5-9035-01-P1-Final

A WEB-BASED PAVEMENT PERFORMANCE AND MAINTENANCE MANAGEMENT AND GIS MAPPING SYSTEM FOR EASY ACCESS TO PAVEMENT CONDITION INFORMATION: FINAL REPORT

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TxDOT Project 5-9035-01: Pilot Implementation of a Web-based GIS System to Provide Information for Pavement Maintenance Decision-Making

JULY 2012, REVISED NOVEMBER 2012
PUBLISHED MAY 2013

Performing Organization:	**Sponsoring Organization:**
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Performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.	

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Printed in the United States of America

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Abstract

State Departments of Transportation, including the Texas Department of Transportation (TxDOT), have long been moving towards the development and implementation of pavement management systems that would enable monitoring of the performance of their roadways, as well as assist transportation officials with maintenance budget allocation and planning decisions. Various past attempts focused on using the available performance databases as well as state-of-the-art concepts for the development of such systems. Texas's unique characteristics, the most predominant of which is the vast size of the managed pavement network—79,696 centerline miles of highways including 49,829 bridges—have made some of the decision support models and/or algorithms a challenge to implement. This report presents a new approach to the development of such a decision-support system with its focus on maintenance management for TxDOT. The new system is web-based and provides functional capabilities that allow transportation officials and engineers to make informed decisions regarding their budget planning and budget allocation for pavement maintenance management, fully utilizing available historical data. The developed system has been successfully pilot-tested in TxDOT's Dallas District.

1. Introduction

Transportation agencies in the United States and around the world have been increasingly using Pavement Management (PM) principles in order to manage their pavement assets and preserve them 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 (Global Positioning Systems [GPS], Geographic Information Systems [GIS]), as well as the overall increase of 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) was issued, creating a federal requirement for PMS (Maze & Smadi 2003). Internationally, many western European and Asian countries, as well as Australian provinces, have also developed and implemented such systems in order 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) was 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. PMIS is updated every year with new pavement condition and other inventory data. This database is one of the largest pavement databases in the U.S., containing 20 years of pavement condition data for approximately 190,000 half-mile sections each year, with a total size of close to four million records.

Recently the Texas Transportation Commission (TTC) set a 10-year statewide goal of having 90% or more of Texas pavements maintained at good or better condition by year 2012 (Saenz 2004). This goal has increased the expectations for managing of the state's roadways and has bolstered the need for optimizing the already stretched maintenance funds in order to meet it. As a result, the programs for monitoring TxDOT pavement network and planning of maintenance and rehabilitation (M&R) activities (with the corresponding budgets) have attracted the interest of various TxDOT District maintenance managers, as they are responsible for achieving the TTC goal within their District boundaries. TxDOT is divided into 25 geographical regions termed Districts for administrative reasons. Each District receives maintenance funds based on a formula consisting of three major factors:

1. The pavement lane-miles within the District boundary
2. The vehicles-miles traveled within the individual District
3. The ride and pavement condition scores from the latest available dataset

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 mangers seeking to be proactive in addressing early pavement issues. Based on this, TxDOT has been working with the Center for Transportation Research (CTR) 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 use of maintenance funds in meeting PM objectives.

Under this effort, the Transportation Infrastructure and Information Systems (TIIS) laboratory at 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 M&R 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 estimate the resulting gain or loss in the future performance of the overall network; and
- 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 the work is focused on the features of the system rather than the details of the algorithms and models.

The remaining of this report is structured as follows. First, a brief overview of the current state of the art of PMS applications is presented with a reference also to the current state of the practice. Second, past efforts in the development of PMS by TxDOT are presented along with the needs that lead to the development of the presented system. Then, the features and capabilities of the web-based application are presented with a brief reference to or description (where applicable) of the models and algorithms behind the user interface. Finally, this report concludes with a discussion of the development process and anticipated benefits from the use of the system, as well as recommendations and plans for future work.

2. Current State of Pavement Management Systems

The state of the art of PM applications has been continuously evolving, mostly due to advancing technology in terms of computing power, various visualization and map referencing techniques, as well as the development of more sophisticated and effective computational

[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.

methods and applications. The application of such sophisticated modeling, data management, visualization and analysis techniques, and related methodologies has been communicated in the literature by many state DOTs and researchers/engineers. Such 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 abound in the literature—more often than not as a result of pilot studies—and further reference to them is outside the scope of this report.

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 are 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 difficult to implement. As a result, many agencies resort to using PMS that utilize models, techniques, and tools that are not the most sophisticated but that can be used by their personnel and can nevertheless 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 actually started to keep 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.

3. Pavement Management Systems in TXDOT

Managing the largest pavement network in the U.S. with approximately 196,000 lane miles of roadways 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 vast corresponding needs have always created an incentive for the consideration of such systems in order for more effective and efficient decision making to take place. It is estimated that TxDOT is currently spending $2.7 billion annually in M&R activities for its 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 the largest pavement inventory database in the U.S., known as PMIS; pavement condition is updated on an annual basis through extensive data collection efforts and the recorded data elements encompass both structural and functional pavement condition 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 10 years and underwent numerous changes and upgrades until it was replaced by PMIS in 1993. PES was abandoned because it was mainly 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.

The pavement sections are uniquely identified in the PMIS using the Texas Reference Marker (TRM) referencing system. This system divides TxDOT highways and roadways into roughly 0.5-mile segments (sometimes as small as 0.1 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. For example, "IH 35 A" refers to Interstate Highway 35, the southbound frontage road (A is the code for the frontage roadbed that travels in the direction of decreasing Reference Markers in the PMIS database). Finally, after the Roadbed ID code, each individual 0.5-mile long 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).

TxDOT officials have long sought to use this enormous database for PM purposes and various attempts to achieve that goal have continued to this day. TxDOT has developed a series of generic deterioration models based on the concept of utility curves in order to predict future section deterioration (Stampley et al. 1995). These curves, developed in the beginning of 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 their 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 presented an insurmountable obstacle, as even with the use of heuristic methods (i.e., 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 M&R actions. In 2002, TxDOT already had a GIS module for visualizing pavement condition on the highway network, namely PMIS MapZapper that was developed in 1998, but it was not Web-based. Under such circumstance, TxDOT decided to work with CTR for the development of a Web-based system for 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 Dallas District 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.

4. The Web-Based System to Support Pavement Maintenance Management Decisions

4.1 General Description of the System

The most central characteristic of this system is that it is a web-based. As such it can be operated by any personal computer that has 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.

4.1.1 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 that 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 4.1 and its key features are outlined as follow:

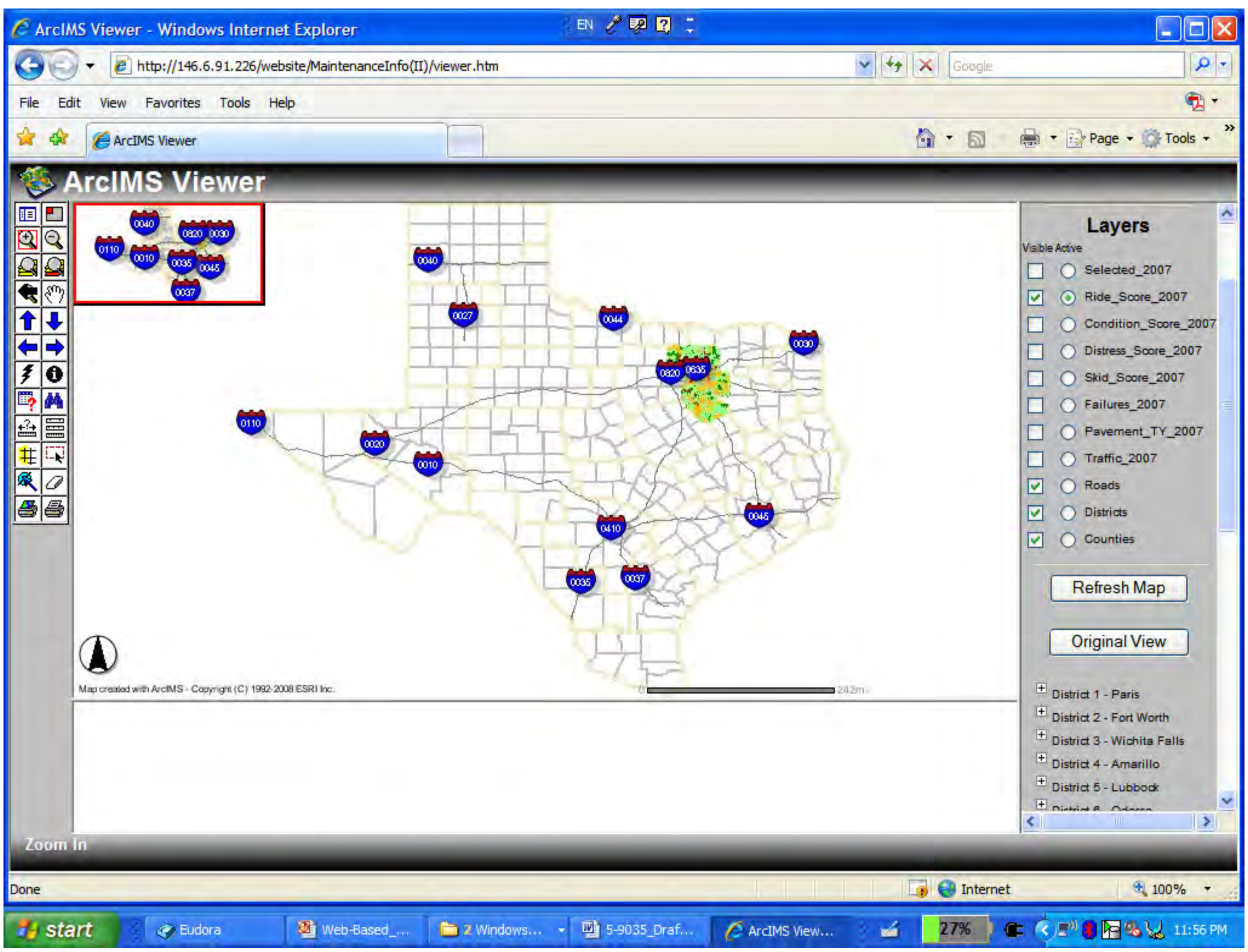

Figure 4.1: Framework of the Web-based GIS Module

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 symbology for each layer in the information system. Users can toggle between the layer list and legends using this button.

c) Layer List: It supplies the 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 unchecking 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.

4.1.2 The Decision-Support Module

The decision-support module has been programmed in PHP v.5 from the server side and JavaScript from the user side and uses a variety of structured query language (SQL) queries and other graphing functions in order 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 the 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) in order for the application to perform the budget allocation and budget planning functions.

4.1.3 Data

The PPMM is an application developed to mine, analyze, and display data originally stored in the PMIS database. To ease use with PHP, a copy of the latest PMIS data was transformed to SQL format and stored at 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 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 4.2.

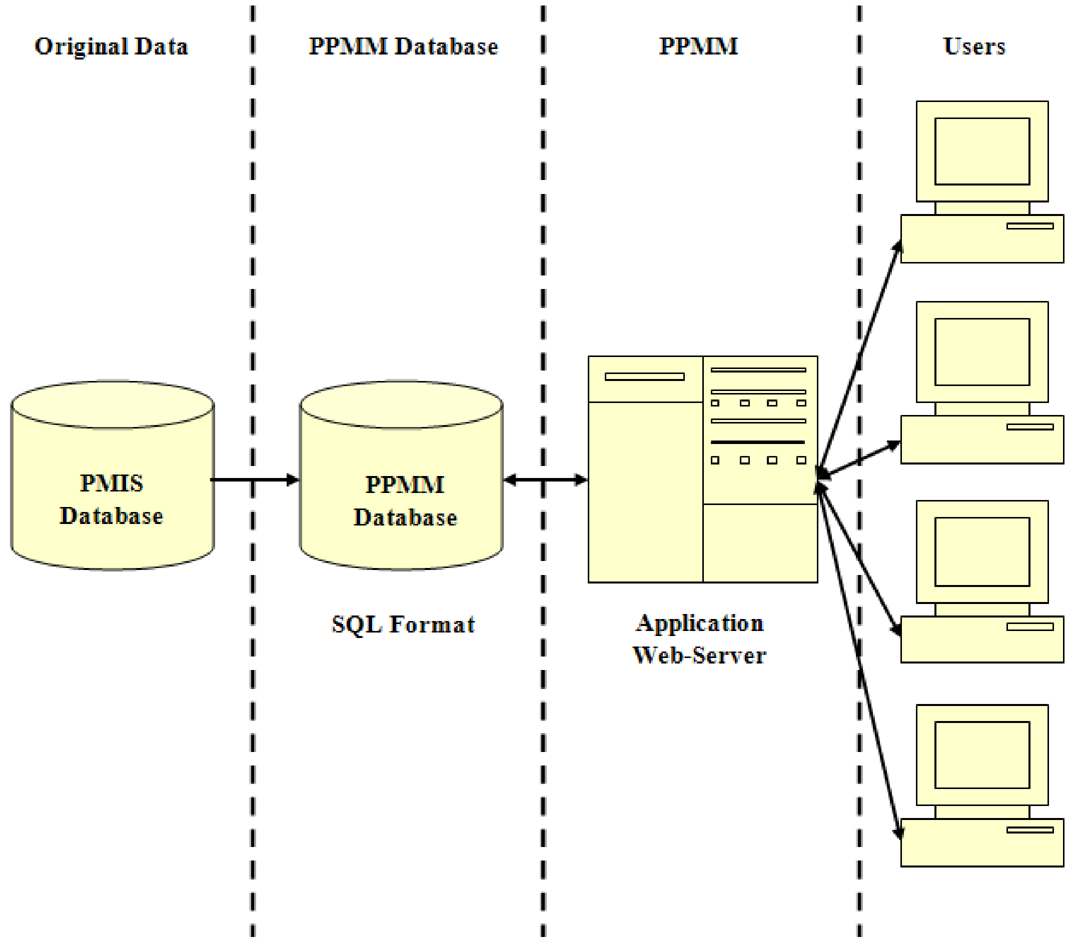

Figure 4.2: Data Format and Data Flow Structure for the Decision-Support Module

4.1.4 Capabilities and Features

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

Performance Monitoring Module – Section Tool

The section tool is for the purpose of visualization. With it the user can specify the location characteristics of a pavement section of interest and visualize its historic performance for the whole duration where performance data are available. 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 form.

Performance Monitoring Module – Network Tool

The network tool is developed for the classification of pavement sections into predefined levels of condition requiring varying degrees of "Attention." Three levels of "Attention" have been defined as “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 different individual ones or two generic groups), and by fiscal year of interest. 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 between the selected fiscal year and the year before. For both these parameters three performance levels have been defined (Good, Fair, and Bad condition and Slow, Medium, and Fast deterioration respectively), based on user-controlled threshold values. The two parameters assessed together hence form a 3x3 matrix of nine possible combinations. The user is then capable of assigning 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 it 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 and budget planning modules in the PPMM system are for demonstrating the concept only. Full development of the two modules is not in the scope of the current project.

The budget allocation tool is intended to assist in allocating a (user-defined) total budget to a regional or sub-regional pavement network of interest. The tool initially ranks the pavement sections in order of their importance for receiving M&R actions based on three criteria: their Ride Score, their Distress Score, and their traffic volumes. Furthermore, each section is also assigned an M&R action (Needs Nothing, Preventive Maintenance, Light Rehabilitation, Medium Rehabilitation, and Heavy Rehabilitation), based on the combination of its Ride Score absolute value in the fiscal year of interest and the change of Ride Score between the selected fiscal year of interest and the year before. 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 afforded by 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 afforded.

This 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 where by 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 obtained 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 also estimated and displayed.

Maintenance Management Module – Budget Planning Tool

The budget planning tool is used to determine future budget needs in order for the pavement network of interest to achieve certain user-defined performance goals. The tool is based on sequential year prioritization utilizing 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 3, 5 or 10 years. Once these parameters are specified, the tool performs 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 conducted by utilizing the same deterioration models used in the budget allocation tool for the annual deterioration of the 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 the 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 desired so.

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. In that same page 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 on 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.

5. Conclusions and Future Work

Many conclusions 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 underway to supplement its 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 story of success. The system development started 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 benefit 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 were tailored to respond to requests from TxDOT engineers and administrators. As such, the degree of sophistication has been customized to the needs of the various user groups that have different requirements of the system. In addition, the system has been developed with the potential for future upgrades, depending on the need for increased detail and precision. In that respect, the system has been successfully designed in a modular way so as to maintain this flexibility and accommodate modifications and upgrades in the underlying models upon request.
- 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. Certainly, future upgrades to these models through further calibration and research are anticipated in order to increase the sophistication and accuracy of the analysis results.
- In terms of implementation, it is important to recognize that GIS is an ever evolving technology. Since the initiation of this project in August 2008, Web-based GIS architecture using ArcIMS has evolved to a different platform; the ArcIMS is no longer supported by the vendor and cannot be implemented on TxDOT hardware. Therefore, it is recommended that the developed Web-based system be maintained at CTR so that TxDOT can continue to benefit from it. Alternatively, additional development work has to be conducted to convert the ArcIMS platform to one that is fully compatible with the new GIS architecture supported by TxDOT.

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