How we fund and plan the preservation of our transportation infrastructure is clearly at a crossroads. The needs of the system are rising yet our ability to adequately fund pavement preservation is in doubt. Over the past few years the US economy has faced numerous challenges such as inflation and rising oil and energy prices. The state of today’s economy is presenting new challenges for transportation agencies. Whether the challenges are the uncertainties about the short-run cyclical performance of the economy, or projected long-term budget constraints, it is of fundamental importance that the pavement asset be preserved. Solid and sustained pavement preservation is a necessary foundation for a sound infrastructure.

Because of funding constraints, there has been increasing incentive to develop an effective budget allocation process for managing and preserving our pavements. Knowing when a pavement needs to be treated is one thing; carrying out a cost-effective treatment on time within a constrained budget is another matter.

The Texas Department of Transportation and the University of Texas at Austin Center for Transportation Research are developing a program that performs multi-year, long-term pavement preservation and rehabilitation needs analysis subject to funding availability and performance requirements. The Pavement Performance and Maintenance Management System (PPMM) is a Web-based GIS application that uses existing data from a Pavement Management System database for the monitoring and analysis of current pavement performance as well as for the estimation of current and future maintenance and rehabilitation needs of the pavement. The system utilizes historical pavement performance data and allows the performance of scenario analysis on multi-year pavement needs.

The Performance Monitoring component of the PPMM System allows the selection of highway sections or entire networks to visualize historic pavement performance parameters based on ride, distress and condition. The system will sort highway sections into one of three different attention categories based on a user defined network classification matrix.

The Maintenance Management component allows the user to specify the pavement network of interest and a budget to determine the best way to spend funds by a ranking method and an allocation algorithm which relies on a user-controlled policy matrix. The ranking method assigns priority to sections with small ride score values, small distress score values, and large annual average daily traffic values. The Budget Planning Tool
within the Maintenance Management component helps to predict the necessary budget for the future predicted performance of a pavement to equal an acceptable overall target condition level over an extended planning period. It also uses a user-controlled policy matrix with associated costs, a user-controlled improvement matrix for sections receiving treatment, and a family of pavement deterioration models for system deterioration at the end of each planning year.

Preserving a pavement system at an acceptable level of service with constrained budgets is always a challenge for every transportation agency. A pavement preservation and rehabilitation needs analysis system provides a valuable tool for achieving cost-effective management of network pavement preservation and performance.

**INTRODUCTION**

Transportation agencies in the United States and around the world are increasingly using Pavement Management (PM) principles to manage and preserve pavement assets in a condition acceptable to the traveling public. Pavement Management Systems (PMS) have been developed for that purpose and have been steadily improving with the advent of technological innovations such as personal computers (PCs), the increase of computing power, new referencing and visualization tools, e.g., Global Positioning Systems (GPS) and Geographic Information Systems (GIS), as well as the overall increase in robustness and reliability of such systems. In the United States, the importance of PMS has become even more evident, especially since the General Accounting and Standards Board Statement No.34 (GASB 34) created a federal requirement for their existence (Maze & Smadi, 2003). Around the rest of the world, many western European and Asian countries, as well as Australian provinces, have also developed and implemented such systems to enhance the stewardship of their pavements, increase their efficiency and improve their accountability to the public (Pantelias, 2005).

The Texas Department of Transportation (TxDOT) has been an early proponent of PMS. As a result, a program for the development of a comprehensive, automated inventory and condition database for the entire TxDOT pavement network was undertaken in the late 1980s. The resulting database, termed Pavement Management Information System (PMIS), was put in production in 1993 and is still used today with annual data updates. This database is one of the largest pavement databases in the U.S., containing information for more than 300,000 road sections of roughly 0.5-mile in length.

Recently the Texas Transportation Commission (TTC) set a 10-year statewide goal of having 90 percent or more of Texas pavements maintained at good or better condition by year 2012 (Saenz, 2004). This goal has increased expectations for management of the state’s roadways and has bolstered the need to optimize already-stretched maintenance funds to meet the 2012 goal. As a result, monitoring the TxDOT pavement network and the planning of maintenance and rehabilitation activities (with the corresponding budgets), have attracted the interest of various TxDOT district maintenance managers, since they are responsible for achieving the TTC goal within their boundaries. TxDOT is divided into 25 geographical regions termed districts. Each district receives maintenance funds based on a formula consisting of three major factors:

- The pavement lane-miles within the district boundary
- The vehicles-miles traveled within the individual district
- The ride and pavement condition scores from the latest available data
As is evident, the system is dependent on past condition score data and as such is reactive in nature and therefore allows less flexibility to maintenance managers in addressing early pavement issues. Based on this, TxDOT has been working with the Center for Transportation Research at The University of Texas at Austin to develop a decision support system that would help TxDOT Districts determine the best strategy to optimize the maintenance funds to meet their preventive maintenance (PM) objectives.

The Transportation Infrastructure and Information Systems (TIIS) laboratory at the Center for Transportation Research (CTR) has developed a new, interactive, Web-based system for pavement maintenance management. This new system consists of two major modules: 1) a GIS module for displaying the PMIS information, and 2) a decision-support module termed Pavement Performance & Maintenance Management (PPMM) focusing on the monitoring of the pavement network and the management of its maintenance and rehabilitation activities. The key functions included in the system enable it to:

- Visualize multiple-year pavement condition data in PMIS with an interactive and user-friendly interface
- Identify pavement sections of interest based on their location characteristics and retrieve their performance history according to available indices (Ride Score\(^1\), Distress Score\(^2\) and Condition Score\(^3\))
- Classify pavement sections according to various levels of “Attention” needs based on their recorded historical performance
- Allocate available funds to pavement sections based on a prioritization algorithm that takes into account pavement performance and traffic, and estimates the resulting gain or loss in the future performance of the overall network
- Estimate future budget needs according to targeted performance goals for the pavement network over a user-defined (short, medium or long) planning horizon.

The application is currently being pilot-tested by TxDOT personnel for its usability, reliability and robustness. Because of the large number of algorithms and models employed to develop the Web-based system, the presentation of this paper is focused on the features of the system rather than the details of the algorithms and models.

The remainder of this paper is structured as follows:

- Brief overview of the current state-of-the-art of PMS applications with a reference to the current state-of-the-practice.
- Past efforts for the development of PMS by TxDOT along with the needs that led to the development of the presented system.
- Features and capabilities of the Web-based application with a brief reference to or description (where applicable) of the models and algorithms behind the user interface.
- A discussion of the development process and anticipated benefits from the use of the system, as well as recommendations and plans for future work.

\(^1\) The Ride Score is a measure of pavement functional performance defined by TxDOT based on the Present Serviceability Index (PSI).
\(^2\) The Distress Score is a measure of pavement structural performance defined by TxDOT based on the measurement of various surface distresses.
\(^3\) The Condition Score is a composite pavement performance index defined by TxDOT based on the combination of the Ride Score and the Distress Score.
CURRENT STATE OF PAVEMENT MANAGEMENT SYSTEMS

The state-of-the-art of PM application has been continuously evolving due to the advances in technology in terms of computing power, various visualization and map referencing techniques, and the development of more sophisticated and effective computational methods and applications. Reports of such sophisticated modeling, data management, visualization and analysis techniques and related methodologies have been communicated in the literature by many states and researchers/engineers. Examples include, but are certainly not limited to, the use of Markov probabilistic deterioration models in the Arizona PMS (Golabi et al, 1982) and the city of Coimbra, Portugal PMS (Ferreira et al, 2002); the use of a web-enabled PMS by the Washington State DOT (Muench et al, 2004); the use of GIS visualization and analysis in the Arizona PMS (Medina et al, 1999); and the use of true optimization techniques for budget planning and allocation in the PMS of Arizona (Golabi et al, 1982), Oklahoma (Chen et al, 1996), the Portuguese road network (Golabi & Pereira, 2003), Kansas (Testa, 2006), and Maryland (Hedfi & Kessler, 2007), among others. Similar applications or variations of these employed models, methods and tools exist in abundance in the literature – more usually than not as a result of pilot studies – and further reference is outside the scope of this paper.

However, despite the technological innovations and the continuous development of more sophisticated tools, the state-of-the-practice of PMS continues to lag behind the state-of-the-art. Although, theoretically, a large number of options and tools can be available, in practice, the size of the pavement networks and the unavoidable lack of sufficient and good quality data, among other reasons, render most of these options very hard to implement. As a result, many agencies use PMS that utilize models, techniques and tools that are not state-of-the-art but that can be used by their personnel and still provide better decision support and solutions than relying just on past agency practices and experience. Finally, an area where the state-of-the-practice has started to keep in pace with the state-of-the-art is the design and architecture of these decision-support systems. Indeed, the use of Web-based system architectures, relational databases and analysis tools based on sophisticated computer programming platforms and coding represent the cutting edge in the way these systems are designed and implemented in practice.

PAVEMENT MANAGEMENT SYSTEMS IN TxDOT

Managing the largest pavement network in the U.S. with more than 193,000 miles of roadway under its jurisdiction, TxDOT was an early champion of PM and has long been investigating the use of PMS for the Texas pavement network. The vast size of this network and its corresponding needs have always created an incentive for the consideration of such systems for more effective and efficient decision making. TxDOT is currently spending $2.7 billion annually in Maintenance and Rehabilitation (M&R) activities for pavements (TxDOT, 2007). The enormous size of the budget and the potential for cost savings has been a key driver for TxDOT to fund PMS-related research and development since 1971. As a result, TxDOT currently maintains PMIS, the largest pavement inventory database in the U.S. Pavement condition is updated annually through extensive data collection efforts. The recorded data elements encompass both structural and functional pavement conditions for many different types of flexible and rigid pavements (TxDOT, 1994).

The initial effort to evaluate TxDOT pavement conditions through an automated process was undertaken through a research project in 1971. It was followed by several research projects that yielded the first TxDOT PMS system called Pavement Evaluation System (PES) in 1982. The primary objectives of this system were to collect and monitor pavement condition data and help in monitoring the use of funds for pavement maintenance. It was used for almost a decade and underwent numerous changes and upgrades until it was replaced.
by PMIS in 1993. PES was abandoned because it was developed as a state-level PMS and was not suitable for project-level PMS purposes, whereas PMIS has been designed to assist with both, network and project-level PM.

Pavement sections are uniquely identified in PMIS using the Texas Reference Marker (TRM) system. This system has TxDOT highways and roadways divided into roughly 0.5-mile segments (although sometimes as small as 0.1 miles and as long as 1 mile), all of which are identified by a combination of alphanumeric codes. After specifying the corresponding district and county, different roadways are identified by their Highway Roadbed ID, a combination of letters and symbols that denote the highway system they belong to and the lane of interest, e.g., IH 35 A refers to Interstate Highway 35, left lane (A is code for the left lane in the PMIS database). Finally, after the Roadbed ID code, each pavement section is uniquely identified by a set of four numbers, which are a Beginning Reference Marker (and a corresponding displacement) and an Ending Reference Marker (and a corresponding displacement).

The use of this enormous database for PM purposes has long been the desire of TxDOT officials and various attempts to achieve it have been made. TxDOT has developed a series of generic deterioration models based on the concept of utility curves to predict future section deterioration (Stampley, et al 1995). These curves, developed in the early 1990s were calibrated to local conditions for all Texas counties using PMIS data, but were never widely used in practice due to technical difficulties in implementation. Furthermore, another PM study was recently conducted focusing on the development of an optimization algorithm for network-level budget planning. However, the vast size of the network proved an insurmountable obstacle, as even with the use of heuristic methods (e.g., genetic algorithms and clustering) a solution for the entire Texas network would not be computationally feasible (Zhang, et al 2004).

The statewide goal for pavement condition put forward by the TTC in 2002 emphasized an already existing need for data-driven decision-making regarding the solicitation of funds for Maintenance and Rehabilitation (M&R) actions. Under this rationale TxDOT decided to work with CTR for the development of certain decision-support functionalities based on the PMIS database. These functionalities corresponded to the following:

- The visualization of pavement conditions of the highway network under the jurisdiction of TxDOT.
- The classification of the pavement network in attention categories for the identification of sections in need of M&R actions.
- The development of a tool that could support decisions on multi-year budget planning and single-year budget allocation and project selection.

The result of this currently ongoing effort is the Web-based system to support pavement maintenance management decisions.

**THE WEB-BASED SYSTEM TO SUPPORT PAVEMENT MAINTENANCE MANAGEMENT DECISIONS**

**General Description of the System**

The most important characteristic of this system is that it is Web-based. As such, it can be operated by any personal computer with access to the World Wide Web using a standard Web browser. The system is composed of two major modules: a GIS module for visualizing pavement condition data and a decision-support module for assisting in making M&R decisions.
The GIS Module

The purpose of the Web-based GIS module is to facilitate easy-to-use access to data that is essential to maintenance decisions from the PMIS database. It relies on interactive GIS tools which allow the user to select regions of interest and display color coded information of key data maintained within the PMIS. The user is able to select individual sections from the map to display additional information on section characteristics. The framework of the GIS Module is illustrated in Figure 1 and its key features are outlined as follows:

Figure 1. Framework of the Web-based GIS module

a) Overview Map: This overview of the entire map can be turned on and off by the “Toggle Overview” button, which is located at the top right corner of the toolbar.

b) Layer List Button: The layer list button is used to show the symbols for each layer in the information system. Users can toggle between the layer list and legends using this button.

c) Layer List: It supplies users with the different layers present in the map and indicates which layers are active.

d) Simplified Selection Tool: This feature presents the user with a simplified tool to select and view the information for a particular district/county.

e) Refresh Map Button: After checking or un-checking the radio button for any of the layers, this function button must be pressed to see the changes in the map.

f) Scale Bar: The scale bar shows the relationship between the actual and scaled-down map distances.

g) Tool Bar: This feature contains various tools for the data extraction and map manipulation.

h) Print Buttons: The bottom two buttons of the tool bar are used to generate printable versions of the maps and tables. The left print button allows the user to print the map and the right one is for printing the table.
The Decision-Support Module

The decision-support module is composed of two groups of functions, each one having two corresponding tools, as presented in Figure 2.

The decision-support module has been programmed using the scripting language, PHP v.5, from the server side and JavaScript from the user side and uses a variety of structured query language (SQL) and other graphing functions to provide the required functions and features. The Performance Monitoring Module is much simpler in terms of programming, as it is only used to retrieve, classify and display information already available in PMIS. On the other hand, the Maintenance Management Module is far more complicated as new information has to be generated (such as projected network/section performance) for the application to perform the budget allocation and budget planning functions.

Data

The Pavement Performance Maintenance Management (PPMM) system is an application developed to mine, analyze, and display data originally stored in the PMIS database. To ease the use with PHP v.5, a copy of the latest PMIS data was transformed to SQL format and stored in the PPMM Web-server. The PMIS database used for developing the PPMM system contains data from 1995 to 2007. The data used for the various requested analyses are initially mined from the PPMM SQL database then analyzed with the use of the analysis tools; finally, the results are displayed to the end users through a client-server structure. The complete data flow structure of the PPMM is shown in Figure 3.
Capabilities and Features

The PPMM employs various algorithms and models for its internal functions to run, according to the corresponding tool used. A more detailed discussion of the capabilities and features of the four PPMM tools follow.

Performance Monitoring Module – Section Tool

The section tool is used to create charts to help with visualization of data. The user can specify the location of a pavement section and visualize its historic performance for the duration of performance data. As mentioned earlier, three performance indices from the PMIS are available, namely Ride Score, Distress Score and Condition Score. The tool uses SQL to sequentially identify a section of interest and retrieve and display the corresponding performance information in a chart.

Performance Monitoring Module – Network Tool

The network tool helps in the classification of pavement sections into predefined condition levels requiring varying degrees of “Attention.” Three levels of “Attention” have been defined, namely “No Attention,” “Vigilance,” and “Immediate Attention.” The classification can be performed by performance criterion of interest (Ride Score, Distress Score, or Condition Score), by pavement type (10 individual types or two generic groups), and by fiscal year. The classification algorithm is based on the consideration of two performance parameters for every section in the pavement network of interest: (1) The absolute value of the selected
performance criterion for the selected fiscal year; and (2) the change of the selected performance criterion be-
tween the selected fiscal year and the previous year. For both of these parameters, three performance levels have
been defined (Good, Fair, Bad condition and Slow, Medium, Fast deterioration, respectively), based on user-
controlled threshold values. The two parameters assessed together hence form a three by three matrix of nine
possible combinations. The user can then assign these combinations to the three different attention categories,
thus classifying the pavement sections accordingly.

The user can obtain performance plots for any of the classified pavement sections by simply clicking on
the section in the results screen. Furthermore, for both the section tool and the network tool, the generated
results and plots can be printed by clicking on the corresponding links.

Maintenance Management Module – Budget Allocation Tool

The budget allocation tool has been developed to assist in allocating a (user-defined) total budget to a
regional or sub-regional pavement network. The tool initially ranks the pavement sections in order of their
importance for receiving M&R actions based on three criteria: Ride Score, Distress Score and traffic volumes.
Furthermore, each section is assigned an M&R action (Needs Nothing, Preventive Maintenance, Light Reha-
bitilation, Medium Rehabilitation, and Heavy Rehabilitation), based on the combination of its Ride Score
absolute value on the fiscal year of interest and the change of Ride Score between the selected fiscal year and
the previous fiscal year. Finally, an estimated implementation cost is calculated for each section based on the
section’s length, number of lanes and assigned M&R action.

Once the ranking is completed the user can then allocate the total budget to the various pavement sections.
The allocation algorithm starts at the top of the ranking list and goes down sequentially, each time adding a
section and subtracting the estimated M&R cost from the total budget. If a section cannot be completed with
the remaining budget, the algorithm moves to the next one. The algorithm terminates when the budget has
been exhausted or no other section can be completed.

The Budget Allocation tool also estimates the overall performance of the selected pavement network
in terms of Ride Score before and after the application of the M&R actions. This feature allows for a “what-
if” scenario analysis whereby using different total budgets, the user can observe their corresponding impact
on the overall network condition and draw related conclusions. The overall performance is determined with
the use of specific deterioration models developed from previous TxDOT research efforts (Stampley, et al
1995). These models are based on a generic s-shaped curve, calibrated with the PMIS data, and stratified by
pavement type (flexible, rigid) and level of traffic (Low, Medium, High). Finally, the total number of treated
sections and the amount of remaining funds, if any, are estimated and displayed.

Maintenance Management Module – Budget Planning Tool

The budget planning tool is used to determine future budget needs for the pavement network of interest to
achieve a certain user-defined performance goal. The tool is based on sequential year prioritization using, in
essence, the same algorithm as the budget allocation tool, but for a series of consecutive years. The user can
initially specify the network of interest, base year of analysis, as well as the type of performance target for the
network. The two available types of performance targets are the “Overall Network Ride Score”, or specific
“Percentage(s) of Network Sections” in various performance categories (Good, Fair, Bad). The user can also
specify the planning horizon to be three, five or ten years. Once these parameters are specified, the tool per-
forms the budget planning and displays the following summary results by year of the planning horizon:
• Target performance score
• Achieved performance score
• Number of sections treated
• Overall estimated budget

The analysis is done by using the same deterioration models used in the budget allocation tool for the annual deterioration of pavement sections, as well as by considering the improvement in the performance score that is achieved from the application of projected M&R actions. The assignment of projected M&R actions and the sequential selection of sections for the achievement of the yearly target performance score are done identically to the budget allocation tool. All parameters that affect the ranking of the sections, their assigned M&R action, their cost and the corresponding gains in performance score are included in matrices that the user can review and modify, if so desired.

Furthermore, from the summary results page, the user can navigate to a detailed results page where all treated sections are classified by type of M&R action. Subtotal costs and lane miles treated per M&R type are also estimated and displayed.

In both the budget allocation and budget planning tools, the user can obtain performance plots for any of the analyzed pavement sections by simply clicking on a section in any of the results screens. Finally, most of the generated results and plots can be printed by clicking on the corresponding link on the results page.

**CONCLUSIONS AND FUTURE WORK**

There are many conclusions that can be drawn from the development of this Web-based system. These conclusions refer to both the cooperative approach within which the system has been developed, as well as to its features and capabilities, the accuracy and flexibility of its components, and future work under way to supplement current functionalities.

The development of the Web-based system to support pavement maintenance management decisions and its adoption by TxDOT has so far been a success. System development began by responding to requests made by TxDOT engineers for a simple but robust decision-support system that could utilize PMIS data for M&R budget allocation. The developed application has been appreciated by and has received strong support from the management of TxDOT’s Maintenance Division and Dallas District. This success story highlights the benefits of working closely with TxDOT, understanding the agency’s needs and requests and producing a solution that caters to these requests in a way that can be easily used and understood by both administrators and technical personnel. Once an initial version of the solution is accepted, then upgrades in terms of functionality and sophistication can be made.

The system features and capabilities have been determined based on the requests of engineers and administrators of TxDOT. As such, the degree of sophistication has been customized to the needs of the various user groups with different needs and requirements from the system. In addition, the system has been developed with the potential to be upgraded in the future, depending on the need for increased detail and precision.

The system tools have been based on models and algorithms that can produce valuable results to support maintenance management decisions by using data available from the existing PMIS database. Future upgrades to these models through further calibration and research are anticipated to increase the sophistication and accuracy of the analysis results.
ACKNOWLEDGMENTS

This study has been funded through collaborative work between the Texas Department of Transportation Maintenance Division and its Dallas District and the Center for Transportation Research of The University of Texas at Austin.

REFERENCES


