway service (v/c ratio and pavement surface width rating of 0 to 70) is first considered to determine eligibility of a section for this portion of the program. If the service rating is less than a threshold value (for example 50), the section is selected as a service improvement candidate. Sections with service ratings above the threshold value are then considered as safety candidates. If the safety rating (accident critical ratio and shoulder width rating of 0 to 50) is less than the threshold value (for example 35) and the v/c is less than a threshold value (for example 0.98), the section will again be a candidate for service improvement. If the v/c is greater than the threshold value and the safety rating is less than its threshold value, the section will be a candidate for some type of safety improvement. Sections not selected as candidates for service or safety improvement programming are then evaluated from the standpoint of structural adequacy.

This structural adequacy evaluation of pavement sections is an addition to the current DelDOT process. It will provide for the use of pavement deflection data and ESAL data (including projections) to compute remaining pavement life using the AASHTO method. Alternate procedures will be developed when deflection data is not available.

The proposed process will involve the combining of ride comfort and distress data to determine a current year Delaware Present Serviceability Index (PSI) for each pavement segment. If the PSI is below a designated threshold value, the need for a structural overlay to accommodate projected traffic loads will be determined using the AASHTO models. Separate cost models will be developed for AC and PCC pavements. If the segment is structurally adequate or requires less than a 3 inch overlay to accommodate projected traffic, alternate rehabilitation procedures will be considered for each pavement type.

If the PSI is above a designated threshold value, the segment will be evaluated from the standpoint of surface distress index (SDI). If the SDI is below a designated threshold value, the need for a structural overlay to accommodate projected traffic loads will be determined using the AASHTO models. The activity will be the same as for segments triggered by low PSI. The proposed process essentially provides for the consideration of pavement segments for rehabilitation based on either ride or surface distress deterioration rather than a combined ride and surface distress index. It also permits the use of rehabilitation activities other than AC overlay for network programming based on the pavement surface type.

Pavement Friction Number (FN) data is routinely collected for Interstate, primary, and secondary roads. All sections not selected as candidates for service improvement, safety improvements, structural improvements, or other rehabilitation activities, will be evaluated from a surface friction standpoint. If the FN is less than the threshold value (for example an FN of 40 for Interstate highways), it will become a candidate for surface friction improvement. The improvements will be based on the pavement surface type and traffic levels. Pavement sections that have not been selected for any activity based on the various threshold values will be in the "do nothing" category.

A feature of the proposed PMS is the inclusion of a separate element for consideration of low traffic volume roads (generally local roads with an AC surface treatment) for which overall pavement condition ratings by visual inspection is the only monitoring data available. If this overall rating is below a threshold value, the only MR&R activity considered for network programming is an asphalt surface treatment. Roads in this classification with traffic above a threshold value will be evaluated by the previously described process as being triggered by surface distress in which case the MR&R activity can be either an AC overlay or surface treatment. It is anticipated that many of the local road segments will be considered by the regular process as more data becomes available.

It is emphasized that this is a network PMS. The suggested activities associated with selected sections are of a general nature primarily for the purpose of estimating required funding. Candidates for improvement should receive project level evaluations to determine specific corrective actions and cost estimates for final programming. A major responsibility of the remaining portions of PMS project is to develop appropriate threshold values for the different road classifications. Based on an unconstrained budget, use of the threshold values will produce estimated total funding required to eliminate all identified deficiencies. The threshold values can also be adjusted to select candidate sections within budget constraints.

In addition to selecting projects for the annual program, the analysis modules of the PMS can be used to produce multi-year programs and to identify long-term needs based on various threshold value strategies. The consequences of different overall funding levels and different strategies for allocation of funds between geographic areas and road classifications are examples of "what if" questions for which responses are generated.

The ability to rapidly and effectively produce a large number of reports including tables, charts, graphics, and color coded maps indicating the current and projected condition of the entire road and street system under DelDOT jurisdiction is an extremely valuable feature of the proposed DelDOT PMS. This type of activity is generally accomplished manually at the present time. Documents of this type are useful for obtaining public and legislative support for Department programs as well as to gain internal support for appropriate program revisions.

As indicated previously, the DelDOT PMS will be operated by the Pavement Management Unit on PC work stations. However, the majority of the required data will reside in the CDD. The current PCS/LAW project is responsible for development and implementation of the PMS as well as the concurrent implementation of the PMS data and bridge inventory components of the CDD. This involves development of database interface/access routines for pavement inventory and condition data for the Pavement Management Unit, pavement structural and friction data for the Materials and Research Unit, traffic data for the Bureau of Traffic, and bridge inventory data for the Bridge Design Unit. Previously digitized map data must also be segmented and incorporated into the CDD in a format that can be used to produce PMS color coded maps.

Implementation of the DelDOT PMS is an extremely important activity following its development. This will be accomplished in two phases. Pilot implementation will involve population of the database with currently available data for the Interstate System segments and all roadways in Maintenance Area 8 and will include primary, secondary, and local roads; conduct of appropriate analyses; and the production of various types of PMS reports. Following a review, evaluation, and revision of the PMS elements, full implementation will be initiated. It is currently envisioned that pilot implementation will be conducted in mid-1991 and full implementation in early 1992.

TABLE 1 -- Data Collection Plan

Road Category	Friction	Roughness	Distress	Subjec. Rating	Struct. Capacity	Traffic	Routine Maint.
SHORT-TERM PLAN (0-5 years)							
Interstate	yes	yes	yes	no	yes	Counts/Class.	no
Primary	yes	yes	yes	no	yes	Counts/Class.	no
Secondary	yes	yes	yes	no	no	Counts/Class.	no
Local	no	no	no	yes	no	Counts	no
Suburban	no	no	no	yes	no	Estimate	no
INTERMEDIATE PLAN (5-10 years)							
Interstate	yes	yes	yes	no	yes	Use of WIM	yes
Primary	yes	yes	yes	no	yes	Counts/Class.	yes
Secondary	yes	yes	yes	no	yes	Counts/Class.	yes
Local	no	no	no	yes	no	Counts	no
Suburban	no	no	no	yes	no	Estimate	no
LONG-TERM PLAN (more than 10 years)							
Interstate	yes	yes	yes	no	yes	Use of WIM	yes
Primary	yes	yes	yes	no	yes	Use of WIM	yes
Secondary	yes	yes	yes	no	yes	Counts/Class.	yes
Local	yes	yes	yes	no	yes	Counts	yes
Suburban	no	no	no	yes	no	Estimate	no

CONTINUED EVOLUTION AND ENHANCEMENTS

Critical to the ultimate implementation of the DelDOT PMS in coordination with other Department activities, such as eventual incorporation into a Geographic Information System (GIS), is the planning for continued evolution and enhancement of the PMS within an overall framework. For pilot implementation, data collection methods and equipment plus other operational procedures will be essentially as currently practiced to expedite implementation and gain early acceptance. However, the database and analysis procedures will be designed with the flexibility to permit easy revisions. A framework for continued improvements over short, intermediate, and long term periods is shown in Tables 1, 2, and 3. The short term plan will be implemented under the current project. Several operational procedures will be considered for

TABLE 2 -- Pavement Evaluation Factors

Road Category	Short-Term	Intermediate	Long-Term
FRICTION			
Interstate	Friction Number	Friction Number	Friction Number
Primary	Friction Number	Friction Number	Friction Number
Secondary	Friction Number	Friction Number	Friction Number
Local	N/A	N/A	Friction Number
Suburban	N/A	N/A	N/A
ROUGHNESS			
Interstate	RCI	IRI	IRI
Primary	RCI	IRI	IRI
Secondary	RCI	IRI	IRI
Local	N/A	N/A	IRI
Suburban	N/A	N/A	N/A
SURFACE DISTRESS			
Interstate	SDI	Intermediate and long-term index value surface distress will depend upon results of on-going SHRP research results (P-020, A-005)	
Primary	SDI		
Secondary	SDI		
Local	N/A	N/A	
Suburban	N/A	N/A	N/A
SERVICEABILITY			
Interstate	PSI	PSI	PSI
Primary	Based on the RCI and SDI	Based upon the IRI	Based upon the IRI
Secondary	Based on the RCI and SDI	Based upon the IRI	Based upon the IRI
Local	N/A	N/A	Based upon the IRI
Suburban	N/A	N/A	N/A
OVERALL PAVEMENT RATING			
Interstate	N/A	N/A	N/A
Primary	N/A	N/A	N/A
Secondary	N/A	N/A	N/A
Local	Subjective Rating (0-5)	Windshield Survey	N/A
Suburban	Subjective Rating (0-5)	Windshield Survey	Windshield Survey
STRUCTURAL CAPACITY			
Interstate	Effec. SN/D, Esg/K	Effec. SN/D, Esg/K	Effec. SN/D, Esg/K
Primary	Effec. SN/D, Esg/K	Effec. SN/D, Esg/K	Effec. SN/D, Esg/K
Secondary	N/A	Effec. SN/D, Esg/K	Effec. SN/D, Esg/K
Local	N/A	N/A	Effec. SN/D, Esg/K
Suburban	N/A	N/A	N/A

RCI = Ride Comfort Index
IRI = International Roughness Index
SDI = Surface Distress Index

TABLE 3 -- Data Collection Equipment

SHORT-TERM PLAN (0-5 years)

- Friction: ASTM E274-85 locked-wheel skid trailer (currently used by Delaware DOT)
- Roughness: Response type roughness measuring device (currently used by Delaware DOT)
- Distress: Raters measure and record pavement distress (currently used by Delaware DOT)
- Subjective Rating: Raters subjectively rate overall pavement condition on scale of 0 to 5 (currently used by Delaware DOT for local roads)
- Structural Capacity: Deflection measuring equipment
- Traffic: Traffic counters and Weight-in-Motion system

INTERMEDIATE PLAN (5-10 years)

- Friction: ASTM E274-85 locked-wheel skid trailer
- Roughness: Profile measuring device
- Distress: Automatic distress measuring equipment
- Subjective Rating: Modified subjective rating for assessing overall pavement condition
- Structural Capacity: Deflection measuring equipment
- Traffic: Traffic counters and Weight-in-Motion system

LONG-TERM PLAN (more than 10 years)

- Friction: ASTM E274-85 locked-wheel skid trailer
- Roughness: Profile measuring device
- Distress: Automatic distress measuring equipment
- Subjective Rating: Modified subjective rating for assessing overall pavement condition
- Structural Capacity: Deflection measuring equipment
- Traffic: Traffic counters and Weight-in-Motion system

immediate revision. For example, it might be appropriate to use IRI pavement roughness values for both the HPMS and the PMS databases. Italso might be desirable to increase the frequency of pavement condition data collection for interstate and primary roads. The selection of different threshold values to trigger MR&R activities for Interstate, primary, secondary, and local roads will influence analysis activities.

Another activity of the current project that will be included in the short term implementation is the interaction with the Coordinated Departmental Database (CDD) on the mainframe computer operated by the Information Resource Management Unit. Rather than PMS data being received by the Pavement Management Unit from other units such as traffic and materials, all data will be received and stored in the CDD. Pavement Management Unit PC workstations will access the CDD to obtain all needed data for analysis and report production. A working PMS database will essentially be produced on the PC workstation for a specific analysis activity.

CONCLUSIONS

The end product of the current project will be implementation of a fully operational DelDOT network level PMS as state-of-the-art engineering and economic analysis tools for cost-effective management of all paved roads and streets under its jurisdiction by mid-1992. The PMS will consist of the typical elements, as shown in Figure 3, of data input, database and analysis software, and report production capabilities that are consistent with the AASHTO Guidelines for Pavement Management Systems[3] and the "FHWA Pavement Policy for Highways."[1] The System is being developed in modular form to permit enhancements as the intermediate and long term objectives are attained.

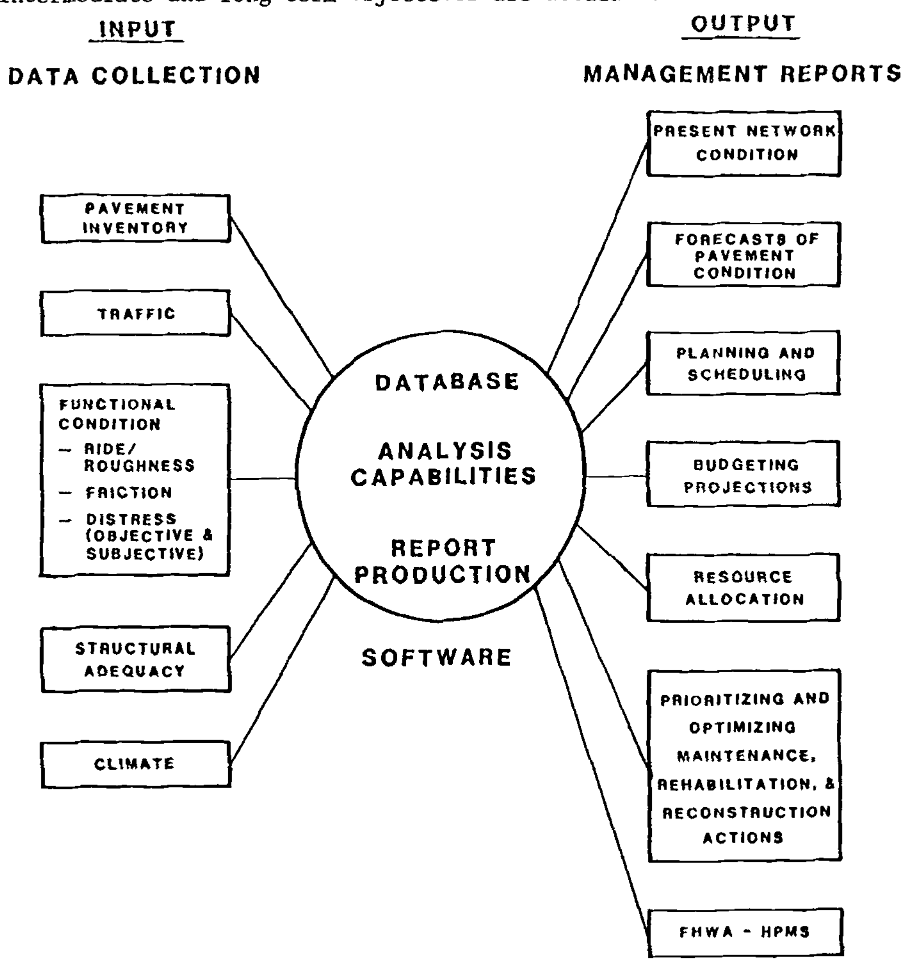

FIG. 3 -- Typical Elements of Network PMS

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A PAVEMENT SURFACE MODEL FOR INTEGRATING AUTOMATED MANAGEMENT DATA

REFERENCE: Haas, C. T. M., McNeil, S., Hendrickson, C. T., and Haas, R. C. G., "A Pavement Surface Model for Integrating Automated Management Data," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: Good data on performance, geometry, materials, environment, costs and other factors provides the foundation for pavement management. While some very advanced technologies have been applied to collecting this data, particularly in non-contact sensing and automation, there is unfortunately also a very wide diversity and incompatibility among methods and results. This paper suggests that such diverse data and technologies can in fact be exploited in a standardized way through the use of an integrated surface representation model. An example application of the model is provided in the paper. It uses data from three current acquisition systems. Data from these systems are integrated into the model's standard representation from which common pavement condition indices are derived using the model's tools. The paper also describes additional benefits of the model in pavement management.

KEYWORDS: surface model, pavement management, quadtrees, inventory database, roads

Reliable, adequate data on performance, geometry, materials, environment, costs and other factors is essential to pavement management. Recognition of this need has been largely responsible for the development of a number of methods and devices for collecting pavement data, and a variety of procedures for evaluating, representing, interpreting, processing, and using the results. While some very advanced technologies have been applied, particularly in non-contact sensing and automation, there is unfortunately also a very wide diversity and incompatibility among methods and results.

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This paper suggests that such diverse data and technologies can in fact be exploited in a standardized way through the use of an integrated surface representation model. The model is based on a generalized quadtree spatial formulation which has the capability of incorporating pavement surface characteristics at various levels of abstraction and aggregation. A spatial framework is used (i.e. x,y and elevation components) for data fusion and structuring. The generalized quadtree has a hierarchical structure and is unified in that its nodes create a useful parallelism among surface characteristics. A relational database management system can be used to handle the model's surface description files.

An example application of the model is provided in the paper. It uses data from the following commercially available acquisition systems: (a) PASCO USA Inc.'s RoadRecon survey system, (b) Roadman - PCES Inc.'s Pavement Distress Imager, and (c) Komatsu Ltd.'s Automatic Pavement Distress Survey System. Data from these systems are integrated into the model's standard representation from which common pavement condition indices are derived.

The implications of using the model for advanced characterization functions are also explored. Opportunities and standardization issues concerning use of the model are identified. The paper concludes by describing the benefits of an intregrated spatial model of surface condition representation in pavement management. With this "open architecture" approach, assessment data from different commercial systems at different points in time may be used in a more cost-effective and combined way.

A SURFACE MODEL

The purpose of combining pavement management data is to exploit the information available in order to manage more effectively. To do this, it is necessary to have a standardized model of pavement surfaces into which many disparate sources of information can be incorporated. Since these sources of information can vary between detailed video scan data and summary condition values, the model must also support different levels of data abstraction and aggregation. It must maintain spatial relationships among surface characteristics, it must support automated characterization, and it should support quick access to surface information.

The most common model currently in use is based on linear representations of roadways with characteristics indexed by milepost. Linear models however cannot represent information that has width as well as length such as rutting or local areas of distress. Linear representations are therefore incapable of representing many types of scanned data at a low level of aggregation or of maintaining two dimensional spatial relationships. The quadtree [1] is an alternative surface model that is symmetric, infinitely decomposable, and easy to construct from pavement sensor data. Quadtrees can also be used to maintain well defined spatial relationships between different sources of surface data, because the individual quadtrees can be arranged to form parallel structures. A quadtree is a hierarchical, tree-like representation in which a surface is repeatedly divided into square surface areas or "quadrants" with finer and finer detail.

The surface model described here uses the quadtree and is defined in [2] and developed further in [3]. The model is the combination of a surface representation and its "characterization". Characterization transforms the state of the surface representation. Common computer data structures support characterization and facilitate the surface representation, and in this way unify the elements of the model.

The model assumes that pavement surfaces are of two and one half dimensions so that pavement contour information can be included. This assumption implies that pavement surfaces can be represented in a manner analogous to topographic maps. Pavement surfaces are represented by characteristics at different levels of aggregation and abstraction. The level of aggregation of a characteristic refers to its spatial extent and its distance hierarchically from original sensor or survey data. Three levels of characteristics are defined:

- **properties** - measured directly,
- **features** - derived from properties and other features, and
- **regions** - aggregations of sets of features and properties

The surface representation is composed primarily of two computer data structures. The first is a grid to which sensor data and survey measurements are registered. Data from different sources are referenced to common points on the grid and thereby related to each other spatialy. The grid forms the foundation of a *generalized quadtree* which is used to relate characteristics in a multi-layer spatial framework useful for data fusion and structuring. The generalized quadtree has advantages over other surface descriptions. It is compact because of its hierarchical structure and is unified because its nodes create a useful parallelism among surface characteristics thus maintaining the spatial relationships among the characteristics.

In this model each node in the generalized quadtree is a data structure, with slots for each surface characteristic in a quadrant and with values for each slot. Descriptions of uniform characteristics spanning a wide area of the surface may be contained in higher nodes and propagated down the tree to access information at any level of detail. For example, Figure 1 illustrates the quadtree's hierarchical representation of two layers of information concerning the same area. They are pavement depression and cracking. In their final state, each quadrant encompasses an area in which the property or feature value is relatively uniform. Quadrants correspond to leaf nodes on the tree, and for any node in the tree its slots may have four states:

- **black** - the characteristic fills the area encompassed by the slot's node
- **white** - the characteristic is not existent in the area encompassed by the slot's node
- **grey** - the characteristic is to some degree existent in the area encompassed by the slot's node
- **undefined** - no knowledge is retained concerning the characteristic at this node

The state of black may have several values. For example rutting may exist as low, medium, and high. In most cases it makes sense to discretize continuous valued properties into a few representative ranges. In Figure 1 the root node slot values for cracking and rutting are both grey, because the state of neither of these properties is homogeneous throughout area A. However in the next level down the value of the cracking slots in the nodes that represent the bottom two quadrants is white. At the lowest level of any branch, all slot values are either white or black. While the number of levels possible is infinite, the division of areas is arbitrarily stopped in the figure at the third level. In practice the level of detail is limited by sensing resolution, computer memory, and the application of the model.

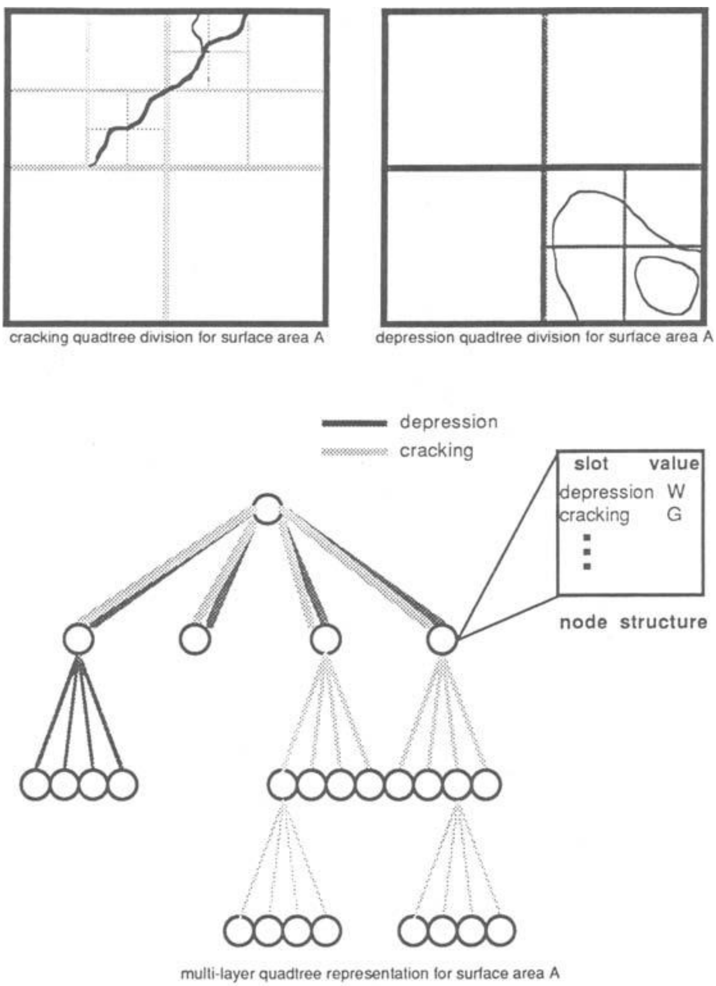

FIGURE 1 -- Generalized Quadtree

Data Registration and Alignment

Registering surface data, especially sensor data, and aligning it spatially is challenging. The model's grid serves as an xy reference plane for these purposes. There are a number of restrictions placed on the grid dimensions based on the nature of the generalized quadtree that impose constraints on the survey patterns for each source of data and the datum dimensions. However the grid can be fitted to virtually any road width and section size. Aligning the data from different sources with respect to the grid requires rigid links between the data acquisition subsystems. This has been achieved for at least two systems. One, a stationary laboratory prototype of a robotic pavement crack filler, acquires a 512 x 512 array of video pixels and a 128 x 128 array of range values over a single 2 x 2 m square work area [4]. Another, the Komatsu pavement surveying system, uses a single argon laser line illuminator which is scanned by two different receiving mechanisms, one to develop an image from which cracking data is acquired automatically and one to develop a transverse profile from which rutting data is acquired automatically. Since all these mechanisms are coordinated via the same system clock, the acquired data can theoretically be precisely aligned and registered.

Characterization

Characterization changes the state of the surface representation in order to produce a useful description of the surface. The four basic operations in characterization can be defined as:

1. **data filtering** - linear and non-linear transformations,
2. **data reduction** - deriving a representative value from a set of data,
3. **data fusion** - combining two or more spatialy concurrent datums into a new datum, and
4. **data structuring** - linking and integrating data.

Computer processing and space constraints along with the nature of the application affect how the balance of these operations are divided between the grid and the generalized quadtree. Data *filtering* and *reduction* are performed most effectively on grid data, and data *fusion* and *structuring* are performed most effectively on the generalized quadtree.

As an example, suppose one wished to extract the feature "fatigue cracking" using the characteristics of rutting, strength, and cracking from a generalized quadtree model. This information can be acquired in raw form as property data using range, deflection, and vision sensors, respectively, and reported in arrays of data mapped onto points on the grid. The grid data is *filtered* and then converted at appropriate levels of aggregation to the generalized quadtree representation. Conversion is a *structuring* operation that places the properties in the generalized quadtree as slot values in node data structures. The slot values are datums which are combined by a feature extraction algorithm composed of set operations into datums in a new slot which represents fatigue cracking. This process is *data fusion*. The structure of the generalized quadtree relates the fatigue cracking feature spatially to the other characteristics and to the pavement surface.

Following this example, the characterization operations can be grouped into several practical classes. The first includes operations on the grid to prepare raw sensor data for conversion to the generalized quadtree. The next includes operations to convert grid data into the quadtree representation and then back for graphic display purposes.

Quadtree set operations form a class, and adjacency and region labeling another. These operations are implemented in software using C++, an object oriented language. They form the Generalized Quadtree Library (GQL), and are flexible and easy to use.

For example, the model implements two binary spatial set operations, namely union and intersection, from which more complex set operations can be constructed. Figure 2 illustrates the intersection of transverse cracking in the top segment with patching in the next segment. The result in the bottom segment displays transverse cracking from which the patching has not been stripped. Each segment is in fact a layer of a single generalized quadtree data structure for the subsection of pavement represented. In addition, each crack can be identified and labeled as a unique object using GQL functions. The area represented is 16 ft (4.88 m) x 88 ft (26.8 m).

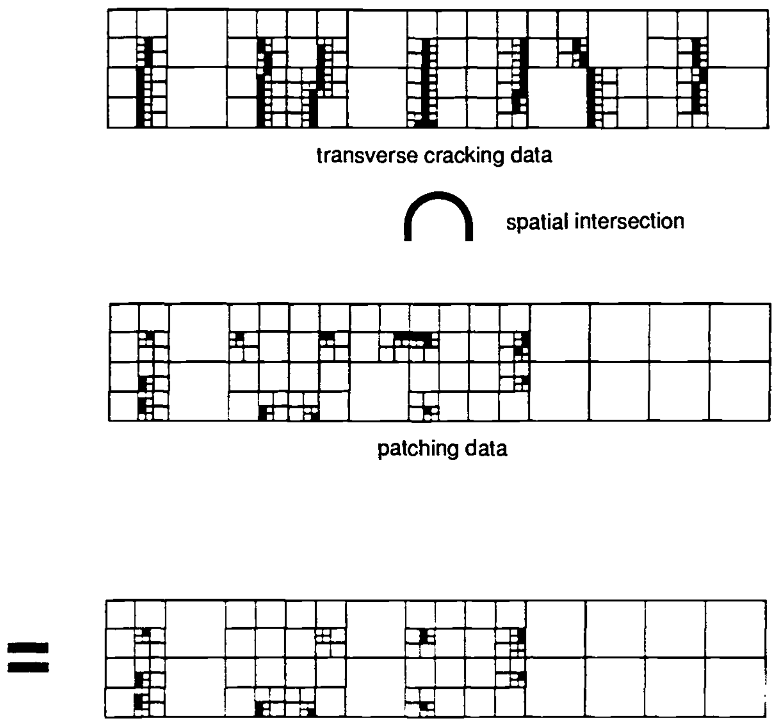

FIGURE 2 -- Set operations

INTEGRATING MANAGEMENT DATA

Pavement management systems make extensive use of surface data. The purpose of this section is to demonstrate how the pavement surfaces model can be used to integrate surface data. It is necessary to first understand how the generalized quadtree is specified for various applications and how its information can be represented and retrieved in a general pavement inventory database. The use of the model as a standard link between acquisition and application systems is illustrated by processing data from a number of different sources to provide two forms of standard input to pavement management applications. The model's use for advanced characterization is also examined.

Data Acquisition

Data was acquired from the following survey systems: (a) PASCO USA Inc.'s RoadRecon survey system, (b) Roadman - PCES Inc.'s Pavement Distress Imager [5], and (c) Komatsu Ltd.'s Automatic Pavement Distress Survey System [6]. Komatsu's survey system acquires aligned cracking, rutting and roughness data at up to 40 mph using laser range sensors, laser illumination, and a unique processing architecture. The PCES system is an on board real time pavement imaging system. The PASCO system acquires film of the pavement surface with a high speed vertically oriented camera while traveling at highway speeds then analyzes the data in a laboratory with a partially automated process. All these systems report one or more aligned layers of data in grid patterns at various levels of resolution.

Data Representation and Management

The generalized quadtree can represent any length of pavement in theory, however restrictions are imposed by computing resources. A direct tradeoff in memory requirements exists between the number of quadtree layers, the minimum level of aggregation and the length of the pavement section represented. As an example, a 100 x 4 m area of pavement is used as the standard subsection for the data samples provided by Komatsu Ltd. The underlying grid coordinates extend from the origin to row and column dimensions of 4096 and 102,400 respectively.

Having established a standard subsection size, the next step is to configure the quadtree nodes. Each slot in a node normally corresponds to a layer of sensor data or a feature. Slots can also be used to store region labels, to act as buffers for set operations, or to retain an attribute value for another slot. Another consideration is the aggregation level at which source information is incorporated in the generalized quadtree. It is apparent that even for a relatively small 100 m subsection, if the underlying grid is as extensive as the Komatsu system's or that of the PCES system, the data should be filtered and reduced to prepare it for conversion to the generalized quadtree representation prior to further characterization. Good judgement must be used to specify the level of aggregation for surface data incorporation.

Rutting values are normally reported for each wheel path at 5 to 30 m intervals along the length of the pavement section. For the PASCO and Komatsu systems, they are derived automatically from transverse profiles acquired while traveling along the road. The rutting values can be discretized into "black" states of low, medium, and high which represent the severity of the rutting or the "white" state of insignificant based on the ranges specified in pavement management manuals such as PAVER [7] or the Ontario Ministry of Transportation's "Pavement Maintenance Guidelines" [8]. Rutting can therefore form a single layer in the generalized quadtree with several black states based on severity.

Cracking information can be reported at the pixel level which is the lowest level of aggregation, or in some reduced form. For example, Komatsu reports cracking existence and type for each 0.50 x 0.50 m quadrant. PCES reports cracking existence for each 0.04 x 0.04 m quadrant. Each type of cracking can form a separate layer in the generalized quadtree if the conversion level for aggregation is high enough that more than one type of cracking may exist in the lowest level quadrants. Alternatively, different types of cracking can occupy the same layer if their spatial existence is mutually exclusive. Different black states corresponding to severity levels can be added to both configurations. Further characterization resulting in features such as progressive edge cracking or slippage cracking may require the use of additional layers. More surface distress types may be included in the model's surface representation than those discussed so far.

In order to use the model's surface representation for pavement management applications the surface representation must be included in a pavement inventory database. The files can be managed and accessed using a relational database management system. With the use of indexing and the relational database, the data can be accessed by pavement section, local area, surface property, surface feature, and different levels of aggregation and abstraction. Information from within a stored pavement section is retrieved by first reconstructing the section. A set of relations specifying a functional core group of tables is presented in Figure 3. Queries for information such as the number of sections with 20 - 30 % cracking coverage arranged according to network or pavement type could be answered with this configuration. Such detailed information would be useful for pavement performance studies. Alternatively, the database could be used to retrieve the generalized quadtree data for a particular section in order to calculate material requirements for maintenance work, or the data could be retrieved for visual review before sending out a maintenance crew. The use of the model's representation as a basis for archiving pavement condition data is one of the model's key benefits because of the flexibility and efficiency of the representation.

subsection quad data file name	subsection's section start position	subsection's section end position

section code	subsection quad data file name

section code	RCI	SAI	VCI

section code	longitude start	longitude end	latitude start	latitude end

network name	section code

FIGURE 3 -- A schema for a GQL to database link

A few figures illustrate how the GQL can be used to retrieve, rebuild and display or print surface condition information. For example, the first 100 m long by 4 m wide Komatsu subsection is illustrated in Figure 4. The rutting layer is shown using light grey, grey, and black for low, medium, and high rutting respectively. White represents no rutting. As another example, a 12 m long segment at the beginning of the first Komatsu subsection is shown in Figure 5 with longitudinal cracking represented as black and transverse cracking represented as grey.

FIGURE 4 -- Generalized quadtree rutting data for Komatsu subsection 3

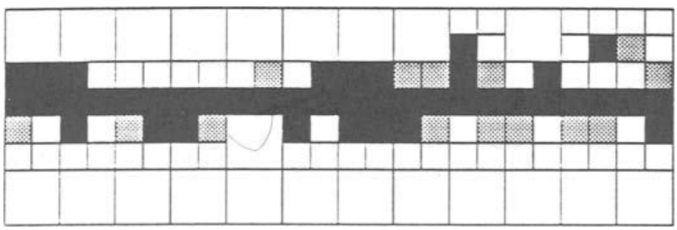

FIGURE 5 -- Generalized Quadtree Cracking Data for first 12 m of Komatsu Subsection 3

Standardized Linkage

A key benefit of the model is its ability to serve as a standardized link in a vertical chain of automated pavement management system modules. The ability of the model to serve as a flexible standardized link is illustrated by incorporating data from the three different pavement surface distress data acquisition systems described earlier into the model's surface representation. The primary unit for aggregating pavement condition survey information in a pavement management system is either a section, subsection, or sample unit. Subsections are represented using the acquired data from which two common types of summary condition measures are then derived. The summary measures include the: (a) Pavement Condition Index (PCI) measure defined by the PAVER system [7] and (b) the Surface Distress Index (SDI) defined in [9].

To prepare it for incorporation in the generalized quadtree representation, the data from each source was translated from its original storage format to one suitable for conversion to the generalized quadtree structure. Komatsu provided cracking, rutting, and roughness data for three 4 x 100 m subsections. The rutting data was reported for each wheel path every 0.25 m. It was averaged over 2.0 m for every level one quadrant in the generalized quadtree (Figure 4). Roughness was reported every 10.0 m. It was prepared for conversion at the first level in the quadtree. Cracking data was reported for every 0.5 x 0.5 m quadrant and was rearranged to prepare it for conversion at level three of the generalized quadtree (Figure 5).

PCES provided cracking data for a 2.44 x 53.6 m (8 x 176 foot) subsection. Each 2.44 x 2.44 m (8 x 8 foot) area is digitized at a resolution of 1024 x 1024 pixels. Cracking data is reported for each 16 x 16 pixel square or 0.038 x 0.038 m (1.5 x 1.5 inch) "tile". Each tile has either a black state equal to 1 or a white state equal to 255. The data was prepared in order to build two 2.44 x 19.5 m (8 x 64 foot) sections. While the orginal pixel data would form a quadtree with 10 levels, the data was converted at the tile aggregate level to create a generalized quadtree 6 levels deep. The first 7.32 m (24 feet) for each of the PCES sections are illustrated in Figure 6.

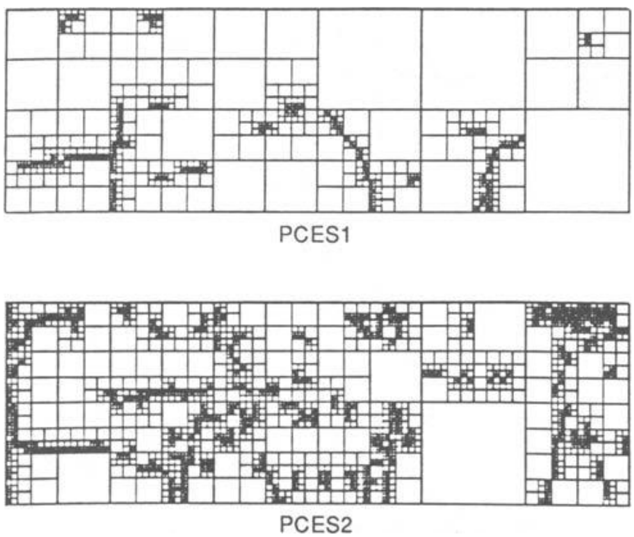

FIGURE 6 -- PCES Cracking Data

PASCO provided general surface distress data for a section of pavement 503 m (1650 feet) long and 3.66 m (12 feet) wide. Rutting data was reported at stations every 76.2 m (250 feet). Since the original file was corrupted near the end, a 122 m (400 foot) subsection at the beginning of the section was selected for conversion. Each cell in the basic grid can contain several distress codes so each distress type was incorporated into the strip quadtree in a separate layer including the rutting data. The concurrancy of a type of cracking and patching in the PASCO data indicates cracking that has been patched or filled. With its set functions the model can make use of this information in order to indicate stripping of or progression of cracking since repair. Such progression may illustrate deterioration. Four columns of blank data was added to the PASCO data to prepare it for conversion. This would not be necessary for the 4.88 m (16 foot) wide sections. For percent-area-covered calculations, the padding described was taken into account. Each layer of the PASCO subsection is illustrated in Figure 7. Only the first 24.4 m (80 feet) have been converted for display.

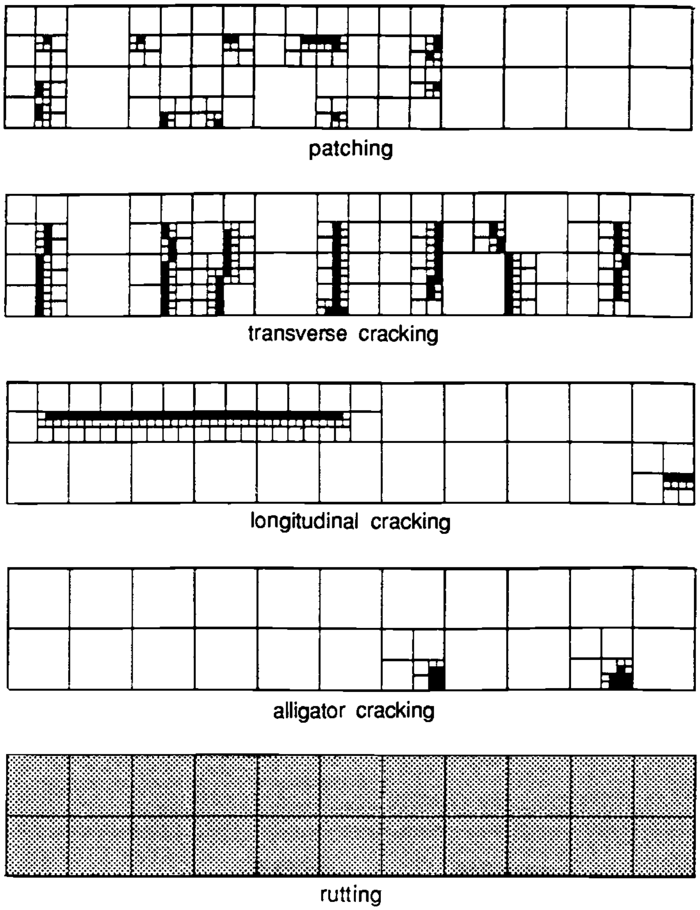

FIGURE 7 -- PASCO quadtree layers

Data volumes for representations of the test subsections at various stages are compared in Table 1. The first column of numbers includes the amount of raw data acquired for each subsection. The next column includes the size of the data in its processed and reduced form prior to conversion to the generalized quadtree representation. The next column over includes the amount of memory required by each company to store the data in its reduced form. PASCO, for example, uses a complex compression scheme. The last column includes the storage requirements for the equivalent generalized quadtree representation for the reduced data. Further characterization would likely increase the requirements. Table 1 illustrates that the generalized quadtree representation is efficient. Moreover, the generalized quadtree representation contains much more information than either the reduced or company formated data. This information includes spatial relationships and can include derived characteristics. The use of that information is demonstrated in this section and the next.

TABLE1 -- Data volumes for the test subsections

Memory Requirements in Bytes				
Subsection	Digitized Raw Data	Reduced Data	Company Format	Gen. Qtree Format
K1	41,991,000,000	1,800	n.a.	496
K2	41,991,000,000	1,800	n.a.	880
K3	41,991,000,000	1,800	n.a.	2,240
PASCO	27,406	25,700	15,000	16,032
PCES1	8,388,608	32,768	32,768	11,328
PCES2	8,388,608	32,768	32,768	5,736

Calculating the PCI for the Komatsu and PASCO subsections is made possible with the use of the tools the model provides. A distinction is made in the PAVER guide between linear and spatial measures for different distress types. For example, longitudinal and transverse cracking are measured in linear feet while alligator cracking is measured in square feet. Using the model's area functions for both is generally acceptable, because cracking running through a square foot area is approximately 1 foot long. Experiments could be conducted to test the accuracy of this assumption if it became critical. None of the cracking data provided was classified according to severity. To include severity information in the surface representation, each severity level can be represented as a different black state for each layer of cracking data. This approach is used for the rutting data in the sample subsections. To calculate the PCI, the cracking data is assumed to be medium in severity. It is difficult to calculate a meaningful PCI from the PCES data because none of the crack elements are classified, as for example transverse. Further characterization of the PCES data using the model's kernel tools such as adjacency functions is possible however. Such characterization could result in data suitable for direct PCI calculations. The PCI values for each Komatsu subsection are respectively 40, 30, and 19. It is interesting to note that if the average rut width is reduced to 1 foot, the PCI value for the first subsection improves to 53. The PCI value for the PASCO subsection is 27.

The functional definition of SDI which is sometimes refered to as VCI (Visual Condition Index) depends on the individual agency. What is important is that each of these indices represents a way of aggregating a number of different surface distress types into a single condition scale, and that the pavement surfaces model facilitates the automation of this process. The method used here for calculating SDI follows New Brunswick's method [9]. Each distress type is assigned a distress score (from a lookup table) that depends on the density and severity of the distress. Again, since severity information was not included with the source samples, it is arbitrarily set at medium. Each distress type is multiplied by a weighting factor that reflects its importance to determining need for rehabilitation or maintenance. The SDI value can be calculated for a whole section and should fall between 0 and 10 with 10 being a newly paved section. The SDI can be included in an overall quality measure such as the Pavement Quality Index (PQI) defined in [9] which also includes a Ride Comfort Index and a Structural Adequacy Index.

The SDI values for the Komatsu and PASCO subsections are calculated from the original density values derived from the pavement surfaces model's representation and listed in tables 2 and 3. Since an extent measure is used rather than density, a reasonable translation was implemented. Also, since neither system collected all of the New Brunswick distress types, the remainder of the weighting factor values were applied to an average of the distress scores for each section. The values for the Komatsu subsections are presented in Table 2. The values for the PASCO subsection are presented in Table 3.

TABLE 2 -- Komatsu SDI calculations

Komatsu SDI Calculations					
Section	Longitudinal Cracking 0.133	Transverse Cracking 0.111	Rutting 0.167	Average 0.589	SDI
K1	7	10	7	6	6.7
K2	7	7	3	5	5.2
K3	3	5	-2	2	1.8

TABLE 3 -- PASCO SDI calculations

PASCO SDI Calculations						
Section	Longitudinal Cracking 0.133	Transverse Cracking 0.111	Rutting 0.167	Alligator Cracking 0.200	Average 0.389	SDI
P1	-1	-1	10	9	4	4.8

Characterization Issues and Opportunities

Condition assessment can be described as the process of deriving summary measures of a section of pavement that characterize its performance. These measures can be very specific in which case they are mainly used for determining the most appropriate maintenance treatments, or they can be quite general in which case they are used for network wide maintenance and rehabilitation priority programing. In current practice, deriving a summary measure is usually a process of reducing a number of measurements from a single sensor to produce a value for a section as a whole, or it is a process of reducing a number of manual observations. For example, it might be reported from a manual survey that alligator cracking covers approximately 30% of a section of pavement. This value has some use, but it is imprecise and poorly defined for determining maintenance treatments. Moreover, the repeatability between different surveyors is subject to considerable variance. The rutting measure for a section may just be an average value over the whole section. Automated systems have and are being developed that collect much more extensive information about cracking, rutting, and roughness, however the information is processed in separate streams and still reduced to summary measures before being archived. As a result it is underutilized. Because the rutting and cracking information is processed separately in current systems, it is also impossible to answer questions such as "How much of the area of alligator cracking also incorporates moderate to severe rutting?". The answers to such questions can prove useful for determining the cause and extent of different distress conditions and consequently the most effective treatment, its extent, and its location.

The pavement surfaces model provides a set of basic tools that facilitate advanced characterization for more flexible and powerful condition assessment. For instance, the spatial extent of cracking expressed as a percentage for a Komatsu data subsection can be given with four digits of precision. The accuracy however as opposed to precision is a function of how well the image analyis software works and how accepted the definition of area cracked is. For instance, if the PCES data is represented at the same level of aggregation as the Komatsu data, the percent area covered by cracking is 32.8 % (Figure 8), but if the area is calculated using the original level of aggregation (Figure 9), the percent area covered by cracking is estimated by the model to be 6.6 %. Given such variation, a standard must be assumed for the basic area unit size for calculating the extent of cracking. Alternatively, cracking can be assessed by length, however level of aggregation of the quadtree also affects the results produced in this case as well. For example, quadrants at a high level might be used to represent longitudinal "cracking" while those at a lower level might be classed as belonging to a longitudinal crack. In the first case there may be several cracks in the quadrant.

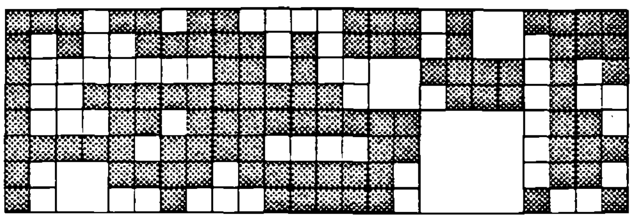

FIGURE 8 -- PCES Cracking data at 0.30 m (1 foot) square level of aggregation

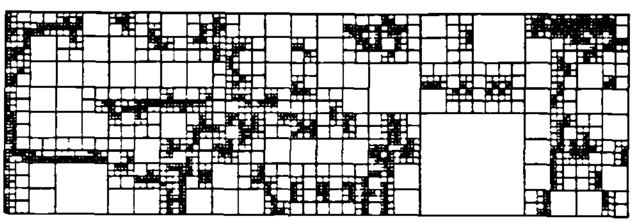

FIGURE 9 -- PCES Cracking data at 0.04 m (1.6 inch) square level of aggregation

Examples of the model's characterization capabilities demonstrate its potential usefulness. The intersection of transverse and longitudinal cracking with moderate to severe rutting for the first 12 m of each of the Komatsu subsections is illustrated in Figure 10. The top strip indicates that for subsection one there is no intersection. In the next two subsections there is an increasing degree of overlap between cracking and rutting. While this result has some value, it is difficult to ascertain from it the cause of the cracking. However, if the rutting data were incorporated at a level of aggregation that described more accurately its spatial extent (such as level two or three of the generalized quadtrees developed here), and cracking of type alligator was found to intersect with it, then the cause of the cracking is likely excessive deflection due to insufficient pavement strength. Another example of the advantages of deriving spatial intersections is to use the temporary quadtree layer described previously to find the intersection of shoulder edge quadrants with alligator or longitudinal cracking. The derived distress can be classified as progressive edge cracking which can have a number of causes including frost action, poor drainage at the pavement edge, insufficient strength at the edge, or inadequate pavement width. Appropriate maintenance treatments can be recommended based on this causal knowledge [8].

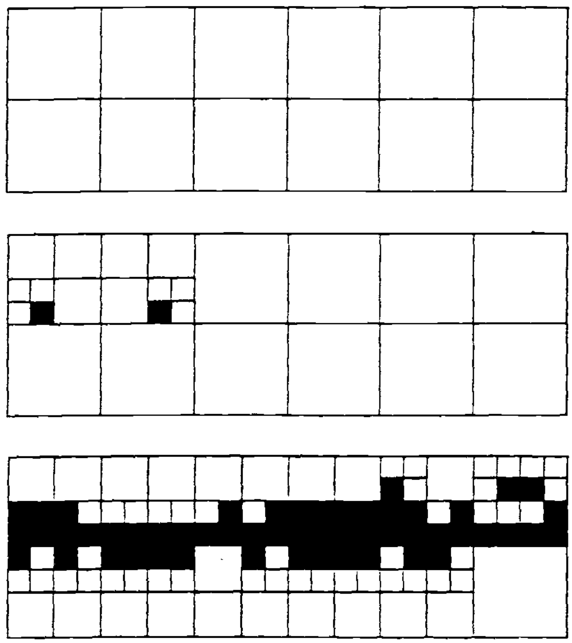

FIGURE 10 -- The intersection of cracking and rutting for the Komatsu subsections

Regions of distress conditions can be useful for assessing pavement condition and for providing interesting and potentialy useful results. Regions can be identified using the GQL's region labeling function. For example, this function was used to find the average length of transverse and longitudinal cracking in the PASCO sample section. They are respectively 1.75 m (5.74 feet) and 3.81 m (12.5 feet). The longitudinal value may be low because some cracks may not have been identified as a single unit by the region labeling function. This could be corrected by a separate connecting step. The average area of alligator cracking regions in the same section is 0.40 square metres (4.27 square feet).

Advanced characterization may be used for deterioration modeling as well as condition assessment. Figure 2 shows the intersection of transverse cracking and patching for the PASCO subsection. It indicates how the model might be useful for deterioration modeling, since the extent of the progression of some types of distress can be assessed with far greater accuracy than what is currently possible. If accurately aligned, time separated surveys of the same surface could be incorporated in the model's representation and used to graphically illustrate the process of deterioration as well as accurately assess its extent at each stage. Results from development of a robotic pavement crack filler demonstrated how the acquisition of cracking and patched cracking data could be automated [4]. It is clear that such uses of the model are therefore feasible in a fully automated process.

CONCLUSIONS

In addition to illustrating the pavement surface model's role as a common link for automated management data, the preceding demonstrations also suggest its potential as a standard. The efficiency of the model compares well with other current representations and it has the advantage of including more useful information.

The model facilitates more flexible, comprehensive and precise assessment and comparison of pavement surface conditions than what is currently available. Because of these advantages, it can form the basis for more informed maintenance selection decisions, more detailed project level design, and potentially more optimal prioritization for maintenance and rehabilitation. The result should be more effective maintenance and thus reduced pavement life cycle costs. The model's capability to provide more precise and comprehensive condition comparisons should also prove useful for acceptance testing and improved deterioration modeling.

ACKNOWLEDGMENTS

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COMPARING STANDARD LOAD EQUIVALENCY CALCULATIONS FOR PAVEMENT MANAGEMENT SYSTEMS

REFERENCE: Hudson, W. R. and McNerney, M. T., "Comparing Standard Load Equivalency Calculations for Pavement Management Systems," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: Pavement Management, at the network level as well as at the project level, requires that load equivalencies be used to define traffic inputs. For the past 30 years, load equivalencies have been calculated using the performance equations developed for the AASHO Road Test. In these performance equations, traffic and accumulated loads are used as indications of performance (that is, serviceability versus accumulated load applications or pavement distress versus accumulated load applications). The paper discusses the load equivalencies recently developed from reanalyses of the AASHO Road Test data. This paper refutes the load equivalencies presented in the book, Road Work, published by the Brookings Institution. This paper also briefly reviews load equivalencies derived from two other studies, one by Illinois Department of Transportation and one by Paul Irick. The paper concludes that the conventionally accepted load power ratio of the fourth power law is still correct and the AASHO Road Test load equivalencies are nearly correct and should remain as a standard for calculating load equivalencies.

KEYWORDS: pavement management systems, load equivalency, AASHO Road Test, load power factor, pavement performance, axle weights, pavement design, serviceability

A characteristic of a complete pavement management system is the existence of a feedback loop which ties actual pavement performance into the design/analysis phase. The principal way to accomplish this objective is to establish or estimate the amount of accumulated traffic that the pavement sections have carried, or expected to carry, during the

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pavement's life cycle or serviceability life. If standard methods relating pavement performance to cumulative traffic can be established then more reliable pavement designs could be achieved.

Pavement performance is influenced both by load and environmental factors. However, comparisons of the load performance of different pavement designs are possible only if the independent variable is based on cumulative traffic converted to a common load application scale. Since the common scale is necessary for defining the load effects of multiple truck types, it is essential that the method for estimating load equivalencies be properly defined and standardized.

For the past 30 years, load equivalencies have been calculated using the results of the AASHO Road Test [1]. During this test the serviceability performance concept was developed and although pavement distress was considered it was not the principal factor in pavement life. This concept provided a true measure of performance without the introduction of variability associated with many different types of distress. Though the AASHO Road Test was conducted over thirty years ago, no other road test has been successful in redefining or changing equivalent load relationships for single and tandem axles in relation to serviceability performance. Although there has been a tremendous investment in the Strategic Highway Research Program (SHRP) Long Term Pavement Performance Study and the Minnesota Road Research Project (Mn/ROAD), neither will produce any load equivalencies based upon serviceability ratings.

Although the AASHO equivalency factors have been the standard for 30 years, this does not mean that an 8.2 ton single axle load of the AASHO Road Test is of the same damaging effect as an 8.2 ton single axle load on the highways of the United States today. The typical truck tire of the AASHO Road Test was a bias belted tire while today radial ply tires with much higher tire pressures are common. Another innovation of modern technology has been the introduction of extra wide single tires to replace and carry the load of dual tires. A recent accelerated load test at the Federal Highway Administration Research Center has shown the single tire causes at least four times as much damage on a thin asphalt section [2].

There have, however, been recent studies in which some reevaluations of load equivalencies for the AASHO Road Test have been undertaken. The authors of the book, Road Work, recently published by the Brookings Institution, have alleged that errors in the regression analysis of the AASHO Road Test resulted in under design of the thickness of our nation's highways resulting in premature failure of those designs [3]. In that book, the authors, Kenneth Small, Clifford Winston and Carol Evans, describe a method of reanalysis of the Road Test data using a Tobit regression analysis. Based on their analysis, they wrongly conclude that the effects of increasing load increases pavement damage at the power factor of 3 instead of the commonly accepted AASHTO 4th power factor.

Since any reanalysis of the AASHO Road Test could result in different prediction equations, each set of new prediction equations can subsequently be used to develop revisions to the load equivalencies. Because of this phenomenon the authors in this paper will compare the revision to load equivalencies possible from other studies including that done by Little and McKenzie of Illinois Department of Transportation, the authors' revision of the Road Work regression analysis, and one done by Paul Irick.

AASHO ROAD TEST

The AASHO Road Test consisted of six Test Loops containing both rigid and flexible pavements. Rigid pavement thicknesses ranged from 32 cm to 6 cm. Axle Loads consisted of 1, 2.7, 5.4, 8.2, 10.2 and 13.6 metric ton single axles and 10.9, 14.5, 18.2 and 21.8 metric ton tandem axles. Figure 1 is a graphical representation of the 264 rigid pavement test sections. Each test lane received 1,113,800 axle repetitions of a specific type of applied load during a two year period. A total of 264 primary experiment, rigid pavement test sections were loaded during the test. The different test sections were defined by variations in subbase thickness and type reinforcement.

The original analysis of the Road Test data was very comprehensive and considered several different mathematical models. The AASHO Road Test used panels of raters to determine the Present Serviceability Rating (PSR) and developed a Present Serviceability Index (PSI) based primarily on slope variance. The traffic loading was continued to a terminal serviceability index of 1.5 to insure that the data would represent the complete serviceability curve. The majority of the test sections never reached a Present Serviceability Index of 1.5 and had a PSI greater than 4.0 at the conclusion of the Road Test. At least five different PSI readings were used in the analysis of all sections, even those sections that showed very little serviceability loss. Of the several methods tested, the method that showed the best fit at the Road Test was a regression analysis using least squares technique.

The general form of the original Road Test performance equation is:

$$\log N = \log \underline{\rho} + G / \beta \qquad (1)$$

where N is the number of load applications
$\underline{\rho}$ and β are complex functions of design and load
G is the serviceability loss term.

For rigid pavements the expressions for $\underline{\rho}$, β, and G converted to units of centimeters and metric tons are:

$$\underline{\rho} = 10^{5.85} ((D_2/2.54) + 1)^{7.35} L_2^{3.28} / (2.2L_1 + L_2)^{4.62} \qquad (2)$$

$$\beta = 1 + (3.63 (2.2L_1 + L_2)^{5.20} / ((D_2/2.54) + 1)^{8.46} L_2^{3.52}) \qquad (3)$$

$$G = \log ((4.5-P_t) / 3) \qquad (4)$$

where L_1 = axle load in metric tons
L_2 = 1 for single axles and 2 for tandem axles
D_2 = slab thickness in centimeters
P_t = Terminal Serviceability Index

Distribution of AASHO Rigid Test Sections

LOOP	2		3		4		5		6		
LANE	1	2	1	2	1	2	1	2	1	2	
LOAD (metric tons)	0.9 S	2.7 S	5.4 S	10.9 T	8.2 S	14.5 T	10.2 S	18.2 T	13.6 S	21.8 T	S=Single T=Tandem
Thickness (cm)	Number of Test Sections of Each Type										Totals
6.4	6	6									12
8.9	7	7	6	6							26
12.7	7	7	8	8	6	6					42
15.2			8	8	8	8	6	6			44
20.3			6	6	8	8	8	8	6	6	56
24.1					6	6	8	8	8	8	44
28.0							6	6	8	8	28
31.8									6	6	12
Totals	20	20	28	28	28	28	28	28	28	28	264

Note: Loop 1 carried no loads.

Figure 1. Distribution of AASHO Rigid Test Sections

For the 8.2 ton single axle load, when $2.2L_1=18$ and $L_2=1$, the log ρ and ß terms reduce to:

$$\log \rho = -0.058 + 7.35 \log ((D_2/2.54) + 1) \quad (5)$$

$$ß = 1 + 10^{7.209}(D_2/2.54 + 1)^{-8.46} \quad (6)$$

ILLINOIS DOT CONTINUATION OF AASHO ROAD TEST

At the completion of the AASHO Road Test, many of the thicker rigid test sections were still in excellent condition. Others were subsequently rehabilitated as new 25 cm thick rigid test sections duplicating the original AASHO construction practices. The Illinois Department of Transportation incorporated the original and new sections into Interstate 80 to continue the research on this historic road test. For inclusion into the rehabilitated roadway, the rigid test sections had to be at least 20 cm thick and structurally sound with no visible signs of deterioration. A few 20 cm sections, most of the 24 cm sections and all the 28 and 32 cm original sections were retained.

This section of Interstate 80 opened to carefully measured traffic in November 1962. The traffic consisted of 71 percent passenger cars, 6 percent single-unit trucks and 23 percent multiple-unit trucks. More than 96 percent of the heavy trucks used the outside lane; therefore, only the outside lane was evaluated. The annual growth rate of average annual daily traffic (AADT) during the first ten years was a very high 22 percent.

The results of the additional trafficking of these original and rehabilitated test sections were published by the Illinois Department of Transportation [4]. Little and McKenzie concluded from their analysis that the Road Test performance equation did not predict the serviceability trend for the 28 and 32 cm rigid pavement sections with the same level of precision that was achieved for the 20 and 24 cm pavements. They concluded that the Road Test performance equation fit the 24 cm rigid pavement data very well. Since the 28 and 32 cm rigid pavements showed so little change in serviceability index during the AASHO Road Test, Little and McKenzie theorized that the Road Test equation might be improved by further analysis.

In their investigation, Little and McKenzie performed a least squares analysis similar to the original AASHO analysis. Using data from five different traffic levels (usually 1968, 1969, 1971, 1972, and 1974), Little and McKenzie reported the following performance equation for 8.2 ton single axles assuming Beta equal to 1.

$$\log N = 2.724 + 4.50 \log ((D_2/2.54) + 1) + G \quad (7)$$

This equation can be compared to the original AASHO equation with the same assumptions rewritten in equation 8 in the same format.

$$\log N = -0.058 + 7.35 \log ((D_2/2.54) + 1) + G \quad (8)$$

TOBIT ANALYSIS OF AASHO ROAD TEST PERFORMANCE DATA

In Road Work, the AASHO Road Test data was reanalyzed. The model for analyzing the data used by Small and Winston was the Tobit model, an econometric model originally developed by James Tobin in the early 1950's as a tool for the economic analysis of household expenditures [5]. The model is functionally the same as a survival analysis such as the LIFEREG procedure in SAS. [6]

It is important to note that many original AASHO Road Test sections, particularly the thicker ones, had not reached a 2.5 serviceability index after 1,113,800 axle repetitions. In the Road Work survival analysis, however, any pavement section that had not yet reached a 2.5 serviceability index was considered a survivor; therefore, the serviceability index of that test section was censored.

The data used by Small and Winston censors 191 of the original 264 Road Test rigid pavement test sections. Figure 2 shows the relative distribution of observed and censored test sections with respect to thickness. Each data point is a recording of the number of axle repetitions when each section reached a 2.5 terminal serviceability index. If the Present Serviceability Index (PSI) is greater than 2.5, whether it was 2.6 or 4.5 PSI (nearly new condition), the survival analysis does not record the PSI value of those test sections. In figure 2, note that the 73 observed test sections include only 3 of the 44 test sections of 24 cm thickness and none of the 28 or 32 cm test sections. Thus the analysis depended heavily on pavements 20 cm or thinner. The resulting mean thickness of the observed test sections used in the Road Work analysis was only 14.7 cm.

The Tobit analysis by Small and Winston yielded the following regression equation:

$$\ln N = 13.51 + 5.04 \ln((D_2/2.54) + 1) - 3.24 \ln(2.2L_1 + L_2) + 2.27 \ln(L_2) \quad (9)$$

Equation (9) is plotted graphically in Figure 3 with the AASHO performance equation for a range of pavement thicknesses for 8.2 ton single axles. From this plot is obvious that there is a vast difference in the two results, particularly for thicker pavements. The significance of these equations for a typical 25.4 cm rigid pavement is a prediction of 9.3 million 8.2 ton ESALs for the Small and Winston equation and 28.6 million for the AASHO equation. To predict a 26.2 million 8.2 ton axle lifetime using the Small and Winston analysis, the pavement thickness would have to be increased from 25.4 cm to 32 cm. The authors of Road Work believe that the difference of these equations is the reason that the AASHO design overestimates the life of thick rigid pavements [7].

AUTHORS' REVISION TO THE ROAD WORK TOBIT ANALYSIS OF PERFORMANCE

The authors of this paper completed an analysis [8] that more

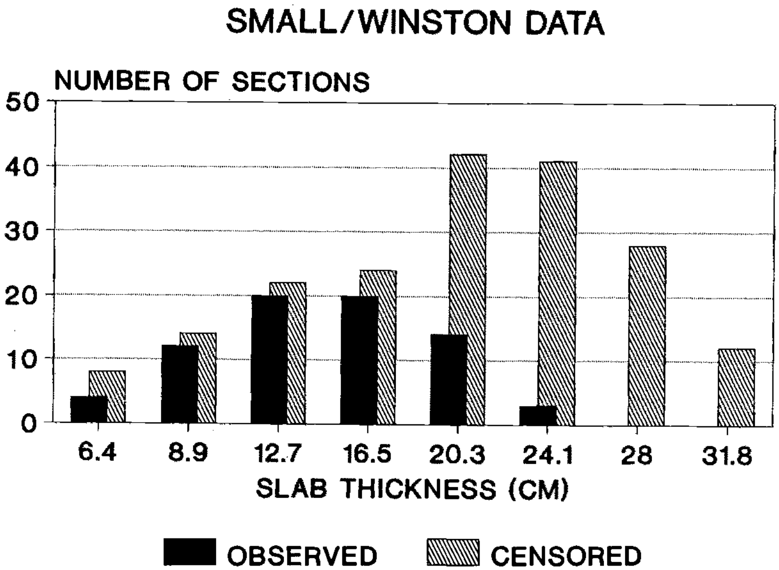

Figure 2. Comparison of AASHO Censored and Observed Failure Sections

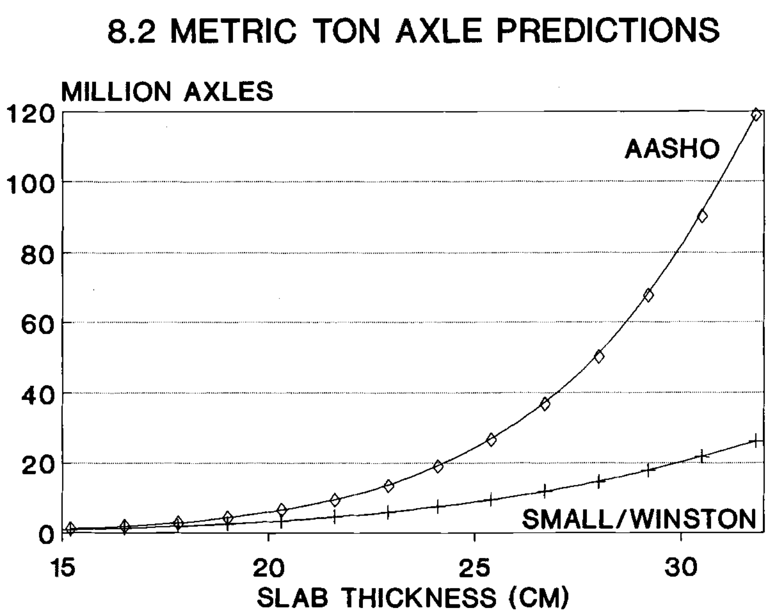

Figure 3. Comparison of Number of Predicted Axle Passes by Thickness

adequately describes the effect of the additional 12 years of traffic on the thick rigid pavements of the original AASHO test sections. From this study it was concluded that the Small and Winston analysis was not valid for thick rigid pavements. Further, it is believed that the survival analysis used by Small and Winston does not yield robust predictions of thick rigid pavement performance because traffic was not continued for an adequate number of load applications for the survival regression technique. The survival analysis censors the serviceability index of surviving test sections. These data, where only 3 of 84 sections were equal or greater in thickness than 24 cm, resulted in skewed results.

The authors of this paper have presented a recalculation of the Small and Winston performance equation using the same survival analysis for the additional traffic on the 24, 28, and 32 cm original test sections that were incorporated in the rehabilitated Interstate 80 roadway. The results of this expanded analysis yielded the following regression equation with different coefficients than the Small and Winston regression equation:

$$\ln N = 14.02 + 6.72 \ln((D_2/2.54) + 1) - 4.46 \ln(2.2L_1 + L_2) + 3.1 \ln(L_2) \quad (10)$$

For a 25.4 cm section, the 8.2 ton single axle prediction is increased from 9.3 million in equation 9 to 24.3 million in equation 10. In other words, simply by adding the additional traffic on the original AASHO test sections the predicted performance of a 25.4 cm rigid pavement is double the Small and Winston estimate. When comparing the equations it shows that the load coefficient in equation 9 is increased from 3.24 to 4.46 in equation 10; which is very close to the 4.62 load coefficient of the AASHO performance equation converted to the same format.

A comparison of four performance equations for a 25.4 cm rigid pavement is presented in Figure 4. The graph shows that the Revised Small and Winston equation is similar to the original AASHO equation. The Illinois DOT performance equation was regressed to fit thicker rigid pavements and therefore over predicts a thin pavement performance. It is evident that the Small and Winston performance equation becomes unrealistic when applied to thick rigid pavements. The underestimation of performance for thick rigid pavements for the Small and Winston survival analysis can be related to the limited number of thick rigid test sections that actually reached failure during the AASHO Road Test.

LOAD EQUIVALENCIES

For a given pavement thickness, the regressed performance equation can calculate the number of axle repetitions for a specific axle load. For example, for a 25 cm rigid pavement, the number of 8.2 ton and 43.6 ton single axle repetition can be calculated using the performance equation. The higher load results in fewer axle repetitions. The ratio of the number of axle repetitions is the load equivalence or equivalent damage. The commonly used AASHTO load equivalence factors are calculated in this manner for 3 different serviceability index levels and various pavement thicknesses in the AASHTO Design Guide [9].

Another analysis of load equivalencies based on the Road Test data was developed for the Trucking Research Institute by Paul Irick with the engineering consultant firm of ARE, Inc. [10]. Unlike the AASHO approach in which the load factors are calculated indirectly, the Irick study made use of replicate and similar sections studied during the Road Test. Since a few replicate pavements were subjected to different loading conditions, load factors can be determined directly for these pavements. Regression models were developed for these comparison data to estimate factors as a function of load, structure and serviceability loss.

The Irick study also investigated alternate failure criteria, such as cracking and rutting for flexible pavement, and cracking and pumping for rigid pavement. A severe limitation of the Irick study is that load equivalence for tandem axles was not addressed. The Irick study resulted in several different equations for load equivalences. The authors have not included the Irick equations for rigid and flexible load equivalencies due to loss of serviceability because of the difficulty in converting the equations to S.I. units.

Another limitation of the Irick study is the limited number of available replicate sections when compared with the total number of test sections. Because of this, it is expected that the variability of the results would tend to be greater. Also it should be noted that for rigid pavements the Irick study found the selection of terminal serviceability index to be non-significant, whereas for flexible pavements it was significant.

COMPARATIVE LOAD EQUIVALENCIES AND POWER FACTORS

One striking comparison of these four different methods of calculating load equivalence factors is the comparison of rigid pavements with respect to loads. Table 1 shows that for a typical 25.4 cm rigid pavement the AASHO and Revised Small models predict the highest load equivalence for higher single axle loads and the Irick method predicts the lowest. But for low single axles loads the reverse is true, the Irick study predicts the highest load equivalency and the AASHO method predicts the lowest.

Table 1 - Comparisons of load equivalencies for 25.4 cm rigid pavements for single axle loads

LOAD, tons	AASHO	IRICK	SMALL	REVISED SMALL
4.5	0.0808	0.3758	0.1701	0.0872
8.2	1.0	1.0	1.0	1.0
13.6	8.788	2.341	4.887	8.944

Another striking comparison of load equivalencies is the sensitivity of the models to pavement thickness. Since the Small and Revised Small analysis equations have no correction term for terminal serviceability, the ratio for load equivalencies has the same thickness term in the numerator and denominator. Therefore, the Small and Revised Small equations are completely independent of slab thickness or structural number when calculating load equivalencies.

For flexible pavements the Irick model in Figure 5 shows that the load equivalence factor increases as structural number increases. The AASHO load equivalence model describes a situation for the 11 ton load where the lowest increase in load equivalence is near a pavement with a structural number of 4 and then increases.

In Figure 6, evidently the Irick model shows that the load equivalence factor decreases for rigid pavements as slab thickness increases. This is the opposite effect that the Irick models shows for flexible pavements. The AASHO model is nearly constant with respect to thickness but does show a minimum load equivalence factor of near 18 cm thickness. Remembering that the Irick study included only replicate sections that reached 2.5 PSI, this study should be used with great caution for higher thicknesses. Only three rigid sections with a thickness greater than 20 cm reached 2.5 PSI at the Road Test.

The load power factor is a measure of the sensitivity of the load equivalence factor (LEF) to load. It is defined as the log of the LEF divided by the load ratio, where the load ratio is the ratio of the load divided by the reference load, usually 8.2 ton. Figure 7 shows the load power factors for three performance equations for a 25 cm rigid pavement.

CONCLUSIONS

Any regression analysis technique using the AASHO Road Test Data could result in a new performance equation. The resulting load equivalencies derived from those revised performance equations should be carefully documented with respect to the assumptions and limitations of the analysis. Performance equations, which are a result of mixed traffic or performance other than serviceability, are not truly comparable with the AASHO Road Test load equivalencies. Although there may be some inaccuracy in the AASHO load equivalencies as a result of current truck loads and inadequate thick rigid pavement loadings, they remain the best estimates and should be retained as standards for data collection and analysis.

The performance equations presented in the book, Road Work, are not an accurate representation of load equivalencies. The choice of the Tobit or survival analysis regression model for analysis of the original AASHO data resulted in an inaccurate presentation of the thicker rigid pavement performance. When the experiment was partially continued with additional traffic, the same survival analysis regression technique provides results closely matching with the results of the original AASHO performance equation. The results of the Revised Small model confirm the 4th power law of load equivalence presented by the AASHO Road Test analysis.

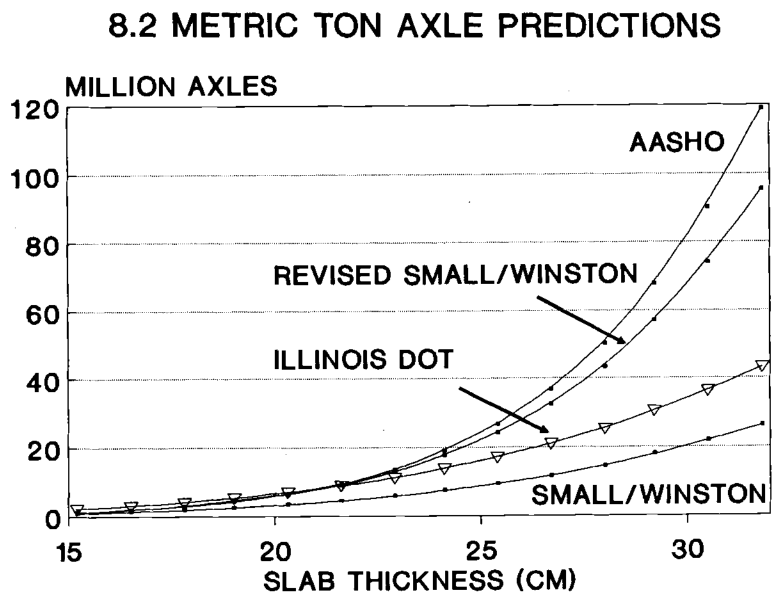

Figure 4. Comparison of Number of Predicted Axle Passes by Thickness

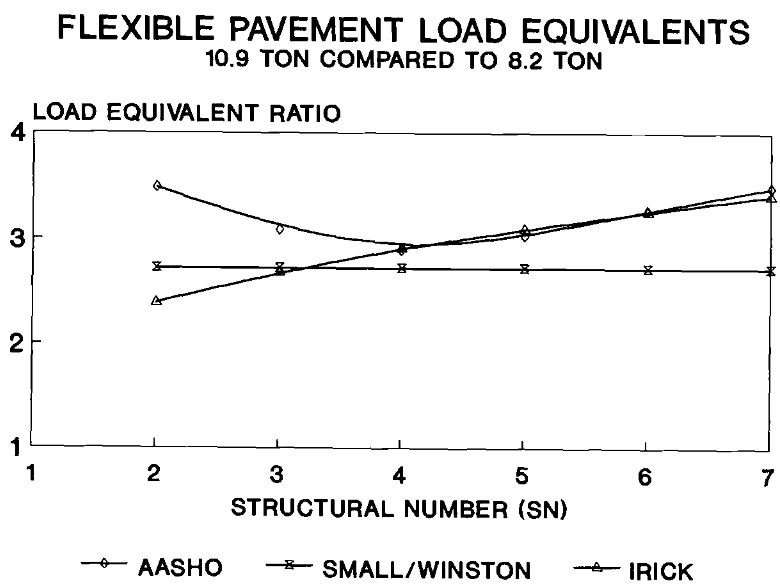

Figure 5. Comparison of Flexible Pavement Load Equivalents

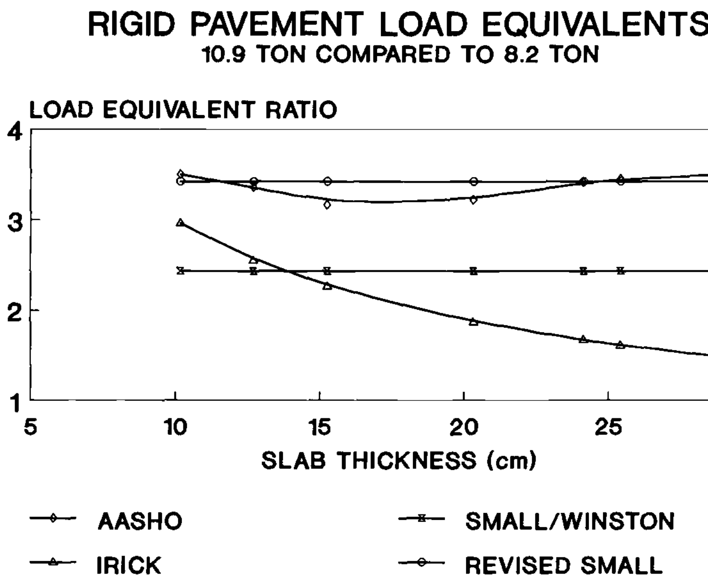

Figure 6. Comparison of Rigid Pavement Load Equivalents

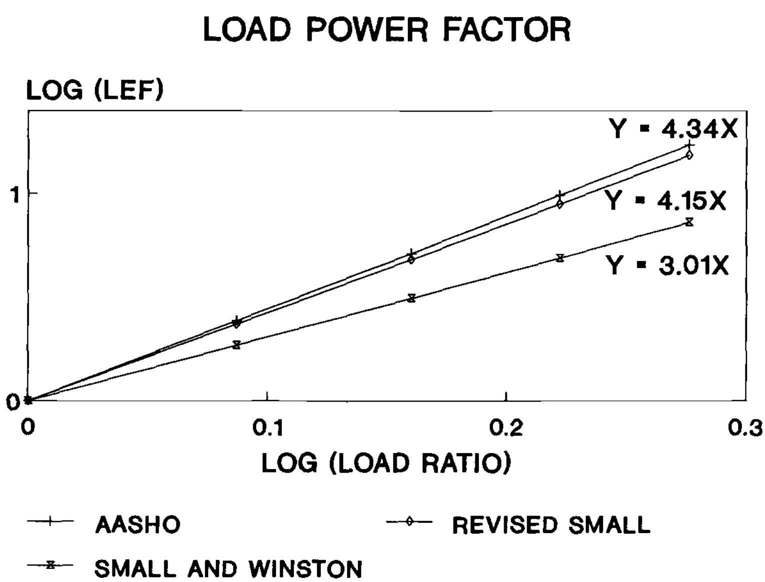

Figure 7. Comparison of the Load Power Factor

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Hosin Lee[1]

STANDARDIZATION OF DISTRESS MEASUREMENTS FOR THE NETWORK-LEVEL PAVEMENT MANAGEMENT SYSTEM

REFERENCE: Lee, H., "Standardization of Distress Measurements for the Network-Level Pavement Management System," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: Pavement distress information is one of the most important inputs to a pavement management system. Each state developed its own procedure to collect pavement distress data, which resulted in the lack of standardization of distress measurements for pavement management. The full standardization of the pavement management system cannot be achieved without standardizing its input. In addition, there always exists an inconsistency among different raters when they are conducting visual distress surveys. The inconsistency among the raters seems to be a problem for most state highway agencies. The automated image processing technology could help develop a standard crack measure. This paper presents a standard crack density method using video images of pavement surfaces, which can be easily adopted by all fifty states for their network-level pavement management systems. The standard crack density can be automatically computed by dividing the number of crack pixels by the number of total pixels of the pavement surface using the existing image processing technique. The standard crack density is an objective, consistent, and repeatable measure of cracks.

KEYWORDS: Pavement Management Systems, Standard Crack Density, Visual Distress Survey, Pavement Distress, Image Processing, Automated Distress Measuring Device, Standardization.

A pavement distress survey is one of the most essential elements of any pavement management system (PMS). Without accurate measurement of pavement distress, a PMS output would become unreliable.

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In the past, a pavement distress survey has been independently conducted by each state highway agency. As a result, the pavement distress survey procedure is not currently standardized across the United States.

The basic problem to be addressed in this paper is the lack of standardization of pavement distress definitions and distress measuring methods. This paper first discusses distress measurement nomenclature and the visual distress survey procedure. The consistency of the visual distress survey procedure which is currently adopted by Washington State Department of Transportation (WSDOT) is then evaluated using the pavement distress data collected from the sample pavement sections. The test sections included only asphalt pavements with various types of cracking. The current status of the automated distress measuring equipment is discussed for its implementation. Finally, the paper presents a standard crack density method utilizing video images which can be adopted by all fifty states.

PAVEMENT DISTRESS MEASUREMENTS

Since the AASHO Road Test, a number of pavement distress identification manuals have been published. Each state developed its own pavement distress survey procedure. In 1979, in an effort to promote standardization, the Federal Highway Administration (FHWA) developed a distress manual [1]. Recently, the Strategic Highway Research Program (SHRP) has published a distress identification manual [2]. Both manuals illustrate different extent and severity levels of various distress types with appropriate pictures. They list eighteen distress types for asphalt pavements, and twenty-one distress types for concrete pavements. This number may grow in the future as we learn more about the pavement behavior.

Pavement distress survey, which is one of the most important inputs to PMS, is not currently standardized in the U.S. Each state highway agency collects different distress data items of its interest depending on their needs in PMS. There are a number of different methods of collecting distress data such as a windshield survey, a portable computer system, and an automated image processing system. Currently, the efforts are being made towards standardizing pavement distress definitions, and determining the accuracy of various distress measuring methods.

Typically, there are two levels of PMS, network and project. Different levels of PMS require different types of distress data. The lessor amount and detail of information would be needed for a network-level PMS [3]. Collecting detailed distress information would be very cumbersome or may not be needed for most applications at the network-level PMS. Therefore, standardization of visual distress survey procedure should be initiated for the network-level PMS which may require less detailed distress data. Usually, for the network-level PMS, different types of distress are then combined into a common index using a subjective weighting scale such as deduct point system, utility functions, etc. As a result, there are many different distress indices developed by different state highway agencies such as Pavement Condition Rating (PCR), Pavement Condition Index (PCI), Pavement Quality Index (PQI), etc.

PAVEMENT CRACK MEASUREMENTS

The next question is "What do pavement engineers really want to know about pavement distress?" This question was well addressed by Mahoney [4]. One question was how wide a "hairline crack" should be. The answer was given by Mahoney as exactly 0.004 inch (0.1016 mm). Another question could be how wide the spacings between alligator cracks should be? One distress survey manual suggests that the alligator crack spacings should be ranging from one inch (2.54 cm) to approximately six inches (15.24 cm) [5]. Another manual defines that the alligator cracks should resemble the pattern of alligator hide with more than 12 inches (30.48 cm) spacing (moderate severity) or less than 12 inches (30.48 cm) spacing (high severity) in longest dimension [6].

The pavement cracking is one of the most important distress types. Again, there is no widely accepted measure for cracking in pavements, and no international standardization has been established [7]. In general, there are three characteristics of cracking such as type, extent, and severity. Cracking can be classified into three types such as network (alligator or map) cracking, line (longitudinal or transverse) cracking, and irregular (meandering or diagonal) cracking. All three characteristics of cracking have been collected by most state highway agencies using visual distress survey procedure. This paper addresses both the standardization of crack measurements and the development of a common cracking index. The scope of the paper is limited to the measurement of cracking on asphalt pavements only.

VISUAL DISTRESS SURVEY PROCEDURE IN WASHINGTON

WSDOT has been conducting a visual pavement distress survey biennially since 1969 on a complete state highway system [8]. For asphalt pavements, the most consistent distress types were found to be cracks. The two digit code system is used to record these three types of crack with their severities and extents as shown highlighted in Table 1. As shown in Table 1, the first digit indicates the distress extent, and the second digit indicates distress severity. "N" denotes that no distress is present in the pavement section.

It is very difficult to evaluate overall distress measurements because different types of distress were measured in different measurement units (i.e., longitudinal crack in linear feet, alligator crack in percent of wheel track, and transverse crack in the number of counts). Therefore, the Pavement Condition Rating (PCR) system was developed based on the deduct point concept [8]. The deduct points were developed by engineers working in pavement design and rehabilitation. The initial deduct points were based on the genesis of distress development and the maximum deduct points required to trigger rehabilitation. Several modifications were made to the original deduct points to achieve a consistent rating over the years. The present deduct points are shown in parentheses in Table 1. The PCR values are computed by subtracting deduct points from 100. The PCR values are then used for developing six-year highway construction budget based on the project specific pavement performance curves for the entire state highway system.

TABLE 1 -- Two Digit Code System with Deduct Points for WSDOT's PMS

a) Alligator Cracking (percent wheel track per station)

	Severity			
Extent	None	Hairline	Spalling	Pumping
1-24%	1N(0)	11(20)	12(35)	13(50)
25-49%	1N(0)	21(25)	22(40)	23(55)
50-74%	1N(0)	31(30)	32(45)	33(60)
75-100%	1N(0)	41(35)	42(50)	43(65)

b) Longitudinal Cracking (linear feet per station)

	Severity			
Extent	None	Hairline	1/4 in	Spalling
1-99	1N(0)	11(5)	12(15)	13(30)
100-199	1N(0)	21(15)	22(30)	23(45)
>200	1N(0)	31(30)	32(45)	33(60)

c) Transverse Cracking (numbers per station)

	Severity			
Extent	None	Hairline	1/4 in	Spalling
1-4	1N(0)	11(5)	12(10)	13(15)
5-9	1N(0)	21(10)	22(15)	23(20)
>10	1N(0)	31(15)	32(20)	33(25)

CONSISTENCY AMONG VISUAL SURVEY RATERS

Currently, over forty state highway agencies still use a visual survey, three agencies use video systems, and one agency uses a photo-logging system [9]. In the past, the accuracy of various visual distress survey procedures has been evaluated by many state highway agencies. A significant amount of efforts has been made towards consistent rating by offering special distress survey schools to train raters. Unfortunately, it has been reported by many states that there still exist substantial variations among raters [10]. The factors which seem to affect the accuracy of visual distress survey most include [11]:

1. the subjectivity of the inspectors,
2. the complexity of the inspection method,
3. weather conditions, and
4. the way the inspections are conducted (walking or driving).

In this paper, the WSDOT visual distress survey method is evaluated with respect to its consistency among three different raters. The three raters were trained through a week-long road raters class offered at WSDOT. For this study, the visual distress survey was conducted by each rater while driving along the pavement sections. The visual survey results were recorded at the field in the categorized form using the two digit code as previously shown in Table 1. The field test sections were selected to include a variety of cracking types, extents and severities. The selected test sections are located on State Route (SR) 283 and SR 28 between cities of Davenport and Ephrata in Washington as shown in Figure 1. At each section, three cracking types, which include alligator, longitudinal and transverse cracking, were measured for their extents and severities by three raters.

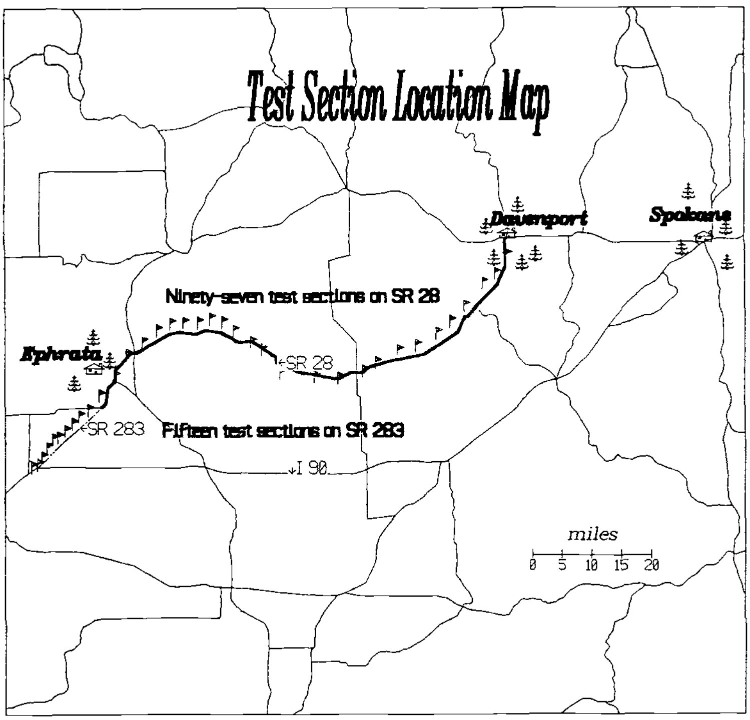

FIG. 1 Test Section Location Map for Visual Distress Survey in Washington

Total of 112 pavement sections located along SR 283 and SR 28 were evaluated three times by three different raters. The three sets of measurement were then compared to determine the consistency among the raters. As shown in Figure 2, approximately 25 percent of pavement sections were consistently evaluated by all three raters with respect to transverse and longitudinal cracking. Regarding alligator cracking, about 50 percent of pavement sections were consistently rated by all three raters. However, when only sections with cracks actually present are included for analysis (excluding all 1N ratings), the consistency among three raters was significantly lower as shown in Figure 3. For example, for alligator cracking, only 5 percent of pavement sections was consistently rated by all three raters.

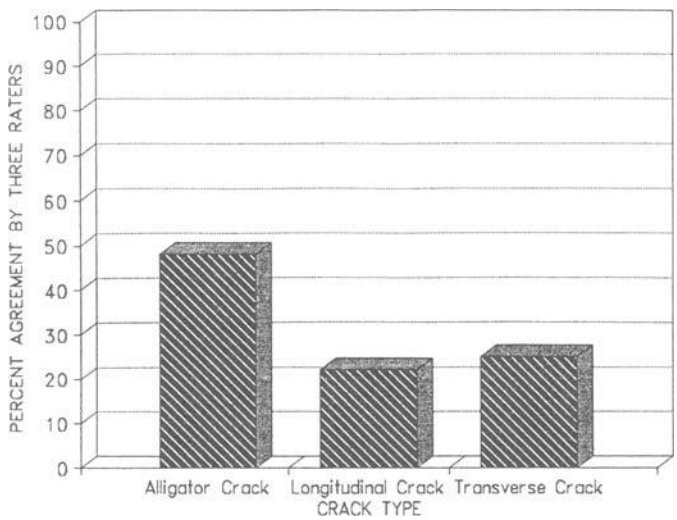

FIG 2. Percent Agreement by Three Raters Using All Test Sections

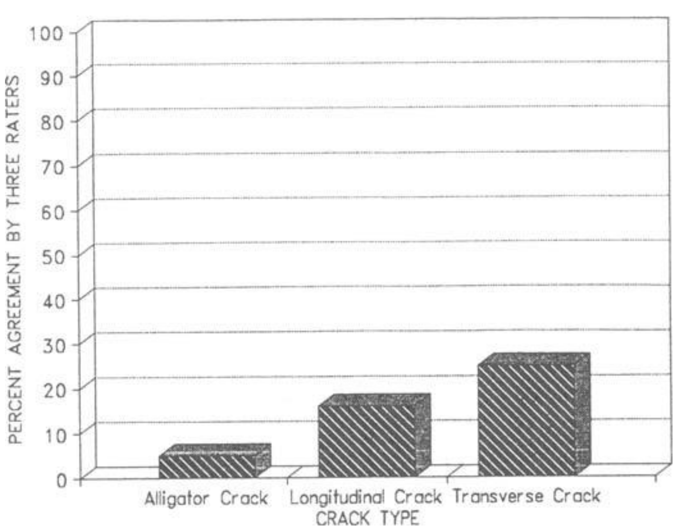

FIG. 3. Percent Agreement Using Test Sections Only with Cracks Present

As shown Figure 4, 5 and 6, some distress categories were never used by any rater. As shown in Figure 4, eight out of thirteen alligator cracking categories was never used by any rater. Five out of ten longitudinal cracking categories and most transverse cracking categories, were used as shown in Figure 5 and 6 respectively. This result seems to indicate that there is a need for modifying the current distress survey procedure. Cracking categories, which are rarely used by raters, should be considered for removal from the survey form in the future.

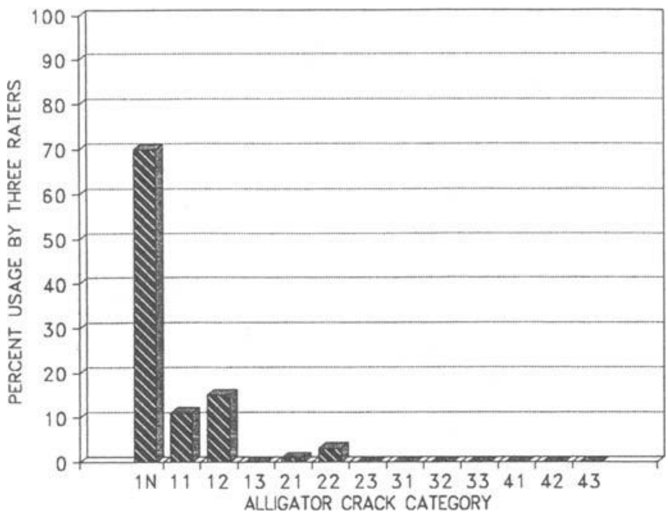

FIG. 4. Percent Usage of Alligator Crack Categories by Raters

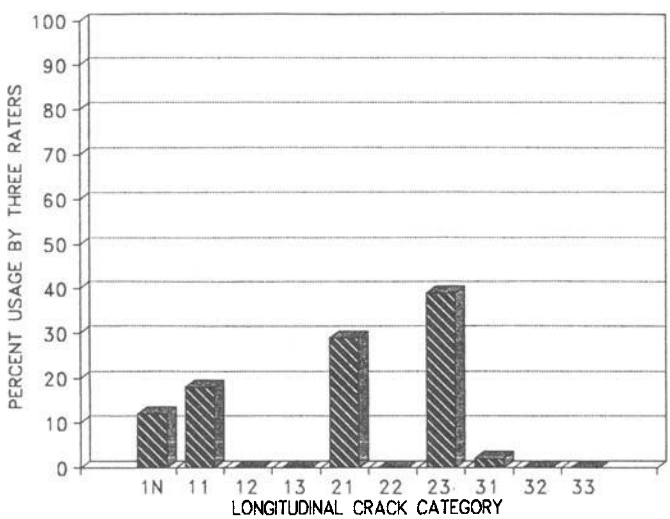

FIG. 5. Percent Usage of Longitudinal Crack Categories by Raters

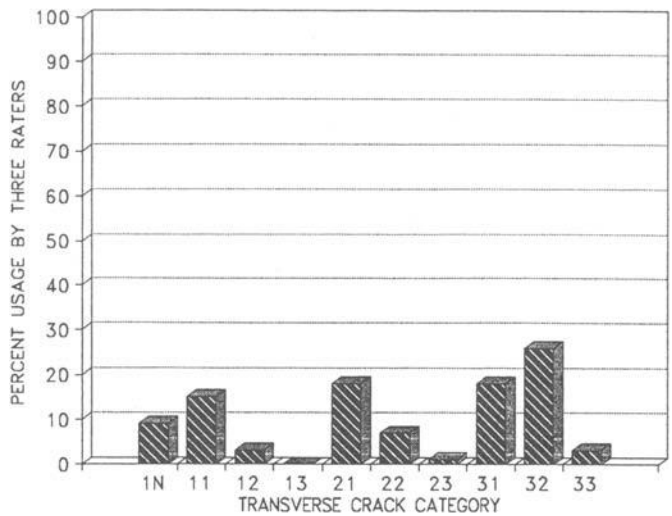

FIG. 6. Percent Usage of Transverse Crack Categories by Raters

The factor which influences the quality of data and subjectivity level most is that the raters are required to collect all three characteristics of crack such as type, extent and severity given limited time and access to pavements. The following recommendations are made for improving the current visual distress survey procedure at WSDOT:

1. The distress survey segment should be short enough to allow raters to reasonably estimate the extent of distress.
2. Raters should be expected to measure distress only severe enough to be observed under any field conditions.
3. The number of extent and severity categories for each distress type should be reduced in order to help improve the consistency of the raters.

AUTOMATED DISTRESS MEASURING DEVICE

The machine vision offers a number of advantages over human vision such as accuracy, consistency, safety, etc., when properly applied in evaluating pavement surface conditions. There are various automated distress measuring devices currently available which apply the fundamental image processing and analysis techniques to process the video image of the pavement surface [10].

There are two classes of the image processing algorithms used in most automated distress measuring devices in general: segment extraction algorithm and connectivity algorithm. The segment extraction algorithm is a set of local operators which determines if each pixel is part of a crack. The connectivity algorithm is a set of global operators which evaluate extracted segments for their connectivities to form a crack after eliminating the noise segments [10].

Most automated distress measuring devices apply threshold technique to classify the crack pixels from non-crack pixels. The system usually allows the user to set the crack threshold level depending on the noise level of the image. The 256 gray scale of each pixel has to be converted into binary black (crack) and white (non-crack) data depending on the predetermined threshold value.

Major efforts were made to detecting cracks from the normal pavement surface. The severity and extent of various types of cracks seem much more difficult to measure than just detecting the existence of cracks [13]. One study compared an automated distress measuring device called "PAS-1" against the visual survey data using the field data. The study came to the conclusion, based on the field data, that the PAS-1 device be more consistent with the field data than the raters [14].

STANDARD CRACK DENSITY METHOD

In this section, a standard crack density method for network-level PMS is proposed. The universal definition should be based on the length and width of a crack which can be defined as a crack area. The crack area can be computed by multiplying the length of crack by its width regardless of crack types. Of course, the longer and wider cracks will increase crack area. Potholes can be considered as a very wide crack with relatively short length. Alligator cracks are combinations of longitudinal, transverse, diagonal and meandering cracks.

The standard crack density is defined as, in this paper, the area of crack over the total pavement surface. However, there is no need to measure the width and length of the crack in order to calculate the crack area. The crack area can be easily obtained by counting the number of crack pixels. The standard crack density value can be then determined by dividing the number of crack pixels by total number of pixels of the pavement surface image. With an advent of the image processing technology, it is now possible to distinguish cracked pavements from non-cracked pavements very efficiently. This image processing capability allows us to automatically compute the crack density on any pavement surface.

Figure 7 depicts a conceptual pavement area of 5x5 inches (12.7x12.7 cm) to illustrate the standard crack density concept. Figure 7 includes various types, extents and severities of cracks. Let's assume that the size of a pixel is 0.25x0.25 inch (0.64x0.64 cm). As shown in Figure 7, there are total 121 crack pixels (6+40+16+20+7+32) out of 400 pixels (20x20) of pavement surface image. The standard crack density can be computed by dividing 121 crack pixels by 400 total image pixels to arrive at 30.25 percent. A value of zero percent can be assigned to a perfect pavement, a value of 100 percent can be assigned to a totally cracked pavement or unpaved roadway section. This standard crack density method is a very simple and logical, and can be readily implemented using the existing image processing technology.

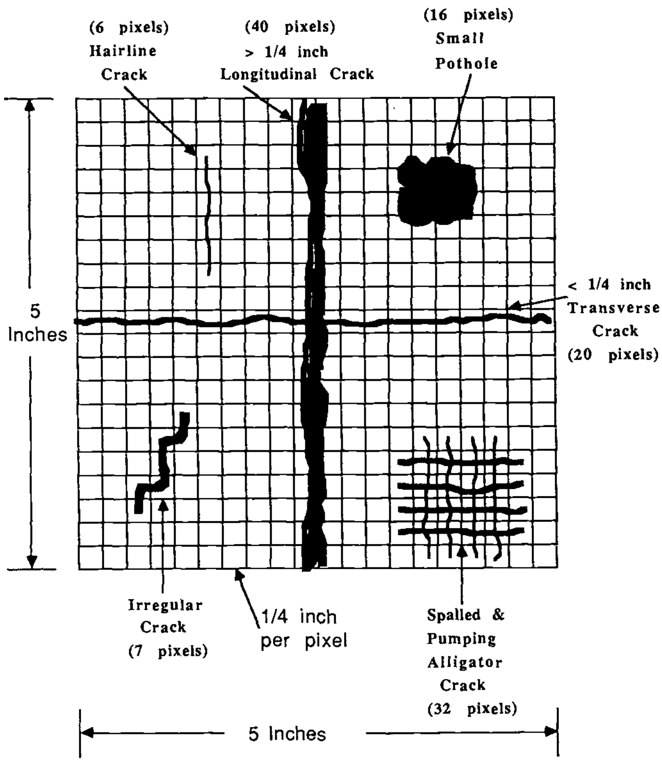

FIG. 7. 5x5 inches square pavement section with various crack types

The standardization of PMS cannot be effectively achieved without standardizing its input. The standard PMS must use standard data which can be easily verified for its validity. This standard crack density method can be adopted for a network-level PMS. If more detailed crack information is required for a project-level PMS, the manual processing of the same video image can be conducted. At this stage, the various cracks can be defined, and severity of individual type of cracking can be observed by viewing a video tape in the office. It may be very difficult to achieve standardization at the project-level PMS because it is usually tailored to meet the local project-specific needs.

The major advantage of this standard crack density method using an existing image processing technique is that it takes into consideration of both length and width of cracks simultaneously. As a result, type, extent and severity of cracking is now combined into one consistent number. This standard crack density value will always increase as the pavement deteriorates unlike some other combined indices. This simple standard crack density approach directly generates a common cracking index without going through subjective deduct point systems, utility functions, etc. This standard crack density can be computed automatically and consistently using the existing image processing technology.

SUMMARY AND CONCLUSIONS

In the past, visual pavement distress survey has been independently conducted by each state highway agency. Each state developed its own pavement distress survey procedure which led to a lack of standardization. Cracking is one of the most important pavement distress types. However, there is no widely accepted measure for cracking in pavements, and no international standardization has been established.

The current visual distress survey method adopted for WSDOT was evaluated for its consistency. The inconsistency among raters has been reported several times by a number of state highway agencies. This study confirms the inconsistency of human vision and judgment which always exists in any visual inspection procedure. The inconsistency among three raters in Washington was illustrated using a set of sample data. The results shown in this paper seem to indicate that the consistency among different raters would continue to be a significant problem in Washington. The consistency among raters seems too low to be used in practice. This result seems to indicate that the current distress survey form should be modified to improve the consistency of raters. Some extent and severity categories for three cracking types were never used by all three raters. Cracking categories which are rarely used by the raters can be removed from the survey form. The inconsistency among raters can be reduced by either simplifying the current distress survey procedure or adopting a new simplified distress definition.

The standardization of PMS cannot be achieved without standardized input to PMS. The standard PMS must use standard data which can be easily verified for its validity. A standard crack density can be computed by dividing the number of crack pixels by the number of total pixels of pavement surface image. This procedure can be conducted automatically and consistently using the existing image processing technique. The standard crack density method takes into consideration of both length and width of cracks simultaneously. This standard crack density value will always increase as the pavement deteriorates unlike other combined indices based on subjective deduct point systems or utility functions.

It is recommended that the standard crack density method be adopted for the network-level PMS at the national level. The standard crack density can be used as a common cracking index for rehabilitation programming decisions at the network-level PMS. This standard crack density can be computed automatically and consistently using the fundamental image processing technique. The existing automated distress measuring devices which apply the fundamental image processing technique cannot accurately measure the types and severities of cracks but can currently detect the existence of cracks on pavements. It is suggested that the existing automated distress measuring devices be evaluated as a means of standardizing pavement distress measurements.

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DISCLAIMER

The contents of this paper reflect the views of the author, who is solely responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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Imad L. Al-Qadi, Peter E. Sebaaly, and James C. Wambold

NEW AND OLD TECHNOLOGY AVAILABLE FOR PAVEMENT MANAGEMENT SYSTEM TO DETERMINE PAVEMENT CONDITION

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ABSTRACT: The feasibility of many old and new technologies that can be used in determining pavement condition have been investigated. These technologies include image processing, electromagnetic waves, nuclear, laser, spin-up/spin-down, eddy current, and ultrasonic waves. Various equipment in use and under development in United States and Europe have been identified and evaluated. The following measurements were considered: Crack, skid resistance, texture, profile, rut, deflection, voids detection, moisture, delamination of thin overlays, joint/crack spalling, and joint/crack damage. Some of the top identified equipment were evaluated for use at the network and project levels. The evaluation was based on technical merit. It was concluded that the existing deflection and longitudinal profiling equipment are adequate. In the case of skid resistance, the information obtained from the existing ASTM skid trailer can be greatly improved with the spin-up/spin-down technology. Electromagnetic waves showed promising results in various areas of application. The nuclear technology also showed some promising results in certain application. On the other hand, ultrasonic technology had serious limitations, especially in penetrating the pavement material, while eddy current technology showed no promise at all.

KEYWORDS: Electromagnetic waves, laser, nuclear, spinup/spindown, image processing, pavement evaluation

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Hundreds of thousands of miles of flexible and rigid pavements were built in the United States prior to the 1970's. Large portions of these pavements have reached their design life, and many types of distress, surface and subsurface, have begun to be noticeable. A severe reduction in the serviceability of the pavement has been observed. The type of distress, its severity, and the pavement rate of deterioration are very important information required to make the right cost-effective decision regarding the type of maintenance needed and the extent of the rehabilitation required.

Pavement condition survey, which is an important part of the pavement management system, used to be performed by raters walking and/or driving along the road and classifying the pavement condition based on their visual observations. This method is time-consuming and subjective, and open to transcription error. To overcome these limitations, methods were devised by various agencies to speed up the process by automating the recording, processing, and storing of the data. This led to a revolution in the condition survey procedures. Vehicles to take photographs of the pavement, and others carry on-board computers for recording and storing the data directly in the field were developed.

The condition survey equipment should at least have the ability to record the pavement condition periodically and thus obtain the rate of deterioration. Also, the instrumentation and techniques used and the equipment performance based on field testing. Other factors, such as ease of processing, ease of interpretation of output, operating restrictions, environmental effects, traffic interference, operating speed, equipment durability and robustness, and cost-effectiveness are strongly considered.

New technologies have been introduced to condition surveys, for both surface and subsurface distresses. Many of these measurement technologies are already used by the highway community, i.e., electromagnetic waves, nuclear, eddy current, laser, image processing, and spin-up/spin-down. In this paper, an evaluation of the technologies used is presented and the top distress survey devices are identified and described. Although there is a difference in the type of condition survey in the project level and network level, much of the equipment can be used for both levels; therefore, no differentiation is presented in this study. Thus, the objective of this study is to develop a ready reference about available nondestructive testing (NDT) devices and methods used in condition surveys of flexible and rigid pavements. The evaluation was conducted on equipment used in the United States and abroad.

TECHNOLOGIES USED IN PMS

The increased deterioration of the pavement system due to the effects of age, environment, and accumulated traffic loads makes the need for new techniques in maintenance and repair more crucial. Using up-to-date technologies will help in producing an accurate and rapid determination of the location and extension of the deterioration or distress. Using an accurate method with proper technology will enhance the preparation for a better maintenance. Also, rapid methods will save time, cover more area, and minimize the interference with traffic.

Various technologies, such as electromagnetic waves, ultrasonic, and others, have demonstrated, to a degree, feasibility for use in pavement condition survey. However, many of these technologies are still under development, especially with regard to data reduction and interpretation, which usually require some expertise. In this section, some of these technologies, which have been evaluated by the authors, are presented.

Image Processing

Image processing, which is also referred to as video image or machine vision, is a well developed technology used in many different fields, from the food processing industry to robot assembly. However, the inspection for defects is a more difficult process than detecting the presence or absence of a constant geometric shape. It requires sophisticated computer algorithms and significantly more processing time. The benefits of using machine vision to replace human inspectors are numerous and vary with conditions. Often, productivity is increased by reducing process time, and a more consistent inspection results from the removal of human subjectivity.

In the application of image processing for pavement distress, most studies have concentrated on the post-processing of video recordings, allowing each video field to be digitized by a computer system and analyzed over several seconds. Several crack detection systems have been developed using this technology for the highway community. Another use of image processing technology is the FHWA Texture System used to determine macrotexture profiles from which the mean texture depth is calculated.

Recent work in the foam rubber business applied this technology to a hand-held unit for counting pores per inch. The unit and the basic analysis methods should prove applicable to the measurement of chip loss, bleeding and embedment, and macrotexture. An initial spot measurement on the project level should be tested, and if proven effective, faster processing can be added to give real-time computation. Then, the count can be used in a mobile van and used at network level.

The images of the pavement surface, to detect crack types and sizes, are taken at speeds varying from 0 to 64 km/h and some systems up to 100 km/h. The cracks are identified based on the shadow of the light as it penetrates the open cracks. Depending on the sophistication of the data analysis software, the sizes and types of the various cracks may be identified. Some of the available systems collect the surface images but do not provide automated image processing; these systems are not recommended because of the long process involving manual image interpretation. The percentage of the total area covered by the image depends on the shutter speed of the camera. However, it was found that most of the available systems provide 100% coverage of the surface at measurement speeds below 32 km/h. As the measurement speed increases, the percentage of covered area decreases.

The macrotexture of the pavement surface can be evaluated through the digitization and processing of the video images of the surface. This is based on the shadows of the various aggregate sizes. The advantage of this technique is that it evaluates a texture measure for the entire wheel track as opposed to a single line measurement. The feasibility of analyzing the surface image to extract the counts of the various aggregate sizes should be investigated because it will help in the detection of chip loss, bleeding, and embedment. The count of the various aggregate sizes in the surface immediately after the maintenance is applied are used as a reference point and subsequent counts are compared to the reference.

Electromagnetic Waves

The use of electromagnetic waves technology to evaluate in situ pavement conditions was investigated for the following problems: void detection under rigid pavements, moisture measurement in flexible pavements, moisture measurement under rigid pavements, thickness measurement in flexible and rigid pavements, and delamination of thin overlays. Electromagnetic waves have been used, so far, in the time domain as pulse radar. The principle of pulse radar is based on inducing a single pulse from a transmitter, then ceasing transmission for a short interval during which reflected signals return to a receiver. When electromagnetic waves are directed into a pavement, a portion is reflected back to the transducer at the surface of the pavement (representing the first boundary). The remaining waves propagate through the pavement until they strike another boundary, representing the second layer (base), and another portion is reflected back. The portion not reflected penetrates through the base layer and the subsequent layers of materials and repeats the penetration and reflection until all the waves dissipate. The amplitude of the reflected waves varies depending on the dielectric properties of the different layers. The changes in the pattern of the reflection amplitude make the distinction between different layers possible. The difference in time at which two successive reflections reach the receiver depends on the dielectric properties and thickness of the layer. Therefore, knowing the dielectric properties of the layer enables the operator to predict the layer thickness, or knowing the layer thickness enables the operator to predict the dielectric properties of that layer [1].

Using the above principle, the air void under rigid pavement can be detected, and the delamination of thin overlays can be noticed. However, theoretical studies show that for small air voids and delamination, a small wavelength should be used to ensure clear time separation between different dielectric materials in the reflection-time relationship, which might limit the penetration of the electromagnetic waves in the target.

Using electromagnetic waves to investigate the water content in fresh portland cement concrete was studied by Clemena [2] using reflection and transmission methods. The study showed a linear relationship between the water/cement ratio and the electromagnetic waves' reflectivity and transmission. However, it was found that the transmission method is more accurate, which is not feasible for determining water content of fresh concrete mixes in a quality-assurance procedure. The presence of the water can be easily detected if proper techniques and equipment are used, as the dielectric properties of water are much higher than for any other materials.

The moisture presence in asphaltic materials has been extensively investigated using electromagnetic waves in the microwave region by Al-Qadi [3]. A new setup and techniques were developed in that study to measured the amount of moisture in the asphaltic materials. The amount of water was predicted successfully using theoretical and statistical methods. The study measured the dielectric constant of asphaltic materials and water as a complex number. The new technique uses microwaves at a frequency of 12.4-18 GHz. The measurements of asphaltic concrete material were performed in the frequency domain using sweep mode of the average of 128 measurements at 801 frequencies in that band. The parameters measured were the reflection coefficient and phase angle which were used to calculate the dielectric constant and loss factor of the asphaltic concrete material.

In this range of frequency, water has a very high dielectric constant and loss factor. Therefore, the presence of water in asphaltic concrete increases both the dielectric constant and the loss factor of the mixture. The calculated dielectric properties of dry asphaltic concrete, wet asphaltic concrete, and water are used in detecting the amount of water presented in the mixture. The most important features of this technique are the nondestructive and contactless setup, the use of focus antenna which allows a plane-wave penetration in the material specimens, and the ability to predict the moisture content of asphaltic concrete at R^2 of 83%.

Measuring rigid pavement thickness by microwave reflection is dependent on the same principles as detecting voids underneath rigid pavement. Many studies have been performed to measure rigid pavement thickness, most of the researchers assumed the dielectric properties of the concrete layer, which can be different from one batch to another. Also, the real part of the dielectric constant was considered, and the imaginary part was ignored. On the other hand, the high dielectric properties of rigid pavement decrease the electromagnetic wave penetration. Therefore, a high power system should be used along with a focused antenna. Clemena and Steele [4] indicated that 3.4% of the microwave reached the bottom of the slab used in their study.

Using electromagnetic waves to detect delamination of overlays is similar to detecting voids underneath rigid pavement. However, the frequency in this case can be increased to obtain a high resolution without jeopardizing the depth of penetration.

Nuclear Technology

Nuclear technology is expected to be applicable in detecting the delamination of thin overlays and moisture in flexible pavement. The principle of backscattered photons is used in pipe-thinning studies to detect any changes in the density of the material [5]. It is expected that the creation of a thin pocket of air between the delaminated overlay and the existing pavement will create a discontinuity in the density and, therefore, be reflected by the photon counts. Minimum energy is preferred for safety and shielding considerations, provided the photon-penetrating capability is adequate to cover the overlay debonding depth. Figure 1 presents a procedure to determine the proper source energy, and Figure 2 compares the relative transmission factors at two different photon energies. This figure indicates that a suitable gamma source or a higher energy x-ray generator will be required. Some knowledge about the essential difference between a gamma source and an x-ray generator will be helpful in the selection of an appropriate photon source. Gamma sources usually have the advantage of being compact, discrete-energetic, and less expensive. In contrast, x-ray generators are good for applications that require versatility and high intensity, especially when low energies are needed where self-absorption begins to be a limiting factor for radioisotope sources.

The Nuclear Magnetic Resonance (NMR) technique is being used to detect moisture in soils [6]. The researchers have performed some preliminary investigations on this technique for use on asphaltic concrete material. They concluded that the technique is safe because it does not use radioactive substances or high-energy particle bombardment. The major danger associated with the technique is that very strong magnets are used and care has to be taken when working near steel objects. Therefore, this technique is not recommended for use with reinforced rigid pavements. The NMR instrument has a flat configuration for the magnets in contrast to the cylindrically shaped magnets used in conventional NMR instruments. A loss in accuracy occurs with this flat configuration because the static magnetic field produced is not spatially uniform, as it is in the cylindrical configuration. The instrument can measure water content at a depth of 6 cm into the soil. The water content can be acquired at a speed up to 16.8 km/h.

Spin-up/Spin-down

Most current skid resistance testers operate at a single speed, usually 64 km/h. Thus, if measurements from different projects and locations are to be compared, they must be made at 64 km/h. The output data only provides information under special conditions. A tester is needed that can obtain the skid number/speed relationship in a single pass and travel at any prevailing traffic speed. This will reduce the cost of measurement and make test operation safer. The spin-up/spin-down methods will satisfy the above requirements. Both are based on the principle that the friction force at the tire-pavement interface at any moment corresponds to the friction force which would be present if the locked tire were pulled along the pavement at the corresponding interfacial velocity.

Spin-up/spin-down method use locked-wheel tester to measure the brake torque instead of friction force. For the spin-up method, the test wheel is locked and then the brake is released while the tester travels at constant speed. An encoder mounted on the wheel shaft is used to record the revolution, and the output is differentiated to

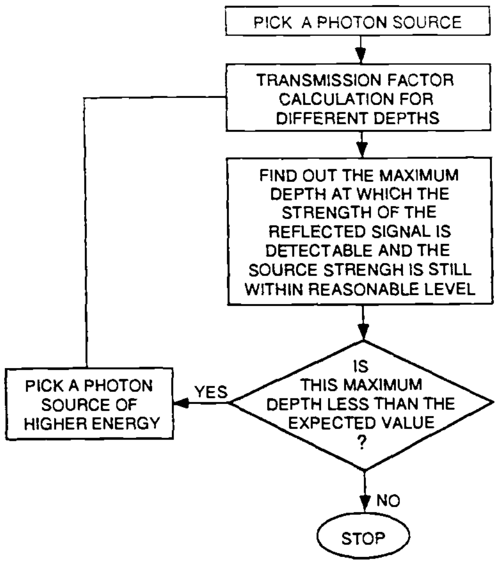

Figure 1 -- Optimization of photon energy and source.

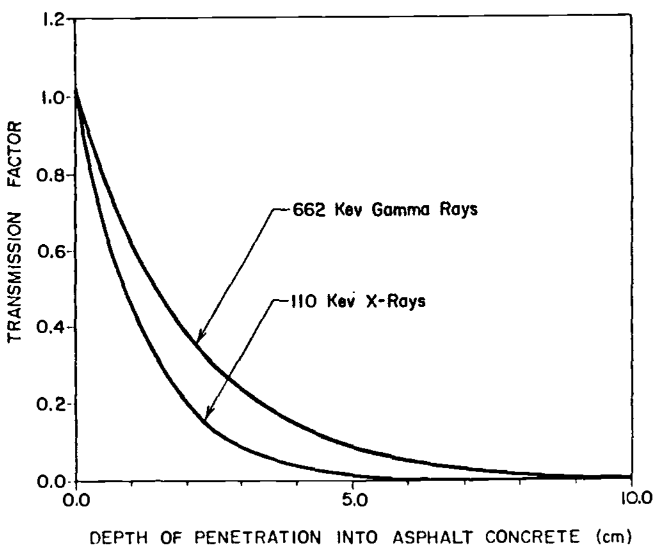

Figure 2 -- Relationship between depth of penetration and transmission factors for gamma rays and X-rays.

obtain the rotational speed (ω) of the wheel. These data can then be processed by an on-board computer to calculate the friction coefficient of the pavement. For the spin-down method, the rolling test wheel is slowed down gradually to minimize inertial effects. A torque-measuring system is required for the brake torque measurement. In this way, the complete skid number/speed curve can be obtained in a single test.

Some experiments show that both methods can achieve good results at speeds up to 80 km/h. The locked-wheel testers can be used to implement these methods, but the cost is reduced significantly and their maintenance is simplified because simple off-the-shelf transducers are used. On curves, the test tire does not remain perpendicular to the road surface, and load shifts influence the measurement. However, to hold errors to acceptable limits for a given tester it would require the operator to anticipate the curve radius before entering the curve and reduce the tester speed accordingly.

Laser Technology

Deviations in the longitudinal profile are of various wavelengths, depending on the cause of the deficiency. The profilometers are based on the principle of measuring the vertical distance to the road surface from several points along the measurement vehicle. The laser technology, discussed here, is the triangulation technique; the interteronetery technique is believed to have more potential, however, it is not available in the market yet. The laser technique can be used for the detection of long longitudinal wave-lengths (indicating, for example, a weak underground) as well as for the detection of short wavelengths (e.g., corrugations and potholes). In contrast to ultrasonic measurement devices, which in most applications may replace the laser at the cost of reduced accuracy, the laser can be mounted at any angle of up to 50^0 to the vertical. At stand of 25.0 cm high, the measurement width can be increased approximately 61.0 cm without increasing the length of the mounting beam.

In the case of the GMR profilometer, the laser is used to measure along the road the vertical displacement of the road surface with respect to the measurement vehicle body, thus producing a longitudinal road profile in a vehicle-fixed coordinate system. In order to convert this profile to an earth-fixed coordinate system, the vertical acceleration of the vehicle body is measured by means of an accelerometer. Double integrating this acceleration and adding it to the vertical displacement of the vehicle body will finally give the desired longitudinal road profile described in an earth-fixed coordinate system.

The other alternative, developed by the Transportation Road Research Lab (TRRL), employs the technique of measuring the distance to a spot on the road surface from a number of lasers mounted along the measurement vehicle as it passes over the spot. Four lasers are mounted along a two-wheel trailer. These measurement methods are inherently limited in regard to measurable wavelength and accuracy of amplitude. However, these limitations depend on evaluation techniques rather than the performance of the laser, which is sufficient for the measurement of longitudinal road profile in the wavelength range associated with road unevenness rather than texture.

A third application of the laser technique, useful for project level measurements only, is the use of a rotating laser mounted on a post at the roadside, forming a horizontal laser plane. The laser plane's altitude above ground level is measured by a vertical sensor mounted on a slowly moving vehicle. By adding the distance between the sensor and the road (measured by a second laser) to this signal, a very accurate picture of the longitudinal profile of the road may be obtained.

The transverse profile, or rutting, can be detected by several distance-measuring lasers mounted side by side on a beam across the road, or by one or more lasers moving on a beam across the road and thus scanning the profile. The beam may be mounted on a fixed structure manually displaced between measurement spots or across a vehicle, in the latter case enabling continuous measurement at various speeds. The accuracy of measurement depends on the land width covered, the distance between the individual lasers, and the sampling distance along the road. However, in most cases, measurement of only a part of the total lane width results in an underestimation of the rut depth. So far, the scanning laser technique has not been used for the measurement of transverse road profiles, and the accuracy of measurement with fixed lasers mounted side by side obviously depends on the distance between the lasers. Also, in this case, the rut depth is more likely to be underestimated as the gap between the lasers increases.

Various surface macrotexture deficiencies such as chip loss, bleeding, snowplow damages, aggregate embedments, polishing, and weathering are believed to be detectable by evaluating the texture profile measured with a displacement measuring laser. After several years of development, the evaluation of the laser technique with regard to smaller light-spots may also provide the ability to measure the coarser part of the microtexture. This capability might make it possible to predict the friction properties of the road surface from contactless measurements, i.e., without the use of a measurement wheel. Detection of cracks with the aid of lasers is a possibility; however, since this technique requires many lasers to find all cracks, it is not recommended. One solution currently under investigation is the combination of a laser and a video image.

Methods for the measurement of road surface deflection under a moving load by means of laser displacement meters are currently being studied. One method employs four displacement meters mounted on a rigid beam, which is mounted on the side of a heavy vehicle at the rear axle. Three of the meters are located outside the range of influence of the load wheel; the pavement below these meters is undeflected. One of the meters is adjacent to the load wheel to measure the induced deflection. By means of an algorithm, all measurements are related to a common datum giving the shape of the deflection basin. This method is in the prototype stage.

Another idea is to measure the cross profile of the whole lane or one wheel track behind the lightly loaded front axle of a heavy vehicle and also immediately behind the heavily loaded rear axle of the vehicle. The first cross profile should be recorded outside the road area influenced by the front axle, while the second should be recorded on the same cross section of the road just as the heavily loaded rear

axle has passed it. The measurement of the cross profiles is performed by several lasers mounted side by side on two rigid beams across and underneath the measurement vehicle.

IDENTIFICATION AND EVALUATION OF EXISTING EQUIPMENT

In this study, a search was made to find and identify all existing equipment that have been used by the highway community. The equipment evaluated include systems in use and equipment under development as well as the top identifiable European equipment. The following measurements were considered: Crack, skid resistance, texture, profile, rut, deflection, and voids. Tables 1 through 6 list the equipment according to their use. Other technologies, like radar, are still under development to be used in moisture detection. Thermography is used by Donohue for detecting delamination of thin overlay, while the Collograph used in France uses dynamic loads in its application. No technologies are available yet to measure stripping in asphaltic concrete, joint/crack spalling and joint/crack sealant damage in rigid pavement.

The equipment was evaluated for use at the network and project levels. The evaluations in this study based on technical merit. After the criteria were developed, weights for each criteria on both the network and project levels were developed. Weights between 0 and 5 were given, with 0 being the least important. Table 7 gives the criteria for each measurement type and the weight for the network and project levels.

Based on technical merit (resolution and accuracy, automatic data processing, identity types and patterns, validity, and pavement coverage), the top-rated equipment are listed in table 8. A description of the equipment most used is presented in tables 9 through 13.

SUMMARY AND CONCLUSIONS

Determining pavement condition is dependent on the identification of the measurements needed. Identifying and evaluating the existing equipment and technologies is the first step in maintenance effectiveness. The maintenance engineer must conduct a number of measurements and define a set of performance factors for each treatment, (what the treatment should accomplish) then identify the failure conditions and identify and measure their probable causes.

In this study, the researchers investigated the feasibility of many new technologies including electromagnetic waves, nuclear, laser, and spinup/spindown. Also, various equipment used by the highway community in the United States and abroad were identified and evaluated. The evaluation was based on technical merit. The following findings were obtained:

Table 1 -- List of in-use and underdevelopment equipment for crack measurement based on technology used.

Human Vision	Image Processing	Laser Technology	Radar
Manual Survey	PASCO ROADRECON (Japan)	Laser Road Surface Tester (Sweden)	Crack Detector (U.K.)
	Gerpho Survey Vehicle (France)		
	Automatic Road Analyzer (Canada)		
	Idaho System		
	Automated Road Image Analyzer		
	Pavedex PAS1 System		
	Videoscan (U.K.)		
	Australian Road Evaluation Vehicle (Australia)		
	Gulf Radar		
	Earth-Tech Vision System		
	University of Waterloo (Canada)		
	University of Birmingham (U.K.)		
	BLH System		
	High Speed Road Monitor (U.K.)		
	Slit Integrator, FHWA		

Table 2 -- List of in-use and underdevelopment equipment to measure skid resistance based on technology used.

Slip Test	Locked Wheel	Side Force
Runway Tester	ASTM E274	Mu Meter (U.K.)
SAAB Friction Tester (Sweden)	Diagonal Braking	Stradograph (Denmark)
BV8 (Sweden)	COMTUCI CS-130 (Hungary)	Odoliograph (Belgium)
BV11 (Sweden)	Cobiert Trailer (Poland)	Skid Tester ST-1 (Finland)
BV12 (Sweden)	LCPC Trailer (France)	Australian Road Evaluation Vehicle (Australia)
Portable Friction Tester (Sweden, (Germany, France, U.K.)	Stuttgarder Reibungnesser (Germany)	British Pendulum Tester (U.K.)
RWL Trailer (Netherlands)	SCRIM (U.K.)	DF Tester (Japan)
Spin-up/Spin-down	Belgium Tester (Belgium)	
	Portable Skid Resistance Tester (U.K.)	
	Friction Measuring Device (Finland)	
	SUMMS Italy (Italy, U.K.)	
	Grip Tester (U.K.)	
	SRT (France)	
	Danish Stradograph (Denmark)	
	Yandell-Mee Texture Friction Meter (Australia)	
	Road Surface Analyzer	

Table 3 -- List of in-use and under development equipment for texture measurement based on technology used.

Image Processing	Volumetric	Stylus/Contact	Laser	Friction Measure
FHWA Texture Equipment	Sand Patch	PTI Stylus Profilograph	Laser Road Surface Tester	TRRL Mini Meter (U.K.)
Shoenfield Stereo Photograph	Draino-route (France)	Profile Tracer	TRLL High-Speed Text-ture Meter (U.K.)	Drag Tester, FHWA
Image Processing Method (Australia)	Outflow-meter	Mechanical Needle Pro-filometer (Germany)	CRR Pro-filometer (Belgium)	Pendulum Tester (U.K.)
Moore Technique (France)		Surtonic (France, Sweden)	High-Speed Road Moni-tor (U.K.) Rosan	Yandell-Mee Tex-ture (Aus-tralia)
Contact Imprint Picture Analysis (Switzerland)		Mechanical Stylus Pro-filometer (Austria)	VIT Mobile Laser (Sweden)	Pavia-meter (France)
Stereophotography ASTM E-770		Dira Tester (Germany)	Macropro-filograph (France)	Numer-istaur (France)
Photogrammetric With Picture Analysis (Aus-tralia)			Rugolaser (France)	
Acoustical Imaging (Netherlands)			Profilon (France)	
			Refocaliza-tion Sensor (France)	
			Range Find-ing Camera (Netherlands)	

Table 4 -- List of in-use equipment for profiling and rut measurement based on technologies used.

Level Survey	Laser	Ultrasonic	Mechanical	Response Type
Rod and Level	K.J. Law 6900	K.J. Law 8300A	Analyzeur de Profil en Long (France)	Mays Meter Vehicle
Straightedge	DNC	South Dakota Profling Device	Bayerischer Unebeuheitsmesser (Germany)	Mays Meter Trailer
FACE Dipstick	PTI Profiling	Michigan Profiling Vehicle	Rut meter (Finland)	Dynatest 5000 RDM (Denmark)
PTI Profiling Beam	High-Speed Monitor	Road Roughness meter (Norway)	Dynamische Querprofile Messgerat DQM2 (Switzerland)	PASCO ROADRECON (Japan)
	Laser Road Surface Tester (Sweden)	Finish Road Surface Monitoring System (Finland)	Mechanical Transverse (Belgium)	Surface and Profilographic (Finland)
	Road Surface Monitoring System (Sweden, Finland)	PURD		System 2uv Analyse der Quermebenheit (Germany)
	FHWA Pro-Rut	Ultrasonic Rutmeter (Ireland)		Querprofil-Aufnahmegerat (Germany)
	Profiling Vehicle (Finland)			Primal (Sweden)
	Australian Road Evaluation Vehicle (Australia)			Bump Integrator (U.K.)

Table 5 -- List of in-use and under development equipment for deflection measurements based on technology used.

Static Load	Slow Rolling Wheel	Fast Rolling Wheel	Impulse Load	Vibratory Load (stationary)
Plate Bearing Test	Lacroix Deflection (France)	Laser System (Sweden)	Dynatest FWD (Denmark)	Dynaflect
Benkelman Beam	PDDLE (U.K.)	Ultrasonic System	Phoenix FWD (Denmark)	Road Rater
	Deflectograph (Denmark)		KUAB FWD (Sweden)	FHWA Thumper
	California Traveling Deflectograph			WES 16-kip Vibrator
	Deflecto Lab (Australia)			
	CEBTP Curviameter (France)			

Table 6 -- List of in-use equipment for void detection based on technology used.

Load Associated Systems	Electromagnetic Waves System
Falling Weight Deflectometer	Pulse Radar
Dynaflect	Donohue Radar
Benkelman Beam	Penetradar
Deflection Gauge (Belgium)	Ground Radar (U.K.)
Transient Dynamic Response (France)	

Table 7 -- Criteria for equipment evaluation.

Measurement	Criteria	Weight	
		Network	Project
Crack	Resolution and Accuracy	4	5
	Automatic data processing	5	2
	Identify types and patterns	3	5
	Validity	4	5
	Pavement coverage	4	5
Skid	Resolution and accuracy	4	4
	Report SN_{40}	5	5
	Predicts PNG, SN_0	4	4
	Continuous test	2	2
	Weather normalization	2	5
	Validity	5	5
Macrotexture	Resolution and accuracy	Not applicable	4
	Field application	Not applicable	4
	Mobility	Not applicable	2
	Short-time requirement	Not applicable	4
	Predict chip loss	Not applicable	5
	Predict polishing	Not applicable	4
	Predict embedment	Not applicable	5
	Validity	Not applicable	5
Macrotexture	Resolution and accuracy	Not Applicable	4
	Field application	Not Applicable	4
	Mobility	Not Applicable	2
	Short-time requirement	Not Applicable	4
	Predict polishing	Not Applicable	4
	Predict embedment	Not Applicable	4
	Validity	Not Applicable	5
Profiling and Rut	Resolution and accuracy	4	5
	Actual road profile	2	4
	Highway speed	4	2
	Validity	5	5
	Automatic analysis	5	3
Profiling and Rut	Resolution and accuracy	5	5
	Speed of test	5	4
	Actual load	2	5
	Variable number of sensors	2	5
	Automated test	5	5
	Validity	5	5

Table 7 -- Criteria for equipment evaluation (Continued).

Measurement	Criteria	Weight	
		Network	Project
Void Detection	Resolution and accuracy	5	5
	Speed of test	5	4
	Actual load	2	5
	Variable number of sensors	2	2
	Automated test	5	5
	Validity	5	5
Moisture	Mobility of test	Not applicable	4
	Sensitivity and accuracy	Not applicable	3
	Field application	Not applicable	4
	Detect different layers	Not applicable	5
	Detect source of water	Not applicable	5
	Validity	Not applicable	5
Delamination of Thin Overlay	Resolution and accuracy	2	5
	Speed of measurement	3	3
	Mobility of the device	4	4
	Automated data processing	4	4
	Validity	5	5
Stripping	Resolution and accuracy	Not applicable	4
	Speed of the measurement	Not applicable	3
	Mobility of the device	Not Applicable	4
	Detect surface stripping	Not applicable	5
	Detect internal stripping	Not applicable	5
	Automatic data processing	Not applicable	5
	Validity	Not Applicable	5
Joint/Crack Spalling	Resolution and accuracy	3	3
	Speed of measurement	5	4
	Automatic data processing	5	4
	Validity	4	4
Joint/Crack Sealant Damage	Resolution and accuracy	5	5
	Speed of measurement	5	3
	Automatic data processing	3	4
	Identify cohesion problem	2	4
	Identify adhesion problem	2	4
	Validity	5	5

Table 8 -- Top-rated equipment based on technical merit.

Measurement	Network	Project
Crack	Pavedex PASI	Pavedex PASI
	Earch-Tech Vision	Earth-Tech Vision
	Autom. Road Image Analyzer	Autom. Road Image Analyzer
	Gerpho	Gerpho
Skid	Spin-up/Spin-down	Spin-up/Spin-down
	ASTM E274	ASTM E274
	BV12 & 8	VV12 & 8
	STUTTGARTER	STUTTGARTER
	Skidding Tester ST-1	Skidding Tester ST-1
	LCP Trailer	LCP Trailer
Macrotexture	N/A	VTI Laser Profilomoter
(including	N/A	FHWA Texture Equipment
chip loss,	N/A	CCR Optical Profilometer
polishing,	N/A	LCPC Defocalization Sensor
and embedment)	N/A	LCPC Macroprofilograph
Microtexture	N/A	VTI Laser Profilometer
(for use with	N/A	TRLL HSTM
skid, noise,	N/A	Rugolaser
etc.)	N/A	CCR Optical Profilometer
	N/A	Drainoroute
Microtexture	N/A	Drag Tester
	N/A	British Pendulum Tester
	N/A	Profile Tracer
	N/A	Surtronic
	N/A	Mechanical Stylus
Longitudinal	K.J. Law 6900D	K.J. Law 6900D
Profile	Laser RST*	Laser RST*
*Same Rating	HSRM*	HSRM*
	RSMS*	RSMS*
	FHWA ProRut	FHWA ProRut
		Dipstick
Transverse	ARAN	ARAN
Profile	Laser RST	Laser RST
(Rut Depth)	Dipstick	Dipstick
	Ultrasonic Rutmeter	Ultrasonic Rutmeter
	All Profling Beam	All Profiling Beam
Deflection	FWD	FWD
	Slow Rolling Wheel	Slow Rolling Wheel
		Vibrating Load
Void	FWD	FWD
Detection	TDR	TDR
	Radar	Radar
Moisture	N/A	N/A

Table 9 -- Important characteristics of crack measurement equipment most used.

Name of Equipment	Principle of Operation	Output	Operating Speed (km/h)	Number of Operators	Resolution (*mm*)	Data Sampling Rate	Multiple Measurement	Advantage	Disadvantage
Laser RST System	Cross cracks and categorize them	Severity and extent of observed distance	8-90	3	1.5	32 KHz	Rut Depth; profile; macrotexture	No environmental restriction	Misses cracking data; does not create true images
PASCO	Continuous photographs of pavement condition	Image File	3-50	2	3	Continuous files; can cover 5 m lane width	Rut Depth profile	Repeatable; permanent record	Complex operation and processing procedures
ARAN	Continued images: one forward and two straight down	Videotapes	30-100	2	1	Continuous video images	Rut Depth profile; roughness gradients; curvature	Covers 400 miles a day; good accuracy	Expensive; surface must be dry; processing is labor intensive
Pavedex PAST System	Continuous video image	Longitudinal, Traverse, alligator, and patching cracks	80	1	2.5	100 percent of the pavement surface	Rut measurement	Identify pattern of cracks and batching; good coverage at high speed	Resolution is not sufficient

Table 9 -- Important characteristics of crack measurement equipment most used (Continued).

Name of Equipment	Principle of Operation	Output	Operating Speed (km/h)	Number of Operators	Resolution (mm)	Data Sampling Rate	Multiple Measurement	Advantage	Disadvantage
Videoscan	Color video-recording of road surface	Color video image	0-20	2	N/A	Continuous	None	Can be modified to give linked image of deflection and skidding	No real time analysis
High Speed Road Monitor	Color video recording of road surface	Color video image	0-100	2	N/A	Continuous	Rut depth; profile; macrotexture; cuvature; cross fall	Combined visual image with other measures including deflection and friction	No real time analysis

Table 10 -- Important characteristics of skid measurement equipment most used.

Name of Equipment	Principle of Operation	Output	Operating Speed (km/h)	Number of Operators	Resolution (mm)	Data Sampling Rate	Multiple Measurement	Advantage	Disadvantage
ASTM Standard (locked-wheel trailer)	Measures the friction force between the locked test tire and the pavement	Skid number (SN)	64	2	Transducer 1%	At an interval less than 0.8 km	None	Accurate results; requires little traffic control	Requires frequent mechanical and electrical repair; and dry surface
SAAB Friction Tester	Slip method measures the brake force	Friction number	Max. 150	1	+1.5% if the friction number = 1	1 value meter ratio	None	Requires no traffic control	Fixed slip rate
RWL Trailer	Measures friction force between test tire and pavement with 86% slip	Friction coeficient	50-100	2	2% repeatability 5% reproductability	Sample interval of 0.5 m	None	Little traffic hindrance; analog registration with high resolution	Needs wetting supply

Table 10 -- Important characteristics of skid measurement equipment most used (Continued).

Name of Equipment	Principle of Operation	Output	Operating Speed (km/h)	Number of Operators	Resolution (mm)	Data Sampling Rate	Multiple Measurement	Advantage	Disadvantage
SCRIM	Measures side force coefficient; test wheel angle is 20 degrees	Side-force coefficient	20-100	2	2% repeatability 6% reproducability	8 samples within 5 meters	Macro-texture	Accurate; no traffic control; measures 240 km per day	Wetting system not sufficiently precise
Mu Meter	Measures side force coefficient of two wheels	Friction value	Max. 150	1	Transducer 2%	Continuous	None	Requires little traffic control	Ineffective in winter, at sharp curves, and steep grades
Stuttgarter Reibungnesser	Measures brake force coefficient	Sliding friction coefficient	Max. 100	2	0.02 units	10 lockings within 250 m	None	No traffic control; accurate results	N/A

Table 11 -- Important characteristics of texture measurement equipment most used.

Name of Equipment	Principle of Operation	Output	Operating Speed (km/h)	Number of Operators	Resolution (mm)	Data Sampling Rate	Multiple Measurement	Advantage	Disadvantage
FHWA Texture Equipment	Light sectioning; vertical light projection; 450 camera angle; 50 mm transverse macrotexture profile	Digital data; statistical information	90	2	0.25 @ 90 km/h 0.12 @ 60 km/h	10 Hz	None	Operator interaction is reduced to a minimum	Limited resolution
Laser RST System	Record the texture height of the pavement	Distribution of texture in 10 amplitude ranges	8-90	2	0.25% of measured range	32 KHz	Crack; rut depth; long profile	Little environment restriction; real-time data processing	N/A
CCR Optical Profilometer	Measures the displacement of the road texture	Profile curve; profile spectrum; texture depth	1.5 min. per measurement	1	0.5 mm vertically; 2 mm wave length	Trailer can be moved to any location	Profile	Measures macrotexture and megatexture	Covers 0-5-2 mm wavelength; impractical in large survey and wet weather

Table 11 -- Important characteristics of texture measurement equipment most used (Continued).

Name of Equipment	Principle of Operation	Output	Operating Speed (km/h)	Number of Operators	Resolution (mm)	Data Sampling Rate	Multiple Measurement	Advantage	Disadvantage
Defocali-zation Sensor	Sensor in-terprets the area of projec-ted light spot	Profile	70	1	0.05 mm verti-cally; depends on light spot size	Arbitrary	Profile	Free of drop-out; small light spot	Requires dry surface; sensitive to light spot reflection
TRRL High Speed Texture	Measures the rela-tive dis-placement of road texture	RMS; tex-ture depth	Up to 110	2	0.01 mm verti-cally; 6 mm hor-izontally at 80 km/hr	4 KHz	None	Fast and extensive survey; 300 km per day	Requires dry weather; high dropout rate

Table 12 -- Important characteristics of *profiling and rut measurement* equipment most used.

Name of Equipment	Principle of Operation	Output	Operating Speed (km/h)	Number of Operators	Resolution (mm)	Data Sampling Rate	Multiple Measurement	Advantage	Disadvantage
Road Surface Monitoring System	Measures the vertical displacement	Various profile and rut data	20-100	2	0.25% of measurement range for vertical displacement	Sampling frequency 16 KHz giving a sampling distance of 0.3-1.6 mm	Profling; rut depth; cross profile; curvature	Real time computation; independent measurement	Requires dry surface
FHWA Pro-rut	Non-contact sensors; using ultrasonic, laser or infrared	Rut depth and long profile	Normal	2	N/A	Four measurements per 3 cm at 3.2 km/h	Rut depth; long profile.	Measures two profiles and rut depth	Not real time measurement
K.J. Law 6900 DNC	Measures relative displacement	Rut depth and long. profile	15-90	2	0.25 mm for vertical displacement	Every 50 mm right and left wheel path; averaged over a 300 mm interval	Cross slope;rut depth; profile	Measurements are obtained in real time	Can't operate in a wet day

Table 12 -- Important characteristics of profiling and rut measurement equipment most used (Continued).

Name of Equipment	Principle of Operation	Output	Operating Speed (km/h)	Number of Operators	Resolution (mm)	Data Sampling Rate	Multiple Measurement	Advantage	Disadvantage
Automatic Road Analyzer	Response type roughness measuring system	IRI; mean rut depth; curve radius; PSI; video tape	30-100	2	N/A	N/A	Transverse profile; rut depth; cracking; roughness	Can detect cracks as small as 20 mm at 100 km/h; it has a lot of potential	Problems in hardware and software; measurements affected by speed and acceleration
Analysuer de Profil en Long (APL)	Measures elevation profile in space domain	Long. Profile	20-70	2	N/A	Depends on application	None	Reliable under all weather conditions	Involves towing one or two trailers; speed should be constant
Laser Road Surface Tester	Measures slope profile in the time domain	Unevenness; IRI; long. profile	15-90	2	0.03 mm (laser gauge)	Sampling frequency is 16 Hz; average over 0.125	Rut depth; profiling; texture; cross fall; curve radius	Real time computation; independent of surface and vehicle	Calibration needed daily for laser and accelerometer

Table 13 -- Important characteristics of deflection measurement equipment most used.

Name of Equipment	Principle of Operation	Min. Load (kN)	Max. Load (kN)	Type of Local Trans-mission	Static Weight on the Plate (kN)	Contact Area	Deflection Measuring System Transition	Number of Deflec-tion Sensors	Max. Distance from Center of Def.	Max. Test Range	Advantage	Disadvantage
Dynatest Model 8081	Impulse	29	245	Rubber-ized cir-cular plate (300 mm diam)	More than 1.3	703 mm2	Velocity transducer	7	3.05 m	80-100 mils	Easy to operate; 200-300 stations per day; relativ-ely fast	N/A
KUAB 150	Two dropping masses	6.7	150	4 sec-tions circu-plate 300 mm diam	N/A	703 mm2	Seismic deflection transducer	5	N/A	N/A	Very simple and fast to oper-ate	N/A
Deflecto-graph	Measures deflec-tion under rear axle in both tracks	Norm-mally 100	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Measure the com-plete in-fluence line of deflec-tion capacity	N/A

- The top-identified crack detection systems should be field-evaluated to determine their actual accuracy, validity, automatic processing capabilities, and cost.
- The ASTM skid trailer can be greatly improved with spin-up/spin-down technology.
- The use of the pores counting/image processing machine is recommended for texture measurement as the most important measure to the maintenance engineer is an objective measure of chip loss, embedding, and bleeding.
- The existing equipment in profile and deflection measurement are adequate and their development should have the lowest priority at this time, compared to the other maintenance treatment technique evaluated.
- Electromagnetic waves are very promising in various areas of application. Based on the feasibility study, the researchers suggested using the pulse mode at a frequency of 1 - 3 GHz in void detection and the frequency sweep mode at 12.4 - 18 GHz in detecting moisture in asphaltic concrete and the delamination of thin overlays.
- Nuclear technology is promising in the area of detecting the delamination of thin overlays. The gamma rays can penetrate to a sufficient depth to detect debonding of overlays.
- The need for using couplant in ultrasound technology causes serious limitation at this stage. On the other hand, eddy current technology held no promise for pavement maintenance effectiveness.

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Wen-Hou Kuo[1], Edwin C. Novak[1], and Gilbert Y. Baladi[2]

DEVELOPMENT OF OPTIMAL LONG-TERM NETWORK STRATEGIES USING REMAINING SERVICE LIFE

REFERENCE: Kuo, W. H., Novak, E. C., and Baladi, G. Y., "Development of Optimal Long-Term Network Strategies Using Remaining Service Life," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: State Highway Agencies (SHA) develop Maintenance, Rehabilitation and Reconstruction (MR&R) programs every year. These programs may be optimal under some criteria. However, the impacts of these programs on the long-term network condition levels and funding needs are generally unknown. This is because the element of controlling long-term network condition and funding levels is not incorporated into the program development process. This paper presents a Strategy Analysis that uses a Remaining Service Life (RSL) concept to estimate long-term network conditions and funding needs. The characteristics of the strategy analysis are then used to develop optimal long-term network strategies. The procedures for incorporating optimal long-term network strategies into a program development process to develop optimal MR&R programs and at the same time control future network condition and funding levels are also presented.

This strategy analysis method is based on RSL which is obtained from pavement performance curves of condition measurements such as distress index, PSR, ride quality, rut depth,..., etc. It is a generic method because it can be used by any SHA that has established pavement performance curves. The linkage between project and network levels for developing MR&R programs are also discussed.

KEYWORDS: design service life (DSL), remaining service life (RSL), strategy analysis, MR&R strategy, preservation strategy, long-term network strategy

1. INTRODUCTION

AASHTO Guidelines for Pavement Management System (PMS) [1] provides the description of a generic PMS. It indicates that a PMS has three essential components: DataBase, Analysis Method, and Feedback Process. In the Analysis Method, the outputs of the most

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sophisticated model (Network Optimization) include Condition Summary, Performance Predictions, Recommended Candidate Projects, Funding Needs, Optimal Long-Term Network Policies, and Optimal MR&R Programs. These outputs are shown in the central portion of Figure 1. Note that this figure is a revision of Figure 1 in the AASHTO Guidelines for PMS. In this paper, AASHTO's ideas are expanded to provide step by step procedures for developing optimal Long-Term Network Strategies which will control the future network condition and funding at the desired levels. The procedures for incorporating optimal long-term network strategies into MR&R program development-process are presented. These procedures allow SHA to develop optimal MR&R programs that satisfy the long-term network needs.

To accomplish the above tasks, the RSL concept is used. Basically, RSL is obtained from the pavement performance curves of condition measurements such as distress index, PSR, ride quality, rut depth,..., etc. The definition of RSL will be given later. To demonstrate how to use the RSL concept to develop optimal MR&R programs and at the same time control long-term network condition and funding levels, the Analysis Method is divided into four components. These are Project Level Analysis, Network Level Analysis, Strategy Analysis, and Program Development as shown in Figure 1. The roles of each component as well as the interactions among these components are discussed in the subsequent sections.

2. PROJECT LEVEL ANALYSIS

A MR&R program is composed of projects to be rehabilitated and specifies when and how to rehabilitate each project. Thus, in order to develop optimal MR&R programs, the recommended candidate projects must be available for selection as shown in Figure 1. The source of candidate projects could be politically motivated as well as those identified by engineers who quickly drive through the entire network pavement. In general, the information obtained in this way is neither retained nor accurate enough for later use. An analytical means of selecting candidate projects is to process condition data using statistical rules and engineering analysis. Such a procedure will be discussed in Section 3. The analytical method of selecting candidate projects has the advantage of analyzing any number of projects. This provides the primary means by which funding efficiencies can be improved.

Once candidate projects are available, the next task is to use Condition and MR&R analyses as shown in Figure 1 to analyze each candidate project. This will provide project information for developing optimal long-term network strategy and MR&R programs. This is discussed below.

2.1. Feasible MR&R Treatments for Each Candidate Project

As an example, the feasible MR&R treatments for a rigid pavement section could be 4 levels of Repair, 5 Overlay thicknesses, and 6 methods of Reconstruction. Furthermore, the combinations of Repair and Overlay are also feasible MR&R treatments. Consequently, the total number of feasible MR&R treatments in this case is 4 + 5 + 6 + 4 x 5 = 35.

2.2. Condition Estimations Before and After Each MR&R Treatment

For each pavement segment, e.g., 0.1 mile, every distress item is recorded by type, severity, and extent [2]. A unit distress point is assigned to each distress item. The unit distress points among distress items are carefully weighted. The distress index of a pavement segment is then defined as the sum of the products of

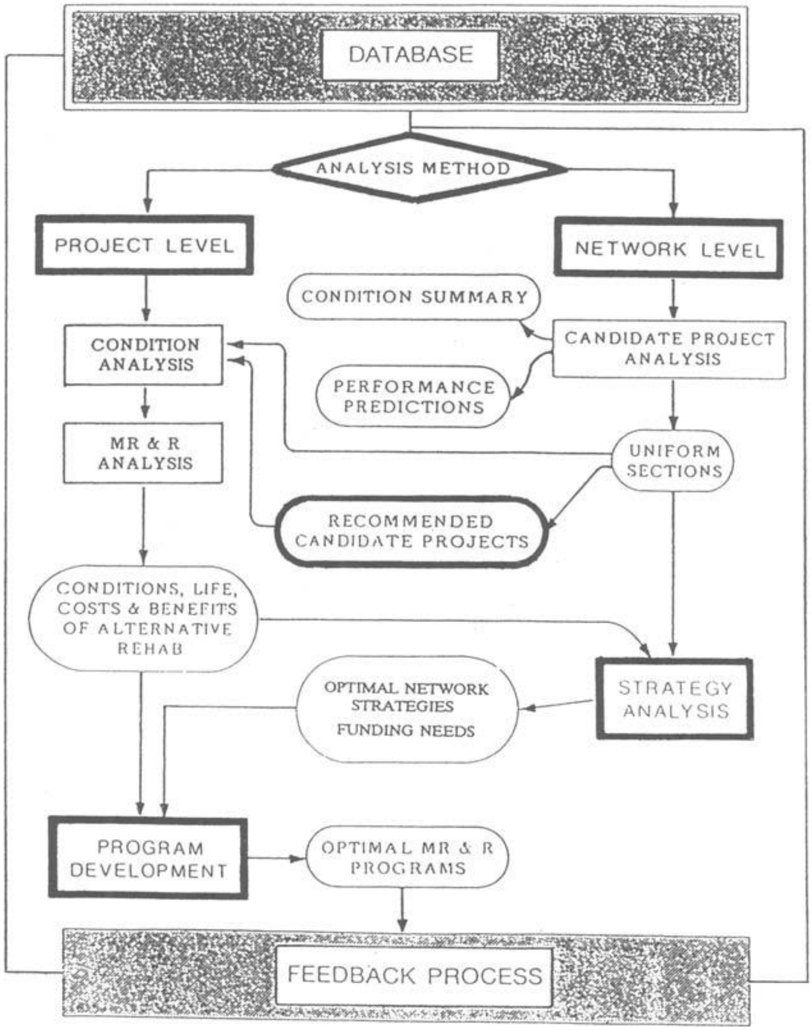

Figure 1. A schematic representation of PMS modules.

distress items and their corresponding unit distress points. The distress index of a project is the average of the distress indices of all pavement segments in the project [3]. If this index is used to evaluate pavement condition, the performance curves of this index before and after each MR&R treatment must be established. It is not the purpose of this paper to show how to establish performance curves. But, for demonstration purposes, it is assumed that the curves in Figure 2 are the performance curves of distress index before and after Repair & Overlay. The typical performance curves of PSR are shown in Figure 3. Theoretically, the area between two curves in Figure 2 is the improvement in distress condition by Repair & Overlay. However, only a portion of the total area could be meaningful improvement in the practical sense. This is discussed below.

2.3. Design and Remaining Service Life

In order to evaluate meaningful improvement, a threshold value must be defined. It will become clear later that the definition of the threshold value has to do with the criteria used to control long-term network condition. For now, the threshold value can be established by some or all of the following criteria:

2.3.1. The value at which an MR&R treatment is needed to remove unacceptable or poor condition.

2.3.2. The value at which routine maintenance is required to maintain pavement serviceability.

2.3.3. The value at which an MR&R treatment will cost the SHA and users less for rehabilitation than it would cost them if no rehabilitation is undertaken.

By establishing this threshold value, the RSL of a pavement section is the estimated length of time, from any given point of time (usually the last surveying date or current date), required to reach the threshold value. The RSL in terms of distress index and PSR are shown in Figures 2 and 3, respectively. Other examples are presented in [4]. If the current condition is already beyond the threshold value, the RSL is zero. However, for some reporting purposes, a negative RSL, -k, is used to indicate that the pavement reached the threshold value k years ago.

Note that the distress index defined in 2.2 is a composite index of distress items. One may prefer to define RSL in terms of each individual distress item. The minimum RSL is then defined as the RSL of the pavement section. In either case, RSL is a function of all distress items. Both methods have their strong and weak points. Neither one is an absolutely better method. For details, see Reference [4]. The RSL of a pavement section can also be expressed in terms of PSR or other measurements. Again, the minimum RSL can be defined as the RSL of a pavement section. This RSL and each individual RSL can be used together to perform PMS tasks.

The RSL of a pavement section at the completion of an MR&R treatment is defined as the Design Service Life (DSL) of the MR&R treatment as shown in Figures 2 and 3. Based on the concept used to define RSL and DSL, the improvement in terms of distress condition and PSR due to Repair & Overlay are the shaded areas shown in Figures 2 and 3, respectively. These areas are called improvement areas and denoted as E.

The RSL is linear in time. It decreases one RSL year for each year of service. It encompasses both condition and its rate of deterioration. It is intuitively easy to understand. Through the criteria used to define the threshold value, the RSL is directly related to the key of controlling network condition and funding

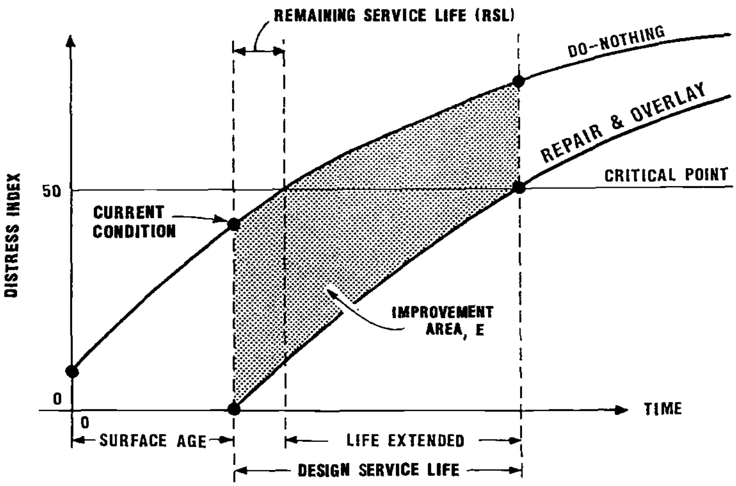

Figure 2. Remaining and design service life.

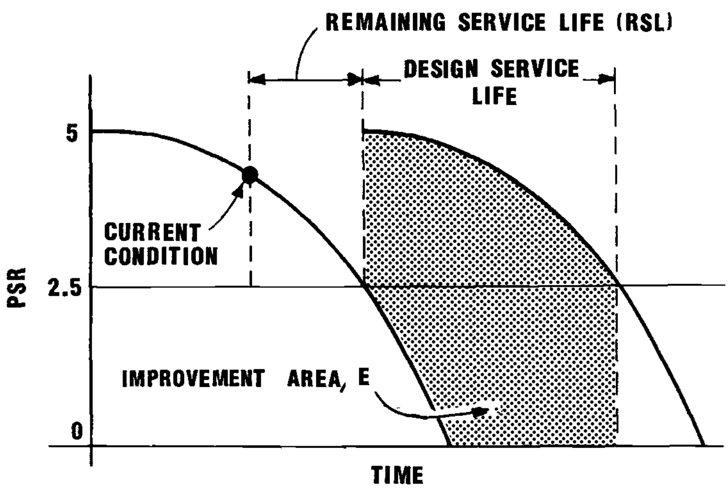

Figure 3. Remaining and design service life.

levels. This subject will be discussed in Section 4. The RSL is obtained from pavement performance curves used by any SHA. This makes RSL a generic parameter. Therefore, SHA can enhance their current condition assessment methodology by utilizing the developed optimization procedures as well as computer software based on RSL. This is an important step toward standardization of PMS procedures.

It is important to realize that zero RSL does not mean that the pavement is "dead or gone." It simply means that the condition exceeds the threshold value. The meaning of zero RSL is defined by the user.

2.4. Costs Associated with an MR&R Treatment

A_1	: cost of MR&R treatment
A_2	: cost reduction in routine maintenance during the period of DSL
U_1	: user cost reduction due to better pavement condition during the period of DSL
U_2	: user cost induced during the construction period
A	: agency cost = $A_1 - A_2$
S	: user savings = $U_1 - U_2$
T	: total cost = A or A - S

2.5. Cost-Effectiveness of an MR&R Treatment

Once the improvement area E and total cost T of a MR&R treatment are established, the cost-effectiveness, C/E, of this MR&R treatment is defined as the ratio of cost to improvement. That is, C/E = T / E. Note that other types of criteria such as cost-benefit ratio can also be used to measure the effect of an MR&R treatment. In this paper, C/E is used as an example for demonstration.

2.6. Remarks

It can be seen that it would be very time consuming to manually compute project information (2.1 - 2.5) for a large set of candidate projects with numerous feasible MR&R treatments. Fortunately, these computations can be easily accomplished in seconds by computer software [3].

The project information obtained by Condition and MR&R analyses (Figure 1) can be used to develop MR&R programs. For prioritization method, the most cost-effective (or other criteria) MR&R treatment is selected for each candidate project. The candidate projects are then ranked according to cost-effectiveness of the selected MR&R treatment. The top-ranked projects (up to funding limit) usually form an MR&R program. This procedure is simple to use, but does not guarantee that the developed MR&R program is optimal. A better way is to use Integer Programming techniques that simultaneously select projects and corresponding MR&R treatments to develop an optimal MR&R program. However, this MR&R program is optimal only in the environment set up for optimization. This environment does not include the element of controlling future network condition and funding levels. This means that the impacts of the developed MR&R programs on the future network condition and funding levels are unknown. To rectify this problem, two things are needed. First, a method for forecasting future network condition and funding levels is needed. Second, a procedure for incorporating this forecasting method into the program development process is needed. This subject will be discussed in Section 4.

Any SHA that is able to generate project information (2.1 - 2.5) can easily advance from prioritization to a full optimization procedure using inexpensive computer software. But, the benefits in terms of improvement in funding efficiency should obscure the cost of developing and implementing such a computer software system.

3. NETWORK LEVEL ANALYSIS

In general, the more candidate projects that are available for selection, the better the MR&R program can be developed. Ideally, the entire network is partitioned into sections such that each section is a candidate project. The question is, "where are the project boundaries?"

3.1. Uniform Sections

For any MR&R treatment, it is more cost-effective to rehabilitate projects that are homogeneous in condition than to rehabilitate projects that are inhomogeneous in condition. For this reason, the entire network should be partitioned into sections in such a way that pavements in each section are uniform in terms of pavement type and condition, as well as functional classifications. Each section is referred to as a "uniform" section and is a candidate project.

For demonstration purposes, the distress condition profile of a rigid pavement is exagerated and shown in Figure 4. Based on the variation of distress condition, it is visually apparent that this pavement section can be divided into six uniform sections. Sections 1, 4, and 6 are in excellent condition; Section 3 is in fair condition; Section 2 is in poor condition; and Section 5 is a short and good candidate maintenance project. When the condition profile is not so obviously divided, a statistical method will be needed to perform the task of identifying boundaries of uniform sections. One of the methods for this purpose is called Automatic Interaction Detection (AID) [5]. This method utilizes Analysis of Variance techniques to find the number of uniform sections that are maximally significant. The rules such as minimum and maximum lengths of a uniform section, as well as other practical and engineering rules are part of the AID procedures. Note that the AID method can be used for any condition data profile such as IRI, rut depth,..., etc.

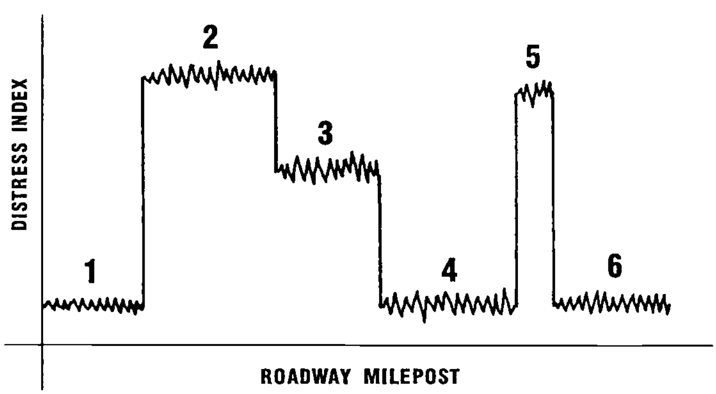

Figure 4. Distress condition of a rigid pavement.

Sections 1, 4, and 6 are in excellent condition and would not be cost-effective MR&R candidate projects compared to other uniform sections in poor condition. Therefore, they are unlikely to be included as projects in an MR&R program. This means that some of the uniform sections can be excluded from consideration. The remaining uniform sections are then the recommended candidate projects as shown in Figure 1. On the other hand, some of the MR&R treatments for uniform sections that are not in excellent condition could be cost-effective. Therefore, these uniform sections should be included as candidate projects. The question is, "what are the criteria for deciding whether a uniform section should be considered as a candidate project?" From the theoretical point of view, there is no need to exclude any uniform section. This is because any not very cost-effective project is unlikely to be included in an optimal MR&R program during the stage of program development with the purpose of optimizing cost-effectiveness. As long as the computer is fast and there is enough memory and storage capacity to handle large numbers of candidate projects, let the exclusion process take place at the stage of developing MR&R programs. Thus, the entire set of uniform sections are candidate projects and are automatically analyzed by Project Level Analysis as shown in Figure 1. This provides the linkage between project and network levels. Note that this linkage requires the 100% survey of the network pavement.

In the process of generating uniform sections, the following network condition summaries should also be generated [3].

3.2. Summary of Condition Measurement

As an example, the distribution of distress index is shown in Figure 5. If distress index 50 or more indicates the need of routine (reactive) maintenance, the current maintenance workload is 12% of the network.

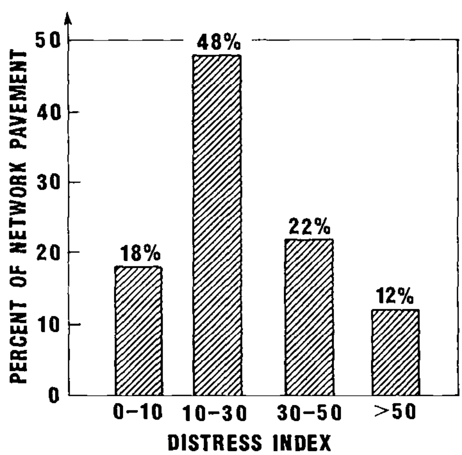

Figure 5. Distress index distribution.

3.3. Summary of Remaining Service Life

The distribution in Figure 5 is converted to RSL by pavement performance curves. The results are shown in Figure 6. If pavements with an RSL of 2 years or less (Category I) are defined in poor condition, then 19% of the network is currently in poor condition.

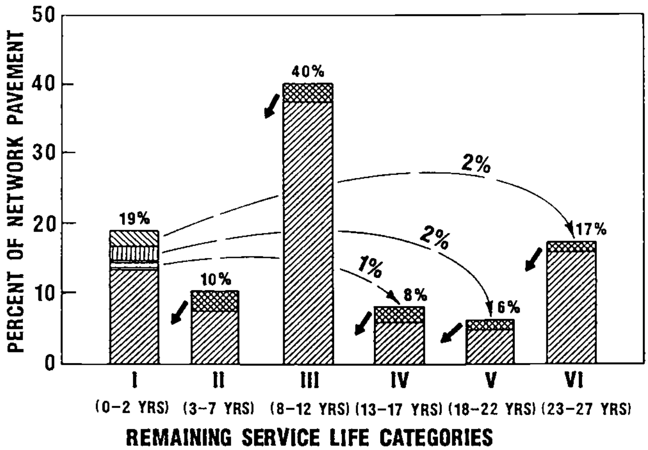

Figure 6. Current condition.

If nothing will be done, this number will grow to 29% in 5 years, and 69% in 10 years,..., etc. This is easy to see from Figure 6 because RSL is linear in time and decreases one RSL year for each year of service. This provides performance predictions of the network pavement under Do-Nothing MR&R program. On the other hand, what will be the distribution of RSL if 5% of the network pavement is to be rehabilitated each year? This subject is discussed in Section 4.

The pavement sections with RSL 0-2, 3-7, 8-12, 13-17, 18-22, and 23-27 years are grouped together as RSL Categories I, II, III, IV, V, and VI, respectively, as shown in Figure 6. This definition is partially in accordance with commonly used DSL of 5, 10, 15, 20, and 25 years. RSL can be grouped into any desired categories by the users. For example, each RSL can be one category. In this case, RSL and RSL category are the same. Note that the network RSL is the weighted average of the RSL of uniform sections.

3.4. Summary of Other Related Information

Pavement Service Life (PSL) of any pavement section is the actual length of time, starting from the completion date of construction or rehabilitation, to reach the threshold value. The PSL of MR&R treatments are to be compared with DSL to improve the accuracy of the design process. This is part of the PMS Feedback process.

The summary of the occurrences of distress items can be used to estimate routine maintenance workloads and costs, as well as the costs of all feasible preventive maintenances and repairs.

The summary of primary causes for pavement deterioration is useful to the design engineer for improving PSL and estimating DSL. It is also useful to predict the performance of the uniform sections. Again, this is part of the PMS Feedback process.

3.5. Remarks

The network condition summaries (3.2 - 3.4) can also be obtained through a sampling survey of the network pavement as done by some SHA.

Survey cost can be reduced by a sampling survey. However, the reduction will diminish as survey and image processing technology becomes more advance. Also, at the network level, the information accuracy based on sampling surveys greatly depends on the design of sampling procedure which requires the prior knowledge of the network pavement variability. This means that the condition data of the entire network must be established, at least at one time, in order to design a good sampling procedure. Moreover, the sampling survey cannot provide the condition data needed for automatic analysis of uniform sections as candidate projects. This means that project and network level analyses are not interdependent. For example, the costs of repair and preventive maintenance actions would not be available for network analysis, nor would network analysis be able to identify short sections of pavement in need of preventive maintenance or repair necessary to provide uniform pavement condition.

4. LONG-TERM NETWORK STRATEGIES

As previously mentioned, the project information (2.1 - 2.5) can be used to develop optimal multiple-year MR&R programs. Due to the reliability level of MR&R programs in the distant future as well as the availability of software (problem-solving techniques) and hardware, the term "multiple-year" generally refers to 5 years or less. If this is the case, the next question is, "what will the network condition levels and funding needs be for Years 6 to, say, 40?" The answer to this question is in the mechanism of pavement deterioration and rehabilitation.

4.1. MR&R Strategy

The RSL distribution of the current network is shown in Figure 6. The double-cross shaded areas are the percents (in terms of network) with RSL 3, 8, 13, 18, and 23 years, respectively. If these pavements are not rehabilitated, their RSL will decrease by one at the end of the year. Therefore, each of these areas will be moved to the next worse RSL category. Suppose that 5% of the network currently in Category I are rehabilitated according to the following DSL:

0.2% with DSL 13, 14, 15, 16, and 17 years, respectively.
0.4% with DSL 18, 19, 20, 21, and 22 years, respectively.
0.4% with DSL 23, 24, 25, 26, and 27 years, respectively.

By summing up each percentage over the 5 years, the above is equivalent to rehabilitate 5% of the network according to the following breakdown (Figure 6):

1% rehabilitated into RSL Category IV (RSL 13-17 years)
2% rehabilitated into RSL Category V (RSL 18-22 years)
2% rehabilitated into RSL Category VI (RSL 23-27 years)

If the above plan is used to rehabilitate the network pavement, the network RSL distribution after 1 year is shown in Figure 7. The above plan is a more general form of rehabilitation program; namely, specify what to do without designating projects. To distinguish this from an MR&R program, we call it an MR&R Strategy. The above MR&R Strategy is denoted by the notation (0,0,0,1,2,2). The definition of an MR&R Strategy will be given later. The network RSL distribution after 2 years is obtained by applying the same MR&R strategy on the RSL distribution in Figure 7. Repeat the same process for 25 years, the network RSL distribution after 25 years is obtained and presented in Figure 8. Note that the RSL distribution after 25 years remains unchanged as long as the same MR&R strategy is used. When this occurs, it is said that the network condition is in a steady-state. Note that the steady-state RSL distribution is independent of the

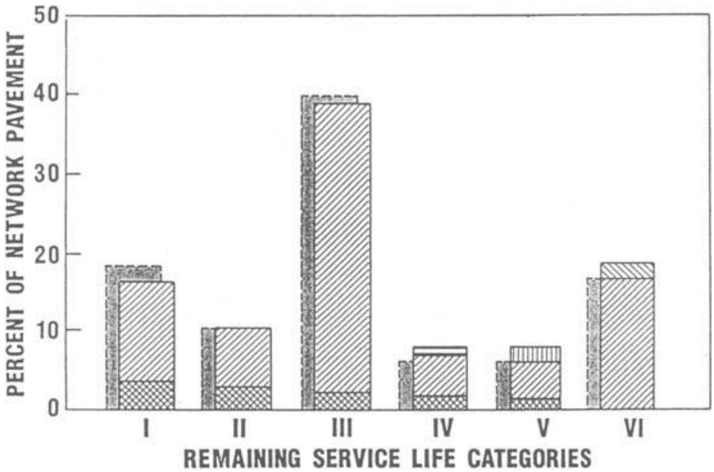

Figure 7. Condition at 1 year later.

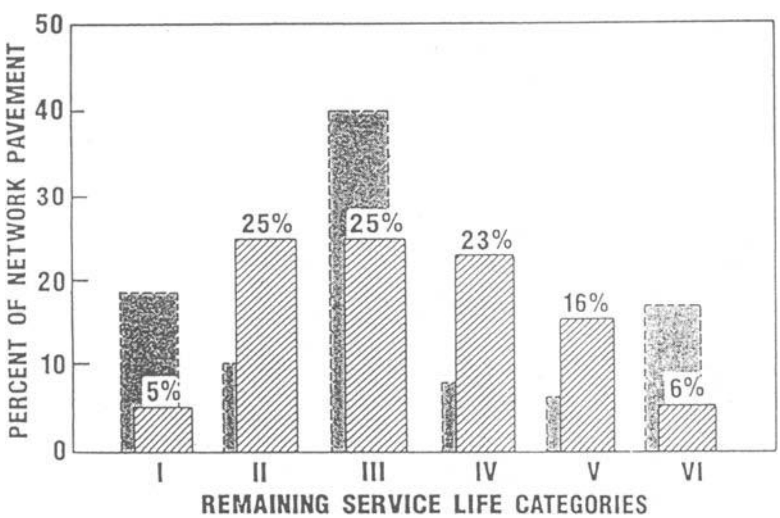

Figure 8. Condition 25 years later.

initial RSL distribution. That is, networks with different conditions rehabilitated by the same MR&R strategy each year will always end at the same network RSL condition. These facts can be mathematically proved and easily demonstrated by computer software or physical models. The mathematical proof will not be given here. In general, the length of time required for a network to reach steady-state condition is the maximum RSL of the pavement at the initial time. Intuitively, this is the length of time required to completely renew the network pavement. The above discussion introduces another important term, Preservation Strategy, defined below.

4.2. Preservation Strategy (PS)

A Preservation Strategy (PS) specifies what MR&R strategy is to be used each year to rehabilitate network pavement. If the same MR&R strategy is used for every year, it is called a Simple PS. The above example is a simple PS and denoted as PS (0,0,0,1,2,2). On the other hand, two or more MR&R strategies may be necessitated either by a policy to rapidly change network condition, or by a cut in funding. For example, due to an extra increase in funding, use MR&R Strategy (0,0,0,1,2,5) to rehabilitate network for each of the next 5 years, then switch back to MR&R Strategy (0,0,0,1,2,2) for the remaining years of an analysis period. This is called a Composite PS because at least two MR&R strategies are used to rehabilitate the network pavement during an analysis period.

The percent of network in RSL Category I (poor condition) and network RSL of the Simple PS (0,0,0,1,2,2) are shown in Figures 9 and 10, respectively. Note that the results of PS (0,1,1,1,1,1) and Do-Nothing Strategy are also included in these figures for comparison. Both MR&R strategies rehabilitate 5% of the network. But MR&R Strategy (0,1,1,1,1,1) has lower average DSL than MR&R Strategy (0,0,0,1,2,2); consequently, the network rehabilitated by the former strategy has higher percent in Category I and lower network RSL as shown in these figures. The results of Do-Nothing Strategy are to be used as basis for computing improvement due to a PS.

It is important to note that the percent of network in poor condition level could be rapidly improved by an MR&R Strategy which has low average DSL and high percent of network rehabilitated such as (0,7,4,0,0,0). This will cause the network RSL to decline and could ultimately result in a poor network performance unless a heavy MR&R Strategy that is high in both DSL and percent of network rehabilitated such as (0,0,0,3,4,4) is used to redirect the course. This indicates that condition measurement cannot be used alone to evaluate network needs.

4.3. Formal Definition of MR&R Strategy

For the remaining sections, RSL Categories 1,2,3,4,5, and 6 are also the RSL Categories I,II,III,IV,V, and VI, respectively. A general MR&R Strategy for a given year k is represented by a matrix $[\ F_{ij}(k)\ ]$. The ij-th element is defined as:

$F_{ij}(k)$ = percent of pavement (in terms of network) to be rehabilitated from the i-th to j-th RSL category if $i < j$
= 0 otherwise

That is, any MR&R Strategy is an upper diagonal matrix. Any MR&R Strategy with $F_{ij}(k) = 0$ for $i > 1$ is represented by a vector as explained previously. Note that matrix $[\ F_{ij}(0)\ ]$ is an MR&R Strategy for the current year and is abbreviated as $[\ F_{ij}\ ]$.

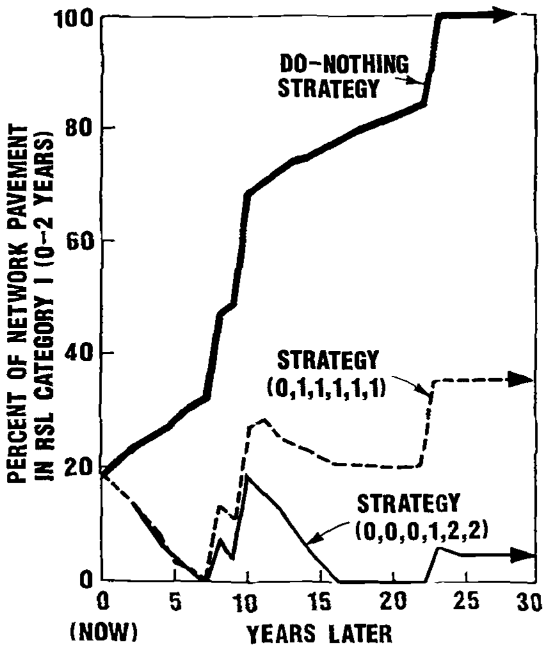

Figure 9. Percent of network pavement in RSL Category I (0-2 years).

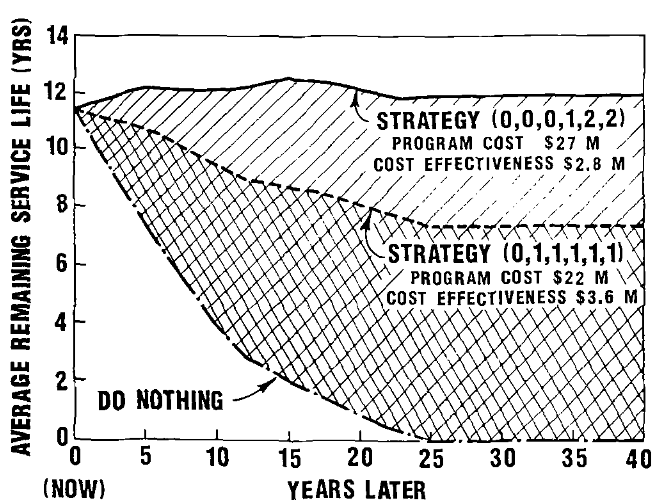

Figure 10. Preservation strategy efficiency.

4.4. MR&R and Preservation Strategy Costs

Denote LM as the total lane-miles of the network and $C_{ij}(k)$ as the cost per lane-mile for rehabilitating pavement from the i-th to j-th RSL category for a given year k. Again, $C_{ij}(0)$ is for the current year and is abbreviated as C_{ij}. Note that $C_{ij}(k)$ is generally a function of C_{ij} in terms of discount or inflation rate. The choice is up to the user and application. The development of this cost will be discussed later. Also denote $[\ M_{ij}(k)\ ]$ as the routine maintenance cost reduction matrix associated with MR&R Strategy $[\ F_{ij}(k)\ ]$. With the above notations the cost of an MR&R Strategy for a given year k is:

$$A(k) = \sum_i \sum_j [\ LM \bullet F_{ij}(k) \ / \ 100 \bullet C_{ij}(k) - M_{ij}(k)\ ]$$

The MR&R Strategy cost A(k) is the estimated agency cost for a given year k. The agency cost of a preservation strategy over a period of, say 40 years, is:

$$A = A(1) + A(2) + \ldots\ldots + A(40)$$

Cost matrix $[\ M_{ij}(k)\ ]$ can be obtained from a Maintenance Management System. This is beyond the scope of this paper and will not be discussed. The C_{ij} is generally the average cost of rehabilitated pavement from the i-th to j-th RSL category. This cost can be obtained from the historical program cost data. It can be the average of costs of MR&R Treatments that will rehabilitate all uniform sections initially in RSL Category i to RSL Category j regardless of their chances to be included in an MR&R program. This could be the average of very widely distributed costs. Consequently, the costs of the developed MR&R programs under guidance of the optimal PS could also be widely distributed even though the average of these MR&R program costs agrees with the MR&R strategy cost of an optimal PS. Thus, it is essential to maximally reduce the variance of costs used to compute C_{ij}. This is not a simple matter. Statistical methods are required to convert the costs of feasible MR&R treatments of all uniform sections into C_{ij} expressed as a function of the percent network rehabilitated from the i-th to j-th RSL category. With this cost function, the proper portion of the costs can then be used to compute strategy cost. This is a lengthy subject and cannot be discussed at this time.

4.5. Preservation Strategy Efficiency

Any curve shown in Figures 9 and 10 is termed as a network performance curve of a PS. The area between performance curves of a PS and Do-Nothing Strategy over an analysis period is defined as the improvement area, E, due to that PS. For example, the double-cross shaded area in Figure 10 is the improvement area of PS (0,1,1,1,1,1). The preservation strategy efficiency, C/E, of a PS is defined as the ratio of strategy cost to improvement area. That is, C/E = A / E. Similarly, If S is the user savings associated with a PS, the efficiency of a PS may be defined as C/E = (A - S) / E. As an example, the PS (0,0,0,1,2,2) is more efficient in terms of network RSL than PS (0,1,1,1,1,1) as shown in Figure 10.

4.6. Optimal Preservation Strategy

The analysis method presented in this section is termed as Strategy analysis. It demonstrates that any PS can estimate the long-term network condition levels as well as funding needs without designating projects. This is one form of the long-term network strategies. The characteristics of PS can be used by an optimization procedure or simulation method to find an optimal PS as follows:

Optimize: preservation strategy efficiency C/E in terms of network RSL or percent of network in poor condition

Subject to the following constraints for each year of the analysis period:

4.6.1. Budget level is within the specified limits or less than the maximum limit. In general, the specified limits are the forecasted revenue range. One can set the maximum limit as infinite to investigate the funding requirement to achieve the desired condition levels set below.

4.6.2. Percent of network pavement in RSL Category I (poor condition or maintenance workload) is less than the maximum limit. For example, one may set the maximum limit at zero to completely eliminate poor condition pavement.

4.6.3. Network RSL is above a minimum limit for each year of the analysis period. The minimum limit should be based on the need to have a cushion that would avoid rapid decline of pavement condition in times of temporary revenue shortfall.

4.6.4. Percent of network pavement to be rehabilitated is within the specified limits. This could be used to ensure uniform annual workload for construction forces.

The above strategy analysis is the third component of the Analysis Method shown in Figure 1. This completes the discussion on long-term network strategy.

5. PROGRAM DEVELOPMENT

The purpose of this section is to demonstrate how to use the project information obtained in Section 2 and the established optimal PS in Section 4 to develop optimal M-year MR&R programs. As previously mentioned, M is generally no more than 5 years. The necessary information for accomplishing this purpose is summarized below:

N	:	total number of candidate projects
P_i	:	percent of the i-th project length
$T_{ij}(k)$	:	cost of the i-th project rehabilitated by the j-th MR&R treatment available for the project at Year k
$C/E_{ij}(k)$	:	cost-effectiveness of the i-th project rehabilitated by the j-th MR&R Treatment at Year k
$X_i(k)$	:	RSL category of the i-th project at Year k before rehabilitation
$Y_{ij}(k)$	:	RSL category of the i-th project rehabilitated by the j-th MR&R treatment at Year k
B(k)	:	upper budget (funding) level at Year k
$[F_{ij}(k)]$	:	optimal PS

When candidate projects are selected to form an MR&R program, it is unlikely that the sum of the percents of the selected projects will match the percent called for by an optimal PS. Thus, a tolerance matrix $[\ e_{ij}(k)\ ]$ is needed for MR&R program to meet MR&R

Strategy [$F_{ij}(k)$] of a PS. To use Integer Programming techniques, an action variable, a, and indicator function, I, are also needed and defined below.

$a_{ij}(k)$ = 1 if the the i-th project is rehabilitated by the j-th MR&R treatment at Year k
= 0 otherwise

$I_x(y)$ = 1 if x = y; = 0 otherwise

With the above information, the optimal M-year MR&R program can be found by using an integer programming software to solve the following problem.

Optimize (Minimize) program cost-effectiveness:

$$\sum_i \sum_j a_{ij}(k) \bullet C/E_{ij}(k)$$

Subject to the following constraints:

5.1. Budget requirement for each program year k

$$\sum_i \sum_j a_{ij}(k) \bullet T_{ij}(k) \le B(k)$$

5.2. Network strategy requirement for each program year k and each pair of RSL categories m and n (m < n)

$$F_{mn}(k) - e_{mn}(k) \le \sum_i P_i \bullet I_m[X_i(k)] \sum_j a_{ij}(k) \bullet I_n[Y_{ij}(k)] \le F_{mn}(k) + e_{mn}(k)$$

5.3. Other requirements such as maximum percent of network in RSL Category I or minimum average network RSL. These constraints are optional, especially if they have been used in developing optimal preservation strategy.

5.4. Constraint to ensure that no project will be treated more than once during the program years M

$$\sum_k \sum_i \sum_j a_{ij}(k) \le 1$$

The Optimal MR&R program obtained from the above analyses is the result of engineer's, planner's and administrator's inputs. But, it provides no flexibility for administrators to make final decisions. It is normally called a black box system and will not be acceptable. Moreover, many procedures were used to estimate costs and network conditions. Therefore, the variable C/E has its variance. This means that some of the alternative MR&R programs with C/E close to the optimal value are not significantly different from the optimal program. For this reason, it is suggested that all feasible MR&R programs (satisfying the required constraints) with C/E close to the optimal value be ranked according to their C/E. At this time, other important information related to the benefits of the program should be included in the ranked list for reference. These benefits could include program cost, safety improvement, roughness condition,..., etc. Since every one of the feasible MR&R programs satisfies the optimal PS, the long-term network condition and funding levels will be properly regulated by the optimal PS regardless of which feasible MR&R program is used. This provides decision-makers with the flexibility to consider other benefits that can influence the decision as to which MR&R program accomplishes their objectives best and provides the most benefits to both users and the agency.

6. CONCLUSIONS AND SUMMARIES

Pavement performance curves of the condition measurements used to evaluate pavement condition must be established and improved through the PMS Feedback Process. By defining threshold values, the pavement performance curves are converted into RSL curves and RSL categories in such a way that some or all of the categories have special meaning and are to be used in conjunction with controlling network condition and funding levels.

A strategy analysis for using RSL to develop an optimal PS (long-term network strategy) was presented in Section 4. As long as the yearly MR&R program meets the optimal PS, the network condition and funding levels are regulated at the levels for which the optimal PS was designed. This provides a great flexibility for decision makers to make final decisions. This strategy analysis is generic because it can be used by any SHA that has ability to establish pavement performance curves.

This strategy analysis can answer many "what if" questions. The following are some of the examples [6]:

6.1. What change in funding level is needed to eliminate all unacceptable condition.

6.2. What would be the total preservation cost over a 20 year period of time, given the following alternatives:

(a) maintain network condition at the current level

(b) do nothing for a period of time and then restore network condition to the original level

6.3. Given various levels of funding reduction, what would be the corresponding number of years that the current network condition level could be maintained by reducing RSL.

The procedures for incorporating an optimal PS into program development process were presented in Section 5. These procedures are standard Integer Programming techniques. Other than those parameters in constraints for regulating condition and funding levels, the only input requirement is candidate projects and their corresponding estimated conditions, RSL, costs, and improvements of feasible MR&R treatments as discussed in Section 2. The candidate projects can be obtained by many methods. How well these candidate projects represent the network pavement will affect the outcomes of the developed MR&R programs. For this reason, a statistical method AID was introduced to fully take advantage of having continuous condition data profiles for developing candidate projects. In this case, the computerized cost-estimating method is absolutely needed to obtain information for developing optimal MR&R programs.

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TOWARD STANDARDIZATION OF A PMS ANALYSIS METHOD

REFERENCE: Novak, E. C., Jr., Kuo, W. H., and Baladi, G. Y., "Toward Standardization of a PMS Analysis Method," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society for Testing and Materials, Philadelphia, 1992.

ABSTRACT: Determining if a PMS meets federal requirements for pavement management is a difficult, inconsistent, and subjective process. The reason is, a PMS and its analysis method are considered to be agency specific. This paper examines the needs and wants of PMS users and transforms them into non agency specific PMS requirements. These requirements, in combination with the flow of processed PMS information from condition summary up to MR&R programs is counter to many agencies desired flow of policy and MR&R decisions. This indicates PMS analysis methods should be a separate planning decision making process that precede operational development of MR&R programs. The AASHTO guidelines indicate the generic analytical nature of PMS analysis and the prerequisites for standardization. The need for ASTM to standardize a PMS analysis method comes from both the historic inability of highways agencies to communicate between technical and decision making activities, and from the confusion that is created when agencies attempt to insert PMS methodology into their operational MR&R program development procedures. The authors believe a standardized PMS analysis is realistic, would do much to break down barriers, and advance the FHWA's objectives for a PMS. This paper proposes a baseline methodology from which the ASTM may be able to further evaluate the possibilities and merits of standardizing a generic analytical PMS analysis method.

KEYWORDS: PMS standardization, strategy analysis, remaining service life, implementation barriers

According to the new Federal Highway Administration (FHWA) Pavement Management and Design Policy, Ref [1], all State Highway Agencies (SHAs) must have an operational Pavement Management System (PMS) by January 1993. Fortunately, the policy is written in general terms that broadly outline requirements. In this way SHAs are not restricted from developing creative and innovative PMS methodology. The policy can be summarized as a requirement to put all the normal program and project development activities of a SHA into a formal PMS for the purpose of improving the efficiency of the Maintenance

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Rehabilitation and Reconstruction (MR&R) program development process and to insure funding efficiency. The purpose for this paper is to examine the difficulties of developing and inserting a PMS in the agency's operational MR&R program development process and look at the possibility that a standardized PMS analysis method could facilitate PMS development while at the same time providing unrestricted creative and innovative PMS development.

The characteristics of a PMS, its various parts or components, and its products are very well presented in the American Association of State Highway and Transportation Officials (AASHTO) Guidelines for Pavement Management Systems Ref [2]. The guidelines describe a generic PMS in a schematic representation is illustrated in Fig. 1. It can be seen from this figure that a PMS consists of three parts a Database System, an Analysis Method, and a Feedback Process. However, specific guidelines for a generic analysis methodology have not been found by the authors. The reason, presumably, is because it is widely held that each agency must develop its own PMS, hence, its own analysis methodology.

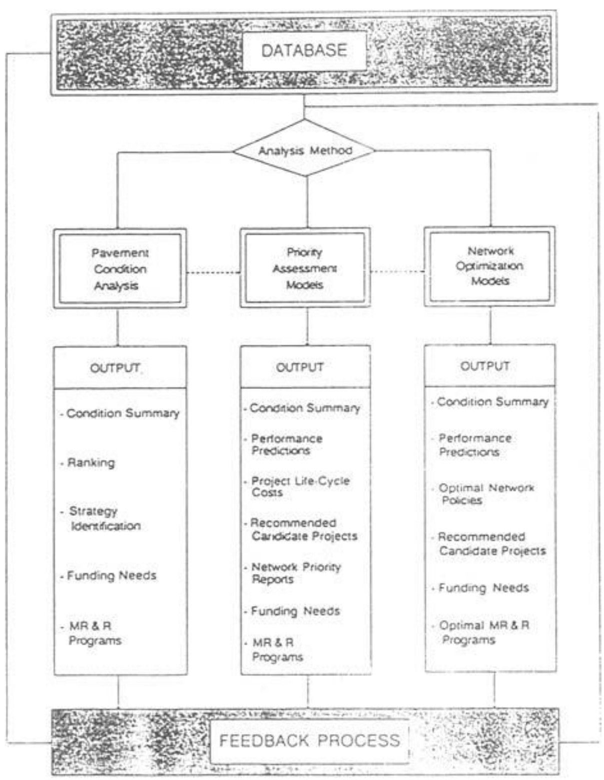

Figure 1. AASHTO's representation of a generic PMS.

PMS DEVELOPMENT FINDINGS

Most SHAs go through a PMS development process similar to that presented in the AASHTO guidelines Ref [2]. The same process was used by the Michigan DOT with the following results:

1. Assessment of agency procedures indicated that the department is satisfied with current procedures which are considered to be in compliance with FHWA requirements.
2. Primary concerns of key staff are that the system should be simple, inflexible, not interfere with the current procedures, and not make decisions or diminish decision making prerogatives of managers.
3. The PMS committee reviewed available literature and could not find a PMS that fit Michigan's operating procedures, address the primary concerns mentioned above, or provide managers with the means to control long term network performance with available funds.
4. The methodology for PMS analysis such as those presented in the AASHTO guidelines, Ref [2], are similar and are integrated into the preservation, or MR&R, program development process. The difference in analysis methods is primarily the quality and completeness of data used for analysis and the degree of development of application software used to produce PMS products.
5. The department is divided into two types of staff, manager and technical, whose goals, objectives, concerns and methods of dealing with pavement problems are widely divergent. Managers deal with subjective issues in which no analytical solution is available like budgeting and allocation of fund, and are expected to make the best rational decisions possible. However, the quality of decisions can be no better than the quality and completeness of the information on which they are based, except by chance. Technical staff, on the other hand, deal with objective issues (pavement layer thickness) which require application of mathematics and engineering analysis for resolution. PMS interviews indicate that managers often do not receive sufficient and high quality data to enable them to achieve the desired funding efficiency objectives. They express the need for more and better information at decision making levels.

PMS DEVELOPMENT AND IMPLEMENTATION BARRIERS

Based on experience in Michigan, it is suggested that it may not be possible to develop and implement a PMS unless the system is designed to remove the reasons why barriers exist. The following describes principal barriers, their justification for existence, and proposed methodology for overcoming or attenuating them.

Barrier No. 1: Technology.

Managers and policy makers place little, if any, emphasis on the use of existing or in developing technology to solve funding shortfall problems. Their emphasis is usually placed on quantifying funding shortfalls which in turn can be used to justify increased revenues.

Pavement technology has not provided administrators with the economic benefits that can be derived via improved technology. Technical papers are written primarily for the technical community, and do not directly address the needs or use the same variables that policy makers must deal with.

Policy makers do not have the means to reliably know the economic benefits that technical improvements could have on funding, network performance, or preservation strategies. And, technologists generally do not have the economic backing to collect and process the large volumes of data needed to support their results in terms of the variables used by policy makers.

The PMS analysis method used must have the ability to relate material properties, design estimates of pavement performance, actual pavement performance, and the actual life cycle cost of projects and to process this data into the forms of information most useful to the policy making level. Further, agency pavement research staff should be responsible for the PMS feedback process.

Barrier No. 2: Consensus Decision Making Process.

Highway agencies have already had or are moving toward consensus management. Teams, committees, and task forces representing a wide cross-section of knowledge and responsibility meet either to perform a specified task or become a permanent part of the organization. Such groups are well suited to develop excellent rational solutions to subjective issues like funding allocations provided they were given sufficient and relevant information of high quality. However, such groups are not well suited to deal with technical problems. The lack of appropriate technical information, time constraints, the responsibility of monitoring daily operations, and pressures for finding prompt solutions to funding problems are principal reasons why technical problems that could have been solved by scientific means are instead converted to subjective issues. The primary barriers created by consensus management include the following:

1. PMS review groups are too diversified and do not have sufficient time nor sufficient technical training to understand, evaluate, or develop PMS analysis methods.
2. Because of the risks involved, review groups tend to play safe. They recommend either no, minor changes or recommend what is known to be popular with upper management.
3. Groups tend to accept only state-of-the-practice methods.
4. Groups cannot assimilate technology; hence, the consensus management setting cannot utilize the technology to effect improvements in MR&R funding efficiency.
5. Groups tend to treat symptoms not problems because they are easier, less controversial, require less effort, and are initially a cheaper treatment than would be true for solving problems.
6. The number of issues and problems on the agenda of the consensus process keeps increasing as more technical problems are converted to subjective issues and because as symptomatic treatments fail, they must be dealt with repeatedly. The tendency in this environment is to reduce the quantity of information used for decision making thus improving its efficiency.

The consensus decision making process is essential for equitable resolution of subjective issues. The conversion of technical problems to subjective issue has been necessitated by the failure of the technical community, as a whole, to provide managers with timely, appropriate, and accurate technical information. Managers seem to be increasingly exposed to general, incomplete, inaccurate, and opinionated so-called technical information. PMS papers frequently emphasize the importance of low cost data collection and diminish the importance of high quality data referring to it as too detailed.

The PMS analysis method should provide the agency with the following benefits:

1. Ready access to the outcome of any preservation policy proposal.
2. Greater decision making freedom than currently exists.
3. More complete and higher quality information for use in the decision making process.
4. Pro-active management capability.
5. Greater reliability and accuracy.

6. Improve creative funding opportunities.

7. Provide policy makers with simpler and more precise means of controlling network performance and funding requirements.

8. Improved intra-agency communications.

9. The means to reduce the consensus decision making process workload.

10. Create at the policy making level an understanding of the improvement that can be made in funding efficiency through improved technology. This is one of the justifications for making the pavement research staff responsible for the PMS feedback process.

Barrier No. 3: Lack of Incentives.

When funds are adequate to solve most or all of the candidate MR&R projects, there is no visible need for a PMS. The personnel needed, the cost, and the agency effort required to develop a PMS analysis method only reduces available resources while offering no needed benefits. Although the literature paints a glowing promise of what a PMS could do, they do not document their economic value or worth. Also, funding efficiencies derived from technological advancements are usually slowly realized, difficult to quantify, require highly skilled staff, expensive, and ineffective for political use. Since increased revenues can temporarily solve most agency problems and are much easier to justify, it dissolves the need for improving technology and a PMS to attain continued improvement in funding efficiency.

The PMS analysis method should provide the agency with the capability of comparing the improvement in network performance derived from its standard MR&R program development process with the results obtained from the PMS. This requires a feedback process which can provide the agency with the means to verify each method with the actual outcome. The PMS analysis method is the framework that enables the technical and decision making activities to communicate. Via the feedback process, each agency's pavement research staff can directly implement technical improvements in data quality and software products that measurably improve funding efficiency.

STANDARDIZING A PMS ANALYSIS METHOD

Requirements Of A Standardized PMS Analysis Method

A standardized PMS analysis method must first and foremost be compatible with all agencies that are responsible for the preservation of roadway networks. To do this, the analysis must be independent of the operational, organizational, and administrative procedures used to develop MR&R programs. The variables that define MR&R programs and network performance must be in line with the current agency procedures. A PMS analysis method that attempts to meet these requirements was developed for the Michigan DOT, Ref [5]. Michigan's PMS is designed to be a pre-MR&R program development process. The system starts with data items such as condition, physical inventory, and cost data; and its final products are constraints that are to guide the MR&R program development process. The constraints are the MR&R programs lane mile length, its average Design Service Life (DSL), and the required budget. These variables are non agency specific. As the direct PMS involvement ends with the setting of MR&R program development constraints, it enables decisions to flow from top down. A conceptual diagram of a PMS designed to be independent of the operational aspects of the MR&R program development process is shown in Fig. 2.

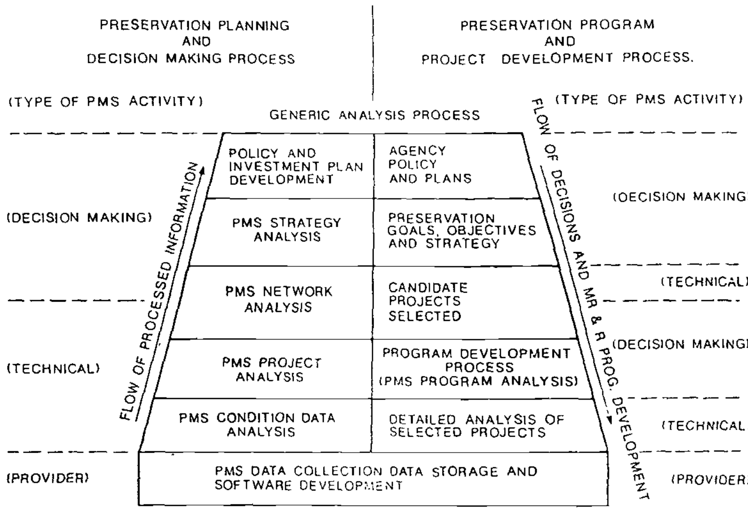

Figure 2. A schematic representation of PMS analysis methods illustrating their role in the planning and decision making process which precedes the operational phase of the MR&R program and project development process.

A PMS must provide the means to measure the degree of maximum utilization of the allocated fund. The current primary concern, as indicated by Refs [1] and [2] is on the compatibility with the agency's resources and needs. All agencies want to utilize their funds as efficiently as possible. However, Refs [1] and [2] direct guidance toward the development of systems that duplicate what an agency has already done, but with improved documentation. What is needed is guidance that agencies can use to gauge the efficiency of current MR&R programs and the means to improve program efficiency. To do this, a PMS which is a pre-MR&R program development process should have the capability of developing the theoretically most cost effective MR&R program for the given funding level. It can then become a yard stick for future programs. However, what is theoretically possible may not be practically achievable, a ratio of the cost effectiveness of a proposed MR&R program and the theoretical model should be introduced to determine the efficiency of the proposed programs.

A PMS that is based on incomplete data of poor quality cannot provide reliable information for decision making or produce cost effective PMS products. It must use high quality complete data and the appropriate software. A standardized PMS should set standards that enable agencies to determine the following:

1. What constitutes complete information needed for the decision making process.
2. The means to evaluate the quality of the data used for decision making.
3.What constitutes complete formal PMS analysis.

A standardized PMS must be acceptable and appealing to all agencies. Other requirements of a standardized PMS are as follows:

1. The ability of the application software to process highly detailed condition data.
2. The ability of the application software to be scaled down

to accommodate less complete and less detailed data.

3. Application software that can completely automate the PMS analysis process.
4. User driven menus.
5. User defined subroutines.
6. Agency specific definitions for threshold values.
7. Agency specific MR&R treatments.
8. Agency specific cost data.

Suggestions For Standard PMS Analysis Products

The AASHTO Guidelines for PMS list products that a standard PMS must be capable of providing. The following are suggestions on how this may be accomplished using non agency specific methods.

1. The current and projected performance of the network requires non agency specific measures of performance. Performance can be broken down into two variables, condition and rate of condition change. Condition, as shown in Fig. 3, can be derived on the basis of different means of condition assessment. The problem with using levels of condition is that it does not indicate the rate of deterioration and it is agency specific. A non agency specific condition parameter is percentage of the network in unacceptable condition. The agency defines the threshold value beyond which condition is no longer acceptable based on its condition assessment methods. Rate of change of condition can be based on the Remaining Service Life (RSL) concept as shown in Fig. 4 and presented in Refs [3] and [4]. When the pavement's condition reaches the threshold value for unacceptable condition, it would have zero RSL. A network's performance (percent in unacceptable condition and its average RSL) can be plotted on a network performance chart such as that shown in Fig. 5.

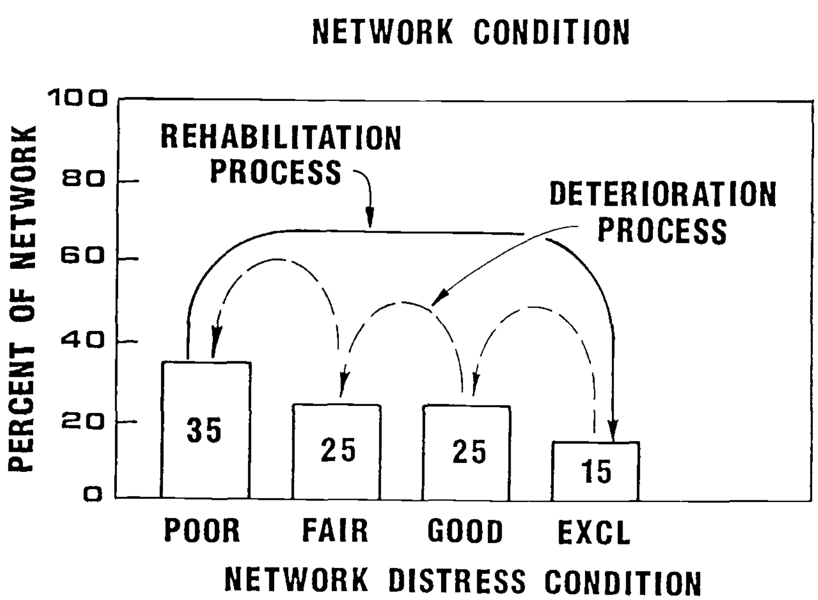

Figure 3. Generic representation of network condition, illustrating the deterioration and rehabilitation process.

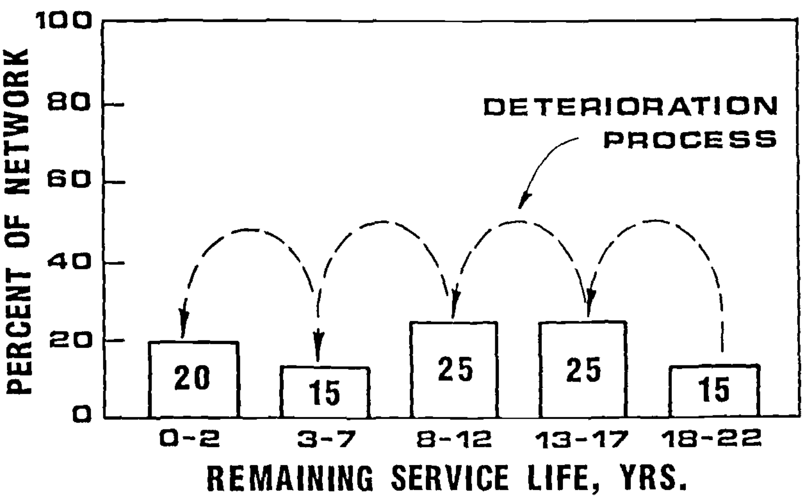

Figure 4. Illustration of a networks remaining service life distribution.

(Note that at the time of construction, a projects design service life is the same as its remaining service life.)

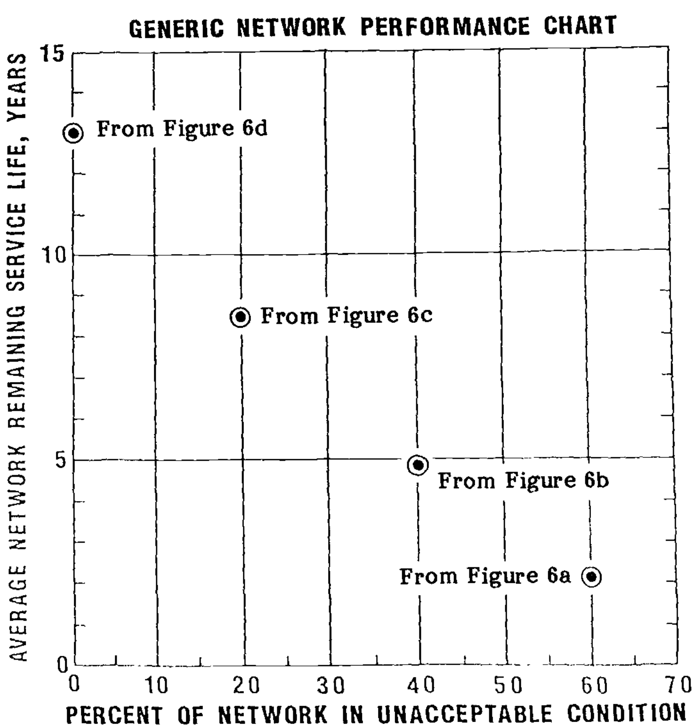

Figure 5. The resulting performance of any given network based on the consistent annual use of the four different MR&R program strategies shown in Figure 6.

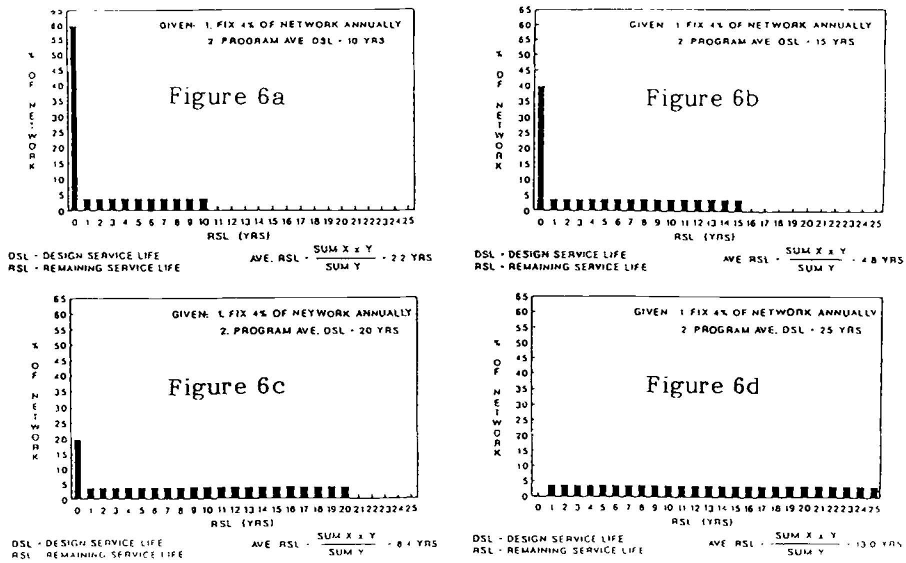

Figure 6. The Relationship between the remaining service life of a network and the given MR&R strategy.

2. The suggested means of relating any given MR&R program to resulting network performance is to use the same parameters to describe each of them. If a networks performance is defined in terms of its average RSL and percent of network in unacceptable condition, so must the MR&R program. A surrogate for the MR&R program must be used which is equal to the sum of the length of its projects and the average DSL of its projects. For convenience, the surrogate is referred to as network MR&R strategy. An important relationship between RSL and DSL is that at the time an MR&R action is completed, the projects DSL is equal to its RSL. This enables keeping track of the networks performance as each MR&R project is completed. This is done on the basis of the length (or percentage) of the network in each RSL category as shown in Fig. 4. An MR&R project removes its length from the networks source RSL category (usually zero RSL) and adds it to the networks target RSL category which is the same as the projects DSL.

At the policy/decision making level, it is more useful to deal with network MR&R strategy for developing long range MR&R funding and network condition policies. The idea is that policy makers can determine what network MR&R strategy produces the desired long term performance at the affordable budget level. The network MR&R strategy selected then becomes the policy constraints to develop the MR&R program. The existing agency's operational, organizational, and administrative procedures are used to develop the program with the provision that it's total lane mile length and average DSL conform to the prescribed network MR&R strategy.

The simple relationship that exists between a consistently used network MR&R strategy and the resulting network performance are illustrated in Fig. 6. The four different consistently applied network MR&R strategies result in completely different network performance. Fig. 6 results are based on the assumption that all MR&R projects were in unacceptable condition; hence, came from the zero year RSL category and were put in the RSL category which is the same as the program's weighted average DSL. In this manner, it is possible to specify the network MR&R strategy requirements necessary to achieve any given network performance level. It is important to note that the final equilibrium network performance is independent of its initial performance. The network MR&R strategy requirements, percent of network in the MR&R program and its average DSL, shown in Fig. 6 are plotted on Fig. 5 to illustrate how MR&R strategy and network performance can be interrelated on a single chart. The relationships shown in Fig. 6 can be used to produce a wide range of strategy performance relationships which if all plotted on Fig. 5 would result in the chart shown in Fig. 7. This chart can be used to determine the network condition resulting from any feasible and consistent network MR&R strategy, and vice versa. A more thorough explanation of the network analysis chart is presented in Ref [7].

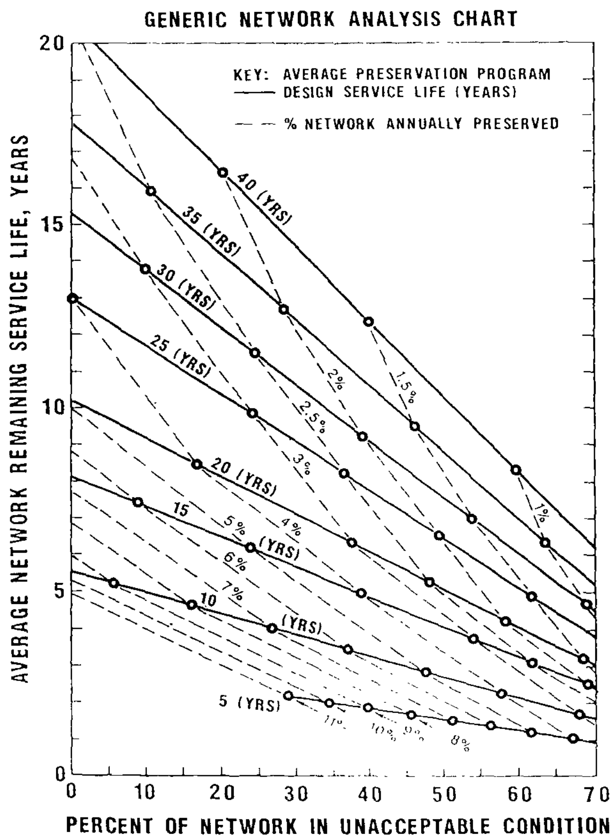

Figure 7. Generic Chart for Relating MR&R Strategy to Network Performance

3. Current and projected budget requirements necessitate a means of relating network performance to the funding level needed to maintain or to change to a different performance level. Although more sophisticated means exist, Ref [5], a simple method is to base MR&R

program cost estimates on historical cost data. Past MR&R programs can be used to establish the average cost per lane mile per each DSL. The chart shown in Fig. 8 illustrates the concept. This non agency specific analysis method can be used to determine the relationship between any network performance, any feasible network MR&R strategy, and the estimated cost of the MR&R program. These procedures are presented in Ref [6].

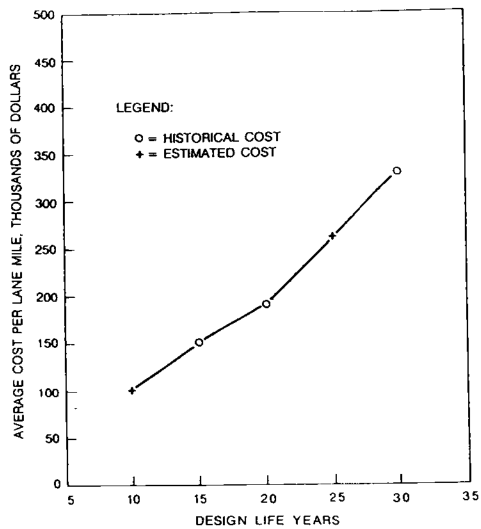

Figure 8. Historical Network Cost.

4. The budget required to bring the total network from its current performance level to any other level can be accomplished by the methods described in items 1 to 3. Most agencies would key in on the networks condition, i.e., percent in unacceptable condition, with a desire to reach zero percent. However, this can be accomplished via a wide range of network average RSL. Then for any given network condition, agencies would have a choice of selecting the network average RSL that has the lowest annual cost or highest affordable average RSL. An example of this problem is presented in Ref [7].

5. Specific programs for single or multi-year planning horizons need only to deal with the network MR&R strategy. If the policy were to designate a network MR&R strategy to annually preserve 4 percent of the network with an average program DSL of 25 years, any list of projects whose current RSL is zero and whose total lane mile length were equal to 4 percent of the network and whose MR&R treatments had a weighted average DSL of 25 years would result in basically the same long term network performance.

6. Method for priortizing expenditures when there is insufficient funding is the same as that described for Items 4 and 5. The decision rule would be what is the most acceptable balance between loss of condition and reduced RSL.

7. A basis for intra-agency communications is established by a standardized PMS analysis method because the simple non agency specific terms used at the policy/decision making level (RSL and percent of network in unacceptable condition) are easily translated to pavement performance and project parameters used by the technical

staff, and vice versa.

8. A basis for communicating outside the agency is established on the basis of easy to understand terminology and concepts for which an adjustment in any one of the variable is easily translated into the impact of that action on the other variables. The network performance chart of Fig. 7 illustrates what will happen if MR&R program funds are cut, increased or how much must revenues be increased if a designated network performance level is to be achieved. The use of this chart simplifies the explanation of the complex relationship among MR&R programs, program cost and network condition. They are essential elements to achieve PMS standardization.

9. A basis for comparing alternate network MR&R strategies is provided by Fig. 7. Program cost is the product of the cost per lane mile obtained from Fig. 8 and the lane mile length of the network MR&R strategy. The cost, MR&R strategy, and network performance of all feasible alternatives can be illustrated for decision making purposes with the Fig. 7 network analysis chart.

10. A basis for developing MR&R programs to emphasize or maximize designated program benefits should be a necessary part of a standardized PMS analysis method. Policy/decision makers must have the ability to control more than budgets and network performance. They also need to assure that the projects selected will maximize agency and user benefits. Program benefits could include items such as the following:

10.1 Ride quality improvement.
10.2 Distress condition improvement.
10.3 Reduction in average network rut depth.
10.4 Reduction of safety deficiencies.
10.5 Reduction in reactive maintenance workload.
10.6 Reduction in user costs.

Program benefits can be dealt with as an economic issue. However, policy makers are often not only interested in lowest cost but in emphasizing specific program benefits. By separately listing the interrelated benefits, it is possible to give policy makers the opportunity to rank their importance. A simple agency rating scale of 1 to 5, could for example, be assigned to each benefit variable to weight its importance. It would be necessary to quantify all the agency designated benefits of all feasible MR&R treatments of all feasible projects. In this way, ranking of benefits of each candidate project can be used to determine which program ranks highest in terms of the weighted benefits provided. A software tool, such as that developed for the Michigan DOT Ref [4], is needed to facilitate sorting through the thousands of possible combinations of projects and treatments. This software tool is referred to as project analysis and would be a part of the MR&R program development process as shown in Fig. 2.

A standardized PMS should also support a maintenance management system. The simplest approach should be to consider maintenance as having two different purposes. Reactive maintenance, which is to maintain a reasonable level of serviceability and safety, but does not effect the pavements RSL. Preventive maintenance which improves (increases) the pavements RSL. The easiest method of handling reactive maintenance is to define the unacceptable condition threshold in terms of when a pavement requires reactive maintenance. Hence, percent of network in unacceptable condition is equal to the reactive maintenance work load. This approach to reactive maintenance is explained in Ref [8]. Preventive maintenance can be treated as a supplement to the MR&R program. That is, preventive maintenance, repair, and reconstruction treatments all compete on the basis of their cost effectiveness.

Suggested Analysis Methods

A complete application software analysis system is needed to provide adequate PMS products for the policy/decision making process. The analysis software modules necessary to make a complete standard PMS are outlined in the following paragraphs in descending order of PMS analysis listed in Fig. 2.

PMS Strategy Analysis. An analysis procedure is needed to relate alternative network MR&R strategy to the long term network performance. The network analysis chart is a manual method that lacks flexibility, accuracy, and the ability to track interim network performance. These problems are overcome by the strategy analysis models presented in Refs [4] and [5]. Another necessary part of strategy analysis is to estimate program cost. While this is easy to accomplish on the basis of the agencies historical MR&R program records, as previously explained, a better method such as that explained in Refs [4] and [5] is needed. This method uses the cost of all feasible treatments of all feasible projects that make up the network to develop a cost matrix that for the designated cost effectiveness limits lists the lane mile cost and lane miles of pavement available to move from each lower RSL category to each higher RSL category. This cost estimating methodology is needed for a standard PMS if it is to have the ability to improve funding efficiency.

PMS Network Analysis. Since network performance is based on its average RSL and percent of the network in unacceptable condition, it is necessary to partition the network into sections of uniform performance. Boundaries of uniform sections could be fixed or moveable and the method of selecting boundaries non agency specific. Regardless of the method used to identify uniform sections, it is necessary for a standardized PMS to track the condition of each uniform section within the network. To be non agency specific, the essential information required at the network level is the RSL and length of each uniform section.

A standardized PMS must provide methodology for the software to perform detailed project analysis of all contiguous uniform sections that make up the network. This should require itemizing each occurrence of distress, and its physical dimensions. Semi-automation of distress surveys have reduced the cost of collecting such detailed condition data and make it affordable for most agencies. With such detailed data, network analysis can produce a listing of all repair and preventive maintenance quantities, their costs, and their cost effectiveness. A standardized network analysis must provide for user driven menus and user defined subroutines such as those presented in Ref [5].

Project Analysis. The requirements of a standardized PMS necessitate the ability to treat each uniform section of the network as a potential project. For each uniform section, project analysis should produce the following output:

1. Current condition and rate of change of condition for each measure of condition; i.e., roughness, distress, rut depth, etc.
2. An inventory of repair and reactive maintenance requirements.
3. Estimated design service life (DSL) of all feasible MR&R treatments.
4. Estimated cost of all feasible MR&R treatments.
5. Probable causes of deterioration.
6. Benefit estimates for each benefit the agency wants to consider for all feasible MR&R treatments of all uniform sections.

Non agency specific condition assessment should include methodology to process the most detailed distress, longitudinal and transverse profiles, and surface friction data. The methodology must also permit agencies to scale down to any one measure of condition and any level of precision desired, via user driven menus and user defined subroutines. This project analysis is presented in Ref [5]. It is the source of cost and cost effective data used to generate a cost matrix which is a key component of strategy analysis. Project analysis also requires that DSL estimates be based on the same parameters used to estimate RSL. This can be accomplished using the methodology presented in Ref [3]. A standardized PMS analysis method must accommodate such detailed analysis to provide the benchmark to evaluate the effectiveness of less detailed PMS methods.

PMS Condition Data Analysis. The current trend to automate pavement condition surveys enables collection of more detailed condition data at lower cost. It should, therefore, be necessary for a standardized PMS to accept everything from the most detailed to the most general condition assessments possible. This could be accommodated via user driven menus and user defined subroutines. The purpose of condition data analysis is to process raw condition data into data forms required for use by project, network and strategy analysis software.

PMS Program Analysis. In a standardized PMS, the policy level sets the network MR&R strategy, the funding level, and the benefits that are to be maximized by the MR&R program. The candidate projects and treatments can be developed via the agency's normal operating procedures. Network MR&R strategy is based on optimizing network performance and available funds. It is the purpose of PMS program analysis to assemble feasible projects and treatments into alternative programs that meet strategy constraints. Program analysis ranks the programs in order of benefits provided. A top ranked program candidate would meet strategy constraints, be within budget limits and rank highest in benefits provided. The more candidate projects and treatments considered, the greater the opportunity is to maximize benefits. Two to five times the number of projects that could normally be programmed in one year should be analyzed to develop each annual program.

SUMMARY

1. The issue of compliance of an agencies system of developing MR&R programs based on FHWA regulations and AASHTO guidance is a difficult, inconsistent, and subjective process. The availability of a standardized non agency specific PMS would minimize this problem.

2. PMS literature indicates each agency is expected to develop its own PMS analysis methods so they can be customized into their MR&R program development process. This approach tends to increase agency cost and reduce benefits compared to a PMS that is not integrated into the operational MR&R program development process. A standardized PMS which is independent of the program development processes is proposed so that agencies can secure at low cost a PMS that can improve funding efficiency and avoid the convulsive effects of inserting a PMS in their operational program development process.

3. The requirements for a standardized PMS can be translated into the following non agency specific PMS requirements:

3.1 Simplicity.

3.2 Maximum flexibility.

3.3 Require no operational, organizational, or administrative changes.

3.4 Possess the capability to provide all the information necessary for rational decision making and answer any rational pavement preservation question.

3.5 Provide information for decision making but not diminish the decision making prerogatives of any users or administrators.
3.6 Provide a top down flow of decisions.

4. Based on the non agency specific PMS requirements, and the conflict between flow of PMS information and the agencies flow of policy and MR&R decisions, a system of PMS analysis for processing pavement condition data into project, network, and policy information must be a separate planning and decision making process that precedes the MR&R program development process.

5. It should be possible for the ASTM to develop a standard PMS analysis method if the PMS is a pre-MR&R program development process and if network and MR&R programs are characterized in terms of non agency specific variables.

6. Major existing barriers that could prevent agencies from developing and implementing a PMS are as follows:

6.1 Inadequate technology.
6.2 The consensus decision making process.
6.3 Lack of PMS development incentives.

7. A standardized PMS analysis method is needed to reduce the cost of PMS development and implementation, to minimize the substantial duplication of effort now going on, and to bring down the major barriers faced by agencies trying to develop and implement a PMS.

8. The stated purpose for a PMS is to "manage Federal-aid highway pavements in a cost effective manner." The only means of objectively evaluating if an agency's MR&R programs are efficient is on the basis of the quality and completeness of the following:

8.1 The information used for decision making.
8.2 The raw data used for analysis.
8.3 The analysis methods used and their output.

A standardized PMS analysis method designed to provide a benchmark measure of MR&R funding efficiency and which is based on a complete set of analysis software should fulfill the FHWA's stated purpose for a PMS.

9. The basic methodology of a standardized PMS analysis method is that it can process detailed condition, physical inventory, unit costs, traffic, and related data into project DSL, project cost, and benefits for each of all feasible treatments of 100% of the uniform sections that make up a network. And, the capability to develop network MR&R strategy and program cost estimates without the need to deal with candidate projects.

10. The use of technology to solve funding shortfall is not normally considered. To address this problem, a standardized non agency specific PMS analysis method that is based on variables common to both manager and technical staffs, that has a software system to process and transform technical data into the variables used by managers, and that utilizes the agency's pavement research staff for the PMS feedback process is proposed.

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