Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-14/0-6683-1		

4. Title and Subtitle A METHODOLOGY TO SUPPORT THE DEVELOPMENT OF 4-YEAR PAVEMENT MANAGEMENT PLAN	5. Report Date Published: July 2014 6. Performing Organization Code
7. Author(s) Nasir G. Gharaibeh, Paul Narciso, Youngkwon Cha, Jeongho Oh, Jose Rafael Menendez, Samer Dessouky, and Andrew Wimsatt	8. Performing Organization Report No. Report 0-6683-1
9. Performing Organization Name and Address Texas A&M Transportation Institute College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-6683
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office 125 E. 11th Street Austin, Texas 78701-2483	13. Type of Report and Period Covered Technical Report: September 2011–August 2013 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Project Title: Develop a Pavement Project Evaluation Index to Support the 4-Year Pavement Management Plan

URL: http://tti.tamu.edu/documents/0-6683-1.pdf

16. Abstract

A methodology for forming and prioritizing pavement maintenance and rehabilitation (M&R) projects was developed. The Texas Department of Transportation (TxDOT) can use this methodology to generate defensible and cost-effective 4-year pavement management plans (PMPs). The developed methodology was implemented in a web-based software tool for evaluation by TxDOT personnel. This tool can potentially be used in the future by TxDOT to generate 4-year PMPs for individual districts and the statewide network. Key components of this methodology are:

- Methods for grouping data collection sections into pavement management sections (potential M&R projects).
- Pavement performance prediction models.
- Methods for measuring performance benefits and life-cycle costs of alternative M&R types and projects.
- A method for prioritizing competing M&R projects using an incremental benefits-cost analysis.
- Analysis of the impact of funding scenarios on network condition throughout the planning period.

Projects are prioritized considering multiple factors that are deemed important by TxDOT's districts. These factors and their importance weights were identified using a web-based survey of TxDOT's districts. The methodology was tested and validated for Bryan, Fort Worth, and Lubbock Districts. The results highlight the potential of the developed methodology to improve pavement management planning by incorporating district priorities, producing cost-effective pavement management plans, and providing insights into the impact of these plans on the network condition.

17. Key Words	18. Distribution Statement
Pavement Management, Pavement Performance Prediction, Maintenance and Rehabilitation Planning, Project Prioritization	No restrictions. This document is available to the public through NTIS: National Technical Information Service Alexandria, Virginia http://www.ntis.gov

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	142	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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Report 0-6683-1
Project 0-6683
Project Title: Develop a Pavement Project Evaluation Index to Support the 4-Year Pavement Management Plan

Performed in cooperation with the
Texas Department of Transportation
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Federal Highway Administration

Published: July 2014

TEXAS A&M TRANSPORTATION INSTITUTE
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DISCLAIMER

ACKNOWLEDGMENTS

This project was conducted in cooperation with TxDOT and FHWA. The authors thank the project director, Ms. Darlene Goehl, and the project manager, Mr. Darrin Jensen, along with the members of the project monitoring committee, Ms. Jenny Li, Mr. Charles Gurganus, Ms. Tammy Sims, Mr. Mykol Woodruff, and Ms. Stacey Young, for their valuable comments during this project. Also, the authors thank participating TxDOT district personnel for their support and cooperation.

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CHAPTER 1 − INTRODUCTION

BACKGROUND

A pavement management plan (PMP) is a living document that identifies candidate maintenance and rehabilitation projects (M&R) for a particular roadway network (e.g., district or state) over a multi-year planning period. The PMP is a living document because projects are re-evaluated and reprioritized every year. The PMP describes the location, treatment type, year, and cost of the planned M&R projects and provides an assessment of the impact of these projects on the network condition throughout the planning period.

The Texas Department of Transportation (TxDOT) instituted the PMP requirement for all 25 districts to help expend its resources and achieve its performance goals in a cost-effective manner and in response to legislative requirements (Rider 55 of TxDOT's appropriations bill). The Texas Transportation Commission in 2002 set a statewide goal of having 90 percent of the state-maintained pavement lane-miles in "good" or better condition by 2012. To address these challenges, each of TxDOT's 25 districts prepares a PMP that identifies candidate M&R projects for a 4-year planning period. The districts PMPs are combined and submitted by TxDOT to the legislative budget board and to the governor to describe how the districts intend to use their pavement management funds and how the proposed plan will impact pavement condition in each district (Liu et al. 2012). In light of this process and the fact that TxDOT is responsible for the upkeep of approximately 194,000 lane-miles of roadway pavement (2030 Committee 2011), it is important that the PMPs are developed in a methodical and defensible manner.

Currently, the general process used by TxDOT districts to develop their 4-year PMPs consists of four primary steps:

1. Identify preliminary M&R projects through input from area offices or analysis of pavement condition data obtained from the Pavement Management Information System (PMIS).
2. Evaluate the preliminary projects through various means (e.g., site visits, PMIS scores and distress data, treatment history, and structural evaluation).
3. Rank preliminary projects based on district staff assessments or using a computed composite index.
4. Select projects for PMP based on their rank and funding availability.

While the primary steps of the PMP development process are similar across the districts, the details of the process vary. This research project seeks to support and enhance this process through the development of a consistent methodology and computational tool. The methodology will help identify pavement M&R projects that yield the maximum performance benefits expected under different budget scenarios over a multi-year planning period.

PROBLEM STATEMENT

TxDOT districts are required to develop pavement management plans that identify candidate M&R projects for a 4-year planning period. Currently, varying data sources and processing methods are used to identify candidate M&R projects for these plans. The conjuncture of this research is that a consistent methodology and computational tool can support and enhance the PMP process, as follows:

- It allows for the automation of the computational parts of the PMP development process.
- It enables TxDOT to justify project prioritization decisions by clearly explaining the methodology used to arrive at these decisions.
- It enables TxDOT's engineers to assess the immediate and long-term impacts of various funding levels on the network condition.
- It provides TxDOT's engineers with a decision support tool that reflects the decision making process and priorities within their organization.
- It brings consistency among the various districts within TxDOT in terms of the process used for generating PMPs. At the same time, the districts will be able to fine tune the input parameters to meet their local conditions and needs.

RESEARCH OBJECTIVE

The aim of this research is to develop a sound and justifiable decision support methodology that TxDOT can use to generate defensible PMPs. The specific objectives of this research are to:

1. Devise a scheme for forming realistic M&R projects out of data collection sections that are typically 0.5-mile long.
2. Identify key factors that influence M&R project prioritization decisions at the district-level and elicit representative weights for these decision factors based on input from TxDOT districts.
3. Develop a multi-criteria project priority index for use in the selection of candidate M&R projects.
4. Integrate the developed project formation scheme, multi-criteria project priority index, and benefit-cost analysis to create a methodology and computational tool for generating PMPs and assessing their impact on the network condition.
5. Test and validate the developed methodology through comparisons to actual district pavement management plans.

RESEARCH TASKS

The objectives of this research project were achieved by completing the tasks described next.

Task 1: Review and Summarize Current Practices in Pavement Management

Current practices in pavement management have been reviewed and summarized, including processes used by TxDOT's districts to develop their 4-year PMPs, pavement management practices at highway agencies in the U.S. and other countries, and analytical methods for supporting project prioritization.

Task 2: Identify and Evaluate Key Decision Factors for Pavement Project Prioritization

Key factors considered by TxDOT's districts in the development of their 4-year PMPs have been identified and weighed through a web-based survey. Availability of data on these factors has been evaluated.

Task 3: Develop Project Prioritization and Ranking Methodology

A methodology for developing 4-year pavement management plans has been developed. This methodology is designed to facilitate the formation and prioritization of pavement M&R projects based on the key decision factors identified in Task 2. The methodology integrates four major analytical capabilities: grouping data collection sections into management sections (realistic projects), performance prediction models, life-cycle benefit and cost analysis, prioritization of competing M&R projects using an incremental benefits-cost analysis, and analysis of the impact of funding levels on network condition over multiple years into the future.

Task 4: Validate the PMP Methodology

The developed PMP methodology was tested, refined, and demonstrated by developing 4-year pavement management plans for the Bryan, Fort Worth, and Lubbock Districts. Additionally, the developed methodology was implemented in a web-based software tool for evaluation by TxDOT personnel. This tool can potentially be used in the future by TxDOT to generate 4-year PMPs for individual districts and the statewide network.

ORGANIZATION OF THE REPORT

This report documents the research efforts and results and is organized in seven chapters as follows:

- Chapter 1 presents the background of the research problem and describes the research objectives and scope.
- Chapters 2 and 3 identifies key factors considered by TxDOT districts when selecting projects for their PMPs and presents weights for these decision factors elicited through a survey of TxDOT districts.
- Chapter 4 evaluates available data at TxDOT to support the consideration of the factor described in Chapter 5 in the PMP methodology.
- Chapter 5 describes an analytical methodology for developing multi-year pavement management plans for TxDOT.
- Chapter 6 presents the results of testing and validating the proposed PMP methodology along with a computational tool to facilitate the implementation of this methodology.
- Chapter 7 presents the conclusions and recommendations of this study.
- Appendix A presents the districts survey instrument.
- Appendix B provides an evaluation of the Structural Condition Index.

CHAPTER 2 − CURRENT PRACTICES IN PAVEMENT MANAGEMENT

This chapter summarizes current practices in areas relevant to the process of developing multi-year pavement management plans, including:

- Processes used by TxDOT's districts to develop their 4-year PMPs.
- Processes used by highway agencies in the U.S. and other countries to develop pavement management plans.
- Literature on analytical methods to support the development of pavement management plans.

PMP DEVELOPMENT PROCESSES AT TXDOT DISTRICTS

The research team reviewed available literature (research reports, sample PMPs, conference presentations, etc.) on the processes used by TxDOT districts to develop their 4-year PMPs. While the details of the process vary among the districts, the general framework for developing the PMPs is similar (see Figure 1).

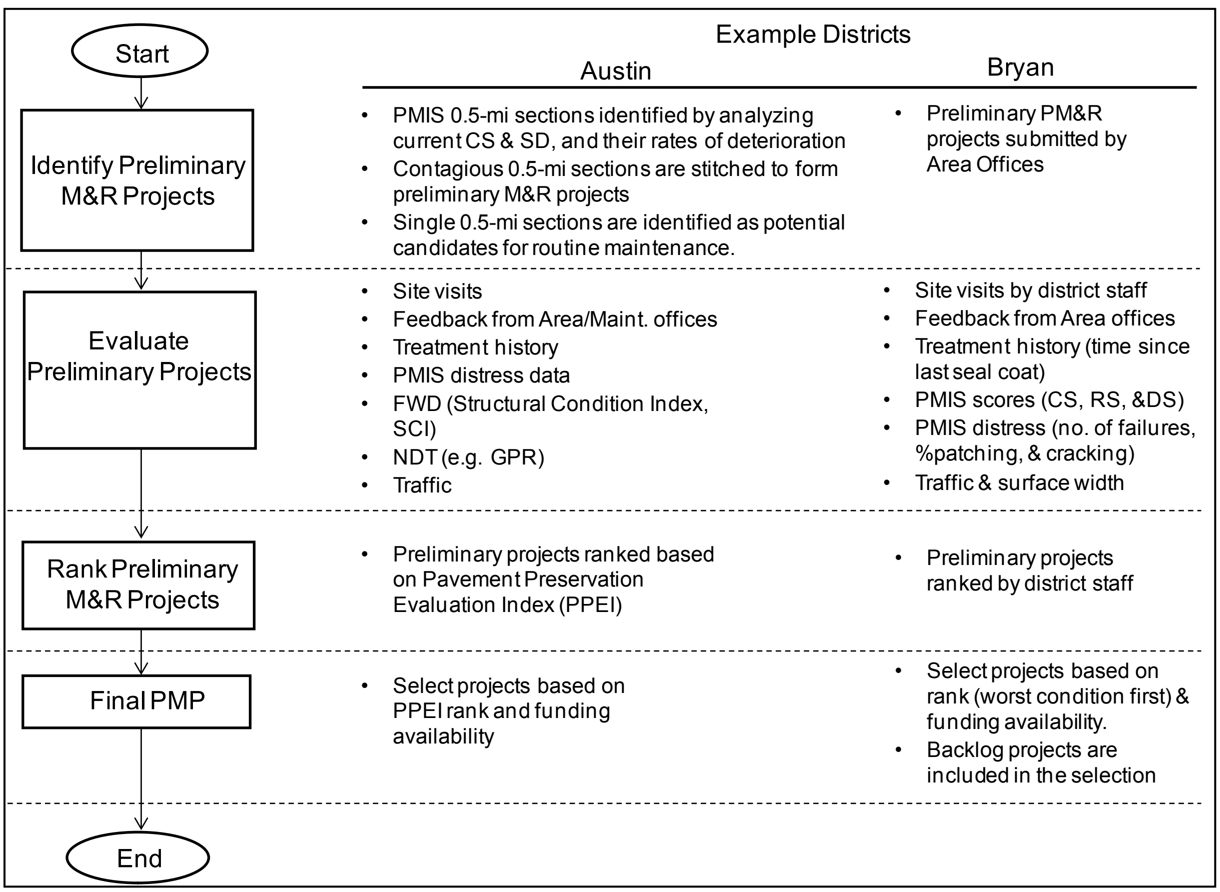


Figure 1. General Process for Developing 4-year PMPs at TxDOT Districts.

The process begins with identifying preliminary candidate M&R projects. A common method for identifying these preliminary projects is to request a list of projects from area and maintenance offices. For example, the Bryan District obtains lists of preliminary projects from the area offices within the district (a similar approach is used by the Yoakum District). The Austin District, on the other hand, uses pavement condition data (extracted from PMIS) to identify 0.5-mile sections as preliminary candidates for M&R. These data include the pavement Condition Score (CS), Distress Score (DS), and their rates of deterioration. Then, contiguous 0.5-mile sections are stitched together to form preliminary M&R projects. Isolated single 0.5-mile sections are identified as potential candidates for routine maintenance.

Preliminary candidate M&R projects are evaluated at the project level using different methods. Generally, these methods include site visits (i.e., TxDOT personnel perform visual assessment of the pavement condition by driving on these candidate projects), feedback from area and maintenance offices, review of treatment history (e.g., year of last seal coat), and analysis of PMIS distress data and scores. As shown in the Austin and Bryan examples, the degree to which physical testing is performed to evaluate the preliminary projects varies among the districts. For example, the Austin District appears to use physical testing [such as Falling-Weight Deflectometer (FWD) and Ground Penetrating Radar (GPR)] more extensively compared to the Bryan District.

Once the preliminary projects are evaluated at the project level, they are ranked using various rating method and indexes. For example, the Bryan District personnel assign a direct rank to each preliminary project, while the Austin District ranks the preliminary projects using the Pavement Preservation Evaluation Index (PPEI). PPEI is competed using the Analytical Hierarchy Process (AHP) as a function of several factors, including Annual Average Daily Traffic (AADT), truck AADT, equivalent single axle load (ESAL), project length, posted speed, Distress Score (DS), DS drop, Ride Score (RS), RS drop, longitudinal cracking, failures, structural condition index (SCI), edge failure (faulting with drop off), rutting, and fatigue cracking. The Austin District is working on adjusting these variables and their weights in computing the PPEI. Thus, these variables are preliminary and might change in the future. Published and unpublished literature (see for example Dessouky et al. [2011] and a collection of presentations made at TxDOT 2011 Short Course) suggests that direct ranking by district personnel is more commonly used than mathematically computed indexes.

Finally, preliminary projects (both new and backlog) are assigned to appropriate funding categories and year based on their rankings, until the anticipated annual budget limit is reached for each year of the plan (i.e., sum of estimated cost for the selected projects equals anticipated funds). New and backlog projects are re-evaluated and reprioritized every year.

A web-based survey was developed and disseminated to TxDOT's 25 districts with the primary purpose of a) identifying key factors considered by the districts in ranking and prioritizing M&R projects for the 4-year PMP, and b) develop weights for these key factors. However, the survey provided additional information about the PMP development process. The survey instrument and results pertaining to the influencing factors and their weights are discussed in the next chapter of this report. Survey results regarding additional information about the PMP process are presented next.

Figure 2 shows the types of projects that are included in the districts' 4-year PMPs. "Others" include bridge projects with a large amount of pavement work, widening projects, and construction and maintenance projects forced by the state.

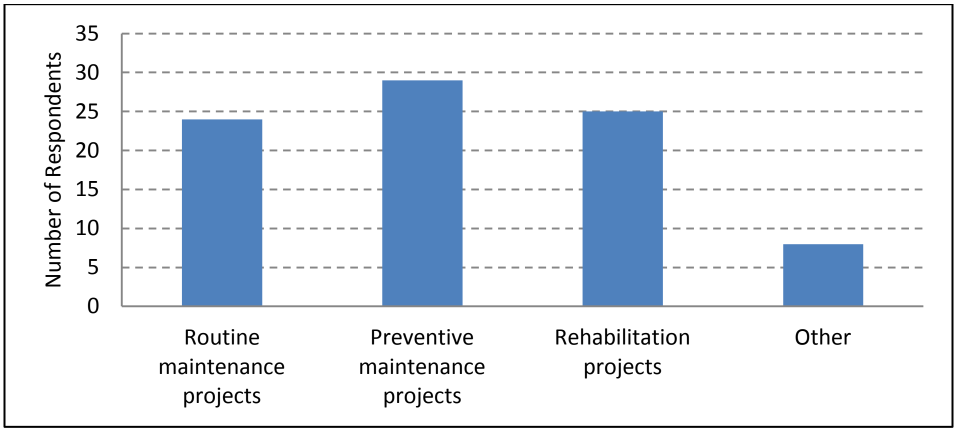


Figure 2. Types of Projects Included in the Districts' PMPs.

Past TxDOT research used the following definitions for pavement treatment categories:

- Routine Maintenance (RM): Crack sealing, edge maintenance, patching (pothole repair), level-up, strip/spot seals, milling, joint repair, localized base repairs, localized concrete repairs.
- Preventive Maintenance (PM): Seal coats (chip seals), thin overlays (less than 2 inches), and micro-surfacing treatments for host-mix asphalt (HMA) pavement and diamond grinding for portland cement concrete (PCC) pavement.
- Light Rehabilitation (LR): HMA overlay with thickness between 2 and less than 3 inches; pavement widening and application of full width seal coat, base repair and seal; milling, sealing and thin overlay.
- Medium Rehabilitation (MR): Mill and inlay; mill, stabilize base and seal; level up and overlay; widen pavement, level up and overlay or seal coat; 3- to 5-inch HMA overlay; thick overlay (without any other activity such as milling); mill, patch, under seal and inlay; base repair, spot seal, edge repair and overlay; mill, cement stabilize base, and overlay or seal.
- Heavy Rehabilitation (HR): Includes reconstruction of the base and surface, milling and thick overlay or similar activities that restore the pavement functional and structural condition to nearly original conditions.

Table 1 shows the number of respondents that use the above definitions of M&R treatment categories.

Table 1. Number of Respondents using above Definitions of Pavement M&R Categories.

Pavement Treatment Categories	No. of Respondents Using above Definitions	No. of Respondents Not Using above Definitions
Routine Maintenance (RM)	30	0
Preventive Maintenance (PM)	27	1
Light Rehabilitation (LR)	24	2
Medium Rehabilitation (MR)	24	3
Heavy Rehabilitation (HR)	26	1

Figure 3 shows the primary sources of data used by the districts for developing the initial list of candidate projects for the 4-year PMP. Finally, Figure 4 shows the month in which the districts prepare their initial list of potential projects for the annual 4-year PMP.

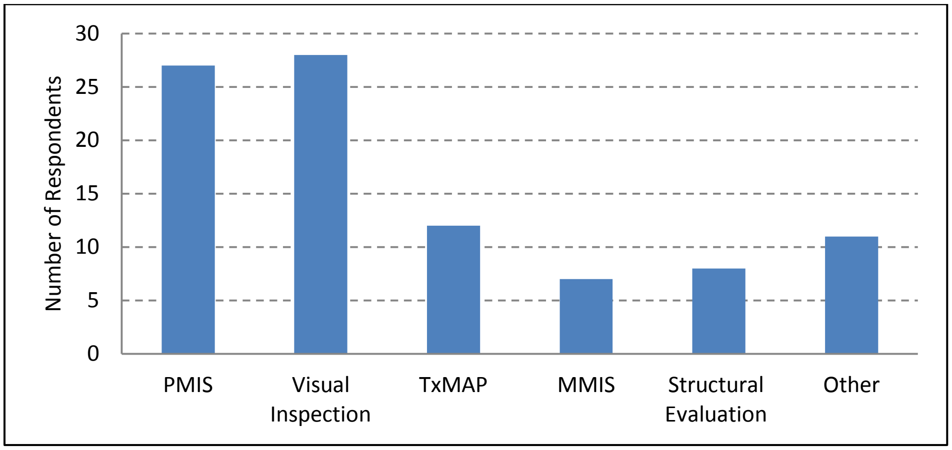


Figure 3. PMP Data Sources.

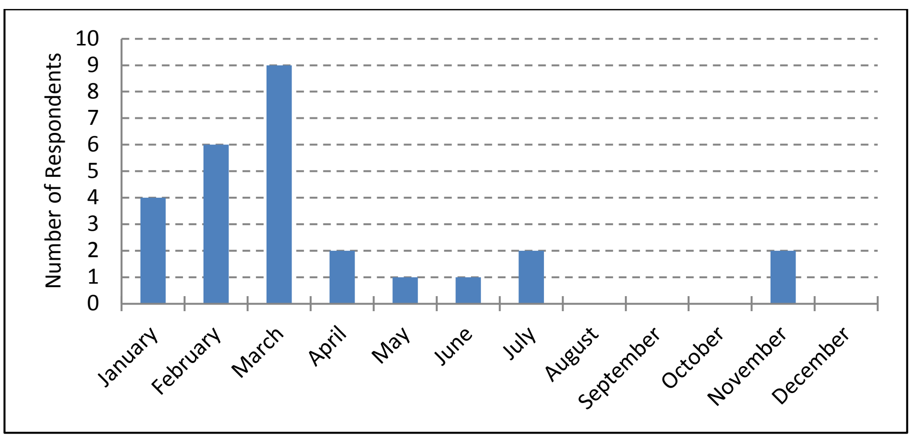


Figure 4. Month in which the District Begins the Annual PMP Development Process.

PMP DEVELOPMENT PROCESSES AT OTHER HIGHWAY AGENCIES

Current practices in developing pavement management plans in a sample of state departments of transportation (DOTs) (Arizona, Washington, Kansas, and Illinois) and international highway agencies (England Highways Agency and Transit New Zealand) were gathered through a review of the literature. Key aspects of these practices are illustrated in Table 2 and are discussed as follows:

- **Pavement Performance Measures:** Different highway agencies use different metrics to measure the structural and material integrity and functional performance of their pavement. Also, these agencies have different policy goals for these metrics. TxDOT research project 0-6386 (Papagiannakis et al. 2009) and Gharaibeh et al. (2010) showed that significant differences exist among seemingly similar pavement condition indexes. Generally, the disagreement among these indexes can be attributed to differences in the distress types considered, importance weights, and the mathematical forms of the indexes.
- **Prioritization Factors:** In most studied cases, the policy goal is set based on a single performance metric, but M&R projects are prioritized based on multiple factors (e.g., traffic volume, functional condition, structural condition, and cost). This may lead to disconnect between the policy goal and M&R projects selected for the PMP.
- **Prioritization Methods:** Ranking is the most common method for prioritizing M&R projects in the studied cases. Projects are ranked based on current condition or a form of remaining life (Illinois DOT, Kansas DOT, and Washington DOT), benefit-cost ratio (Arizona DOT), or incremental cost (England Highways Agency and Transit New Zealand). Generally, highway agencies realize the limitations of prioritizing M&R projects based on worst-first approach (which results from ranking based on current condition) and strive to consider the long-term benefits and costs of these projects (see next section of this chapter for a discussion of these methods).
- **Software:** Most studied cases use electronic databases and analytical software tools to perform project prioritization. The detailed capabilities of these databases and software tools vary significantly among the studied cases.
- **Plan Period:** The PMP plan period for the studied cases ranges from 3 years (Kansas DOT) to 6 years (Illinois DOT).

Table 2. PMP Practices at a Sample Highway Agencies.

State/Country	Condition Indicators	Condition Goal	Prioritization Factors	Plan Period	Prioritization Method	Software
Arizona (Li et al. 2006)	Present Serviceability Rating (PSR), 0-5 AASHTO Road Test rating	-Avg. PSR at 4.0 for Interstate Highways -Avg. PSR of 3.2 for non-interstate highways	-Life cycle Cost -Benefit as a function of AADT, section area, & area under PSR predicted performance curve	5 years	Optimization based on cost-effectiveness (i.e., B/C ratio)	-Analytical software -Database
Illinois (Peng and Ouyang 2010)	Pavement Condition Survey (CRS), 1-9 rating based on distress, IRI, and pavement type	Miles of highway that meet the backlog criteria less than 10% of state highway system	-CRS -AADT -Highway functional importance/class	6 years	Ranking based on current condition	Fragmented databases & spreadsheets
Kansas (Kulkarni et al. 2004)	Performance Level (PL), 1-2-3 rating based on distress and IRI	-Interstate: >85% at PL=1 -Other: >80% at PL=1	Priority score as a function of (road geometry, traffic, rideability, pavement structural evaluation, & observed condition)	3 years	Ranking based on priority formula score	-Analytical software -Database
Washington (Cambridge Systematics et al. 2005, Federal Highway Administration et al. 2008)	-Pavement Structural Condition (PSC) -Pavement Rutting Condition (PRC) -IRI	90% of all state highway pavements with PSC >90% (i.e., in good or fair condition)	-Predicted time to reach a PSC of 50 (Due Date) -Traffic volume	6 years	Ranking based on priority group, which is a function of the "Due Date"	-Analytical software -Database
England (Federal Highway Administration et al. 2005, Hawker and Hattrell 2001)	-Residual life -Rutting -Skid resistance -Surface macro texture	-Proportion of network length with residual life < 0 years -Proportion of network length with avg. rut depth > threshold (e.g., 10 mm) - Percentage of network length with macro texture less than 0.5 mm	-Current condition -Initial cost -Life cycle costs (including user costs) -Risks	4 years	Ranking based on Economic Indicator (ratio of economic gain relative to "Do Minimum" option)	-Analytical software -Databases
New Zealand (Federal Highway Administration et al. 2005)	-Roughness -Rutting -Texture -Skid resistance	90% or more of road users rating the road network as good or above	Cost, network condition, national objectives, and the asset management plan	NA	Cost justification	-Analytical software -Database

PROJECT PRIORITIZATION TECHNIQUES

Table 3 illustrates common ranking methods, and Table 4 illustrates common optimization methods that are (or can be) used for prioritizing M&R projects. While ranking based on current condition (i.e., worst-first approach) is perhaps the simplest approach, it ignores the long-term cost and performance impacts of competing projects. Ranking based on total life-cycle cost (LCC) (e.g., present worth value) or benefit-cost (B/C) ratio is likely to lead to more cost-effective PMPs (i.e., better economic use of limited funds) compared to the worst-first approach. However, these ranking methods require calibrated models for predicting pavement performance, rationally-quantified benefits, and accurate estimation of costs and benefits. TxDOT has recently developed a set of calibrated pavement performance prediction models under Project 0-6386. These calibrated models can potentially be used to perform LCC and B/C analyses for M&R projects.

Current condition, LCC, and B/C ranking methods allow for prioritizing M&R projects based on a single parameter (i.e., condition index, present-worth value, and B/C ratio, respectively). Multi-Criteria Analysis (MCA) methods, on the other hand, allow for prioritizing M&R projects based on multiple factors that may have different units (e.g., dollars, vehicles/day, and inch/mile). Examples of MCA methods include the Analytical Hierarchy Process (Saaty 1990) and multi-attribute utility theory (MAUT) (Keeney and Raiffa 1976). The decision factors may include current parameters (e.g., current condition indexes, current individual distress types, current traffic, and current truck traffic) and long-term parameters (e.g., present-worth value and B/C ratio). The main limitations of considering multiple criteria, compared to a single criterion, is that establishing priority ratings (i.e., weights) for each factor may require somewhat extensive effort.

The M&R project prioritization problem can be framed as an optimization problem. Several optimization methods are available for this purpose (see Table 4). The selection of a suitable optimization method is dependent on the form (e.g., linear vs. nonlinear) and number of both objective functions and constrains. An example objective function would be to maximize the average condition score for the network, and an example constraint would be to keep the total cost within a budget limit. Linear programming is the simplest optimization method, but is most appropriate for simple linear objective functions. Genetic algorithms appear to be the most promising method because: 1) they can be applied efficiently to virtually any form of objective function and constraints, and 2) they can reach near-optimal solutions rapidly even for a large number of alternatives that need to be evaluated.

Table 3. Common Ranking Methods for Prioritizing M&R Projects.

Method	Features	Advantages	Limitations/ Disadvantages
Current Condition Ranking (Vatn 1997, Zimmerman 1995)	• Worst-first: Ranking based on current condition from worst to best Year-by-year ranking	• Simple to apply	• No trade-off among treatment types • No consideration for initial and future costs • No multiyear analysis
Life-Cycle Cost Ranking (Ozbay et al. 2004, Sinhal et al. 2001)	• Ranking based on life-cycle cost from lowest to highest	• Initial and future costs are considered	• Requires calibrated performance prediction models to estimate future costs.
Benefit-Cost Ratio Ranking (Bemanian et al. 2005, Farid et al. 1994, Farid et al. 1996)	• Ranking based in B-C ratio from highest to lowest	• Alternative treatment strategies can be evaluated for each candidate project based on trade-off between benefit and cost	• Benefit may be difficult to quantify • Requires calibrated performance prediction models
Multi-criteria Analysis: (Keeney and Raiffa 1976; Saaty 1990)	• Numerical weights • Ranking based on a composite priority index • Examples: Analytical Hierarchy Process (AHP) & multi-attribute utility theory (MAUT)	• Systematic way to assign weights. • Considers multiple factors (long and short term)	• Extensive work may be needed to establish priority weights and ratings

Table 4. Common Optimization Methods for Prioritizing M&R Projects.

Method	Features	Advantages	Limitations/ Disadvantages
Linear Programming (Golabi et al. 1982, Smilowitz and Madanat 2000)	• Objective functions and constraints are formulated as linear equations • Decision variables are continuous Commonly used in existing PMSs	• Relatively simple to formulate and apply	• May not apply for nonlinear objective functions
Non-linear Programming (Abaza 2006)	• Objective functions and constraints can be formulated as non-linear equations	• Not limited to linear objective functions	• Difficult to ensure that the global optimum is found rather than a local optimum
Integer Programming (Ferreira et al. 2002, Wang et al. 2003, Ouyang and Madanat 2004)	• Objective functions and constraints are formulated as non-linear equations Decision variables are bound to take only integer values 0 or 1	• Very efficient for a large number of variables and constrains More realistic in PMS as "Do" or "Do-nothing" approach	• All variables need to be binary
Dynamic Programming	• The problem is divided in stages and states where decisions has to be taken at each stage • The solution procedure is to find an overall optimal policy	• Renders optimal solution Used when a number of decisions must be made in sequence (e.g., year-by-year PMP)	• Too many stages for large problems • Difficult to handle large number of decision variables
Genetic Algorithms (Ferreira et al. 2002, Pilson et al. 1999)	• Based on natural selection (evolutionary solution)	• Efficient for solving large optimization problems (large pavement network, large number of variables, and multiple years) • Flexible in defining objective functions and constrains	• Renders near-optimal solutions (not necessarily absolute global optimal solutions)

CHAPTER 3 − PAVEMENT M&R PROJECT PRIORITIZATION CRITERIA

This chapter serves two main purposes: a) it identifies factors considered important by TxDOT districts for prioritizing pavement M&R projects, and b) it presents weights for these decision factors elicited through a survey of TxDOT districts.

POTENTIAL FACTORS INFLUENCING PROJECT PRIORITIZATION

Many technical and non-technical factors can potentially influence the prioritization and selection of pavement M&R projects. These factors can be grouped in six main categories: pavement current condition, current traffic volume, project initial cost, project long-term performance benefit, project life-cycle cost, and non-technical factors. The following describes each category:

- **Pavement Current Condition (CC)**. This group of factors represents the overall health of the pavement as described by the following parameters:
  - **Distress Score (DS)**. A pavement surface distress index used by TxDOT to rate a pavement according to the type and amount of key distresses present. DS has a 1–100 scale (with 100 representing no or minimal distress). DS data are available in PMIS.
  - **Ride Score (RS)**. A 0.1 (worst ride) to 5.0 (best ride) measure of ride quality. RS data are also available in PMIS.
  - **Condition Score (CS)**. A composite index used by TxDOT that combines distress score and ride score. CS has a 1–100 scale (with 100 representing no or minimal distress and roughness). CS data are available in the PMIS.
  - **CS Rate of Deterioration (CSRD)**. A factor that is measured in terms of the drop in CS per year. CSRD is computed as the average drop in CS for the last three years.
  - **Skid Number (SN)**. A measure of wet pavement surface friction. The PMIS database has a data field for Skid Score, but in many cases, the values are not available.
  - **Structural Assessment (STRUCT)**. A measure of the structural soundness of the pavement obtained from structural capacity tests (e.g., Falling-Weight Deflectometer). The PMIS database has a data field for Structural Strength Index, but in most cases, the values are not available.
  - **Visual Assessment (VISUAL)**. An overall visual assessment of pavement condition conducted by district staff.
- **Current Traffic Volume (CTV)**. The higher the number of users that will be impacted by the pavement improvement, the higher would be its priority. Current traffic volume is described by two parameters:
  - **Annual Average Daily Traffic (AADT)**. This parameter represents overall usage of the road and is available in the PMIS.
  - **Truck AADT (TAADT)**. This parameter specifically represents usage by commercial vehicles and therefore is a proxy for the economic importance of the road. Truck traffic as a percentage of AADT can be found in the PMIS.

- **Initial Cost of the M&R Project (IC)**. This factor was considered since a short-term outlook will usually favor M&R projects with lower initial cost.
- **Life-Cycle Cost (LCC) of M&R Treatment**. This factor can be considered when comparing different M&R alternatives based on their long-term costs. In a long-term approach, the lower the LCC, the higher the priority. This is in contrast to a short-term view where only initial cost is considered and subsequent costs are ignored.
- **Long-Term Performance Benefit (LTPB) of M&R Treatment**. This factor is measured by the Area Under the Performance Curve (AUPC) as shown in Figure 5. It can be considered when comparing different M&R alternatives based on their long-term performance benefits. The greater the AUPC, the greater the benefit in the long-term, and therefore, the higher the priority.

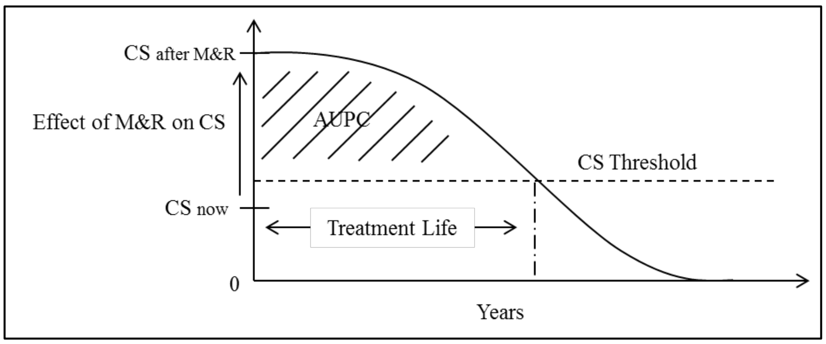


Figure 5. Graphical Illustration of Area under the Performance Curve.

- **Non-technical Factors**. Participants in a survey of TxDOT's districts (discussed next) suggested that other non-technical factors are considered in prioritizing and selecting pavement M&R projects. These factors include evacuation routes, population density, economic development, and feedback from highway users.

WEB-BASED SURVEY OF TXDOT DISTRICTS

A web-based survey was developed and disseminated to TxDOT's 25 districts to determine the relative importance (weights) of the above factors when prioritizing pavement M&R projects for the 4-year PMP. The survey instrument (see Appendix A) was designed based on a review of the literature, an onsite interview of maintenance personnel at the San Antonio District, and feedback from the project monitoring committee.

The AHP (Saaty 1990) was used to elicit and synthesize importance weights for these factors from the survey participants. The factors are organized on a 2-level hierarchy (see Figure 6), and the participants were asked to compare the factors within each level one pair at the time according to their influence on prioritizing pavement M&R projects.

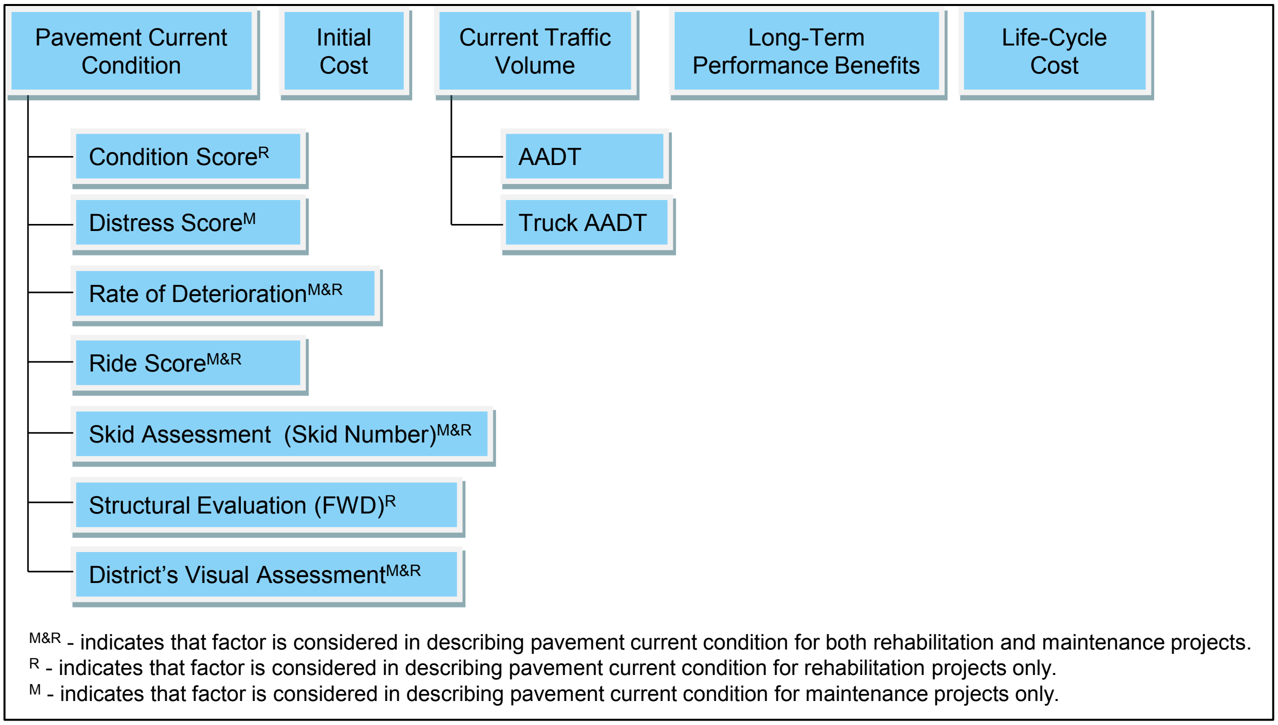


Figure 6. Hierarchy of Potential Technical Factors Considered in Prioritizing Projects for PMP.

The pairwise comparisons are made on a scale of 1 to 9 (see Table 5), where a rating of one means that the factors being compared are of equal importance, while a rating of nine means that one factor is absolutely more important than the other. Figure 7 shows a sample screenshot of a portion of the survey instrument, with actual responses from TxDOT district staff. In this example, five decision factors (distress score, rate of deterioration, ride score, skid number, and district's visual assessment) were compared, one pair at the time, as to their influence on determining pavement current condition for maintenance projects. In this example, the respondent judged that distress score has "somewhat greater importance" over rate of deterioration in describing pavement current condition. The district's visual assessment was deemed to have "very strong importance" over rate of deterioration.

Table 5. Importance Scale in AHP.

Value	Meaning
1	Equal Importance
3	Somewhat Greater Importance
5	Strong Importance
7	Very Strong Importance
9	Absolute Importance
2,4,6,8	Intermediate

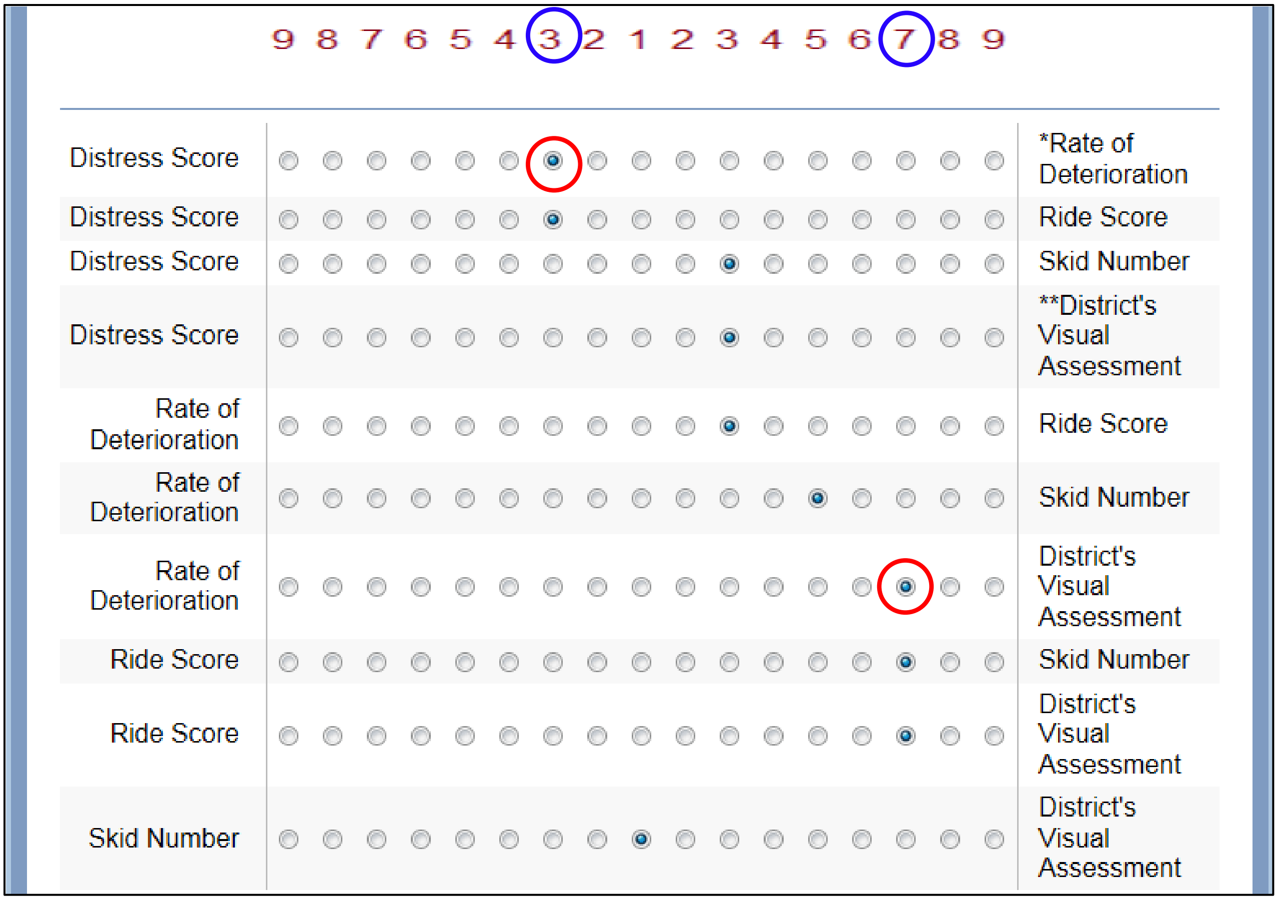


Figure 7. Sample Screenshot of the Web-Based Survey.

The pairwise comparisons build an *nxn* matrix, where *n* is the number of factors included in the decision. The final weights for the decision factors were computed as the normalized maximum eigenvector of the group pair-wise ratings matrix, as suggested by Saaty (1980). These weights are indicators of the importance of each factor in the project prioritization decision.

Twenty-seven individuals responded to the survey, representing 17 out of the 25 districts of TxDOT (68 percent district response rate). The positions held by the respondents include director of maintenance, maintenance engineer, director of operations, maintenance supervisor, district pavement engineer, design engineer, transportation specialist, director of construction, engineering specialist, transportation engineer, director of transportation planning & development (TP&D), area engineer, and pavement/materials engineer.

The responding districts are as follows:

- Metro Districts: Austin, Fort Worth, Houston, and San Antonio.
- Rural Districts: Amarillo, Brownwood, Childress, Lufkin, Odessa, Paris, Wichita Falls, and Yoakum.
- Urban Districts: Beaumont, Bryan, Lubbock, Pharr, and Tyler.

In AHP, it is important to check the pair-wise comparisons for consistency. That is, if the respondent rates factor A as more important than factor B and factor B as more important than factor C, then the respondent must logically rate factor A as more important than factor C. Likewise, if factor A was rated as “absolutely more important” than factor C and factor B as “absolutely more important” than C, then factors A and B must have equal importance. However, human nature suggests that this level of perfect consistency is difficult to attain. Hence, AHP introduces a measure of consistency, called consistency ratio (CR), where a value of zero means perfectly consistent pairwise ratings. The consistency ratio, *CR*, is computed by first calculating the consistency index, *CI*, using Equation 1.

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad \text{Equation 1}$$

where λ_{max} is the maximum eigenvalue and n is the size of the pairwise comparisons matrix.

CR is then computed using Equation 2, where *RI* is the random index. The random index is the consistency index of a randomly generated reciprocal matrix from the 1–9 scale with reciprocals forced. Average RIs for matrices with sizes, n, equal to 1–15 are provided by Saaty (1980) and are shown in Table 6. AHP allows a maximum acceptable CR of 10 percent (Saaty 1980).

$$CR = \frac{CI}{RI} \qquad \text{Equation 2}$$

Table 6. Random Indexes for Different Matrix Sizes.

n	*RI*	*n*	*RI*	*n*	*RI*
1	0.00	6	1.24	11	1.51
2	0.00	7	1.32	12	1.48
3	0.58	8	1.41	13	1.56
4	0.90	9	1.45	14	1.57
5	1.12	10	1.49	15	1.59

Table 7 shows the consistency ratios of the four pairwise comparisons matrices for the statewide, rural, urban, and metro groups. All CR values fall within the allowable limit suggesting consistency of the aggregated group responses.

Table 7. Consistency Ratios of Pairwise Comparison Matrices.

Matrix	CR (%)			
	Statewide	Rural	Urban	Metro
Set 1 (5x5)	1.7	1.3	1.1	7.8
Set 2 (6x6)	2.6	2.2	5.8	5.2
Set 3 (5x5)	1.9	3.3	5.1	3.0
Set 4 (2x2)	NA	NA	NA	NA

PRIORITY WEIGHTS FOR PMP DECISION FACTORS

The individual responses to the web-based survey were grouped into an overall group (consisting of all 27 responses), a metro group (consisting of responding metro districts), a rural group (consisting of responding rural districts), and an urban group (consisting of responding urban districts). The weight for each factor was computed as the geometric mean of the weights assigned by the individual respondents. Mathematically, the group pairwise ratings are computed as follows (Saaty 1980):

$$G = \sqrt[m]{x_1 x_2 x_3 \ldots\ldots x_m} \qquad \text{Equation 3}$$

where G is the geometric mean pairwise rating (i.e., representing the group response); x_i is the pairwise rating of the *ith* respondent; and *m* is the total number of responses within the group. The final priority weights computed for the above groups are presented and discussed in the following sections.

Priority Weights Considering All Responses as One Group

Figure 8 shows that pavement current condition is the top criterion considered in prioritizing pavement M&R projects. This is followed by initial cost and a tie between current traffic volume and long-term performance benefit.

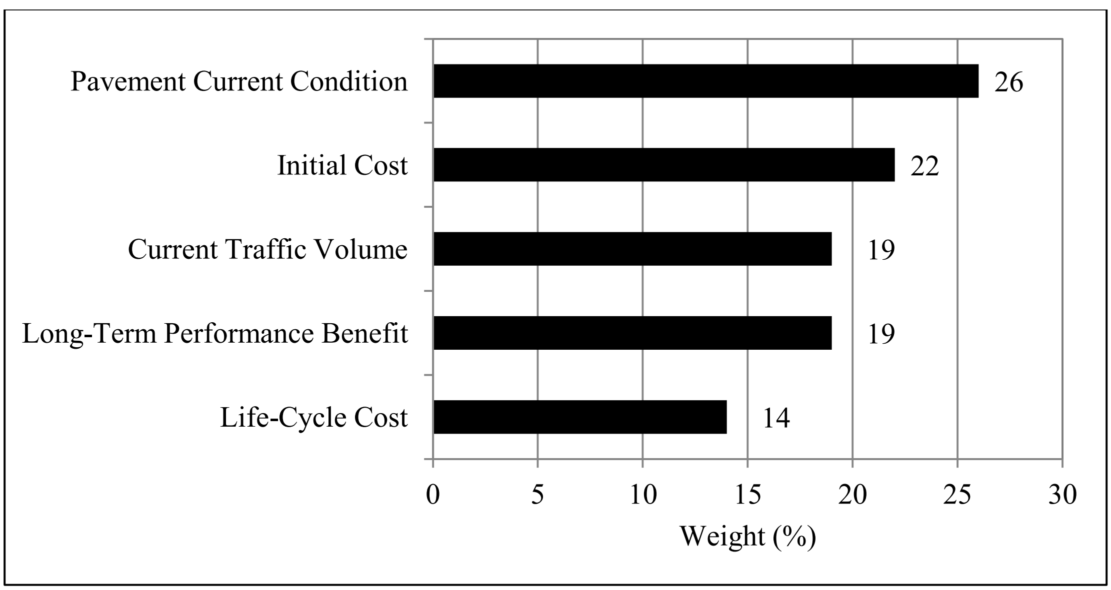


Figure 8. Weights of Categories of Factors.

Figure 9 and Figure 10 show the weights of the factors that represent pavement current condition for rehabilitation and maintenance projects, respectively. The weights and the order of priority for both cases are very similar. District visual assessment is the top consideration for both cases and it is followed by a pavement condition index: CS for rehabilitation projects and DS for maintenance projects. Similarly, ride score received the least weight for both cases. This implies that TxDOT has the option to use separate weights for maintenance and rehabilitation, or to combine the two to generate common weights for both rehabilitation and maintenance projects. For the latter case, it is recommended that the weights for rehabilitation be adopted and to simply replace CS with DS. The rationale for this is that while CS, which is a combination of DS and ride score, receives a high weight, ride score receives a low weight. Thus, one can infer that the respondents are only interested in the component of CS that represents distresses. Therefore, replacing CS with DS may be logical.

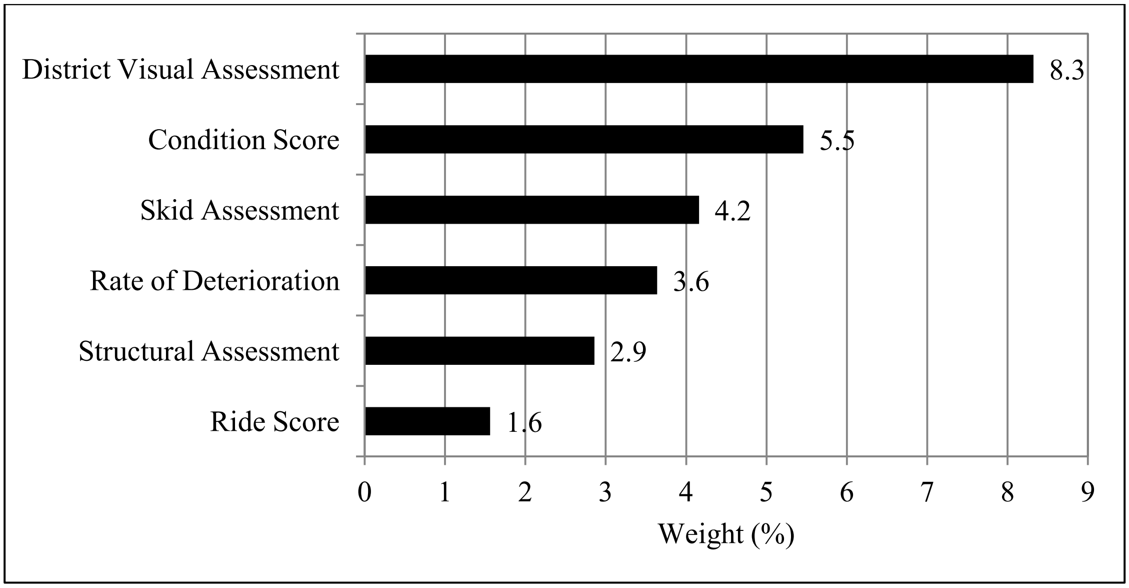


Figure 9. Weights of Pavement Current Condition Indicators for Rehabilitation Projects.

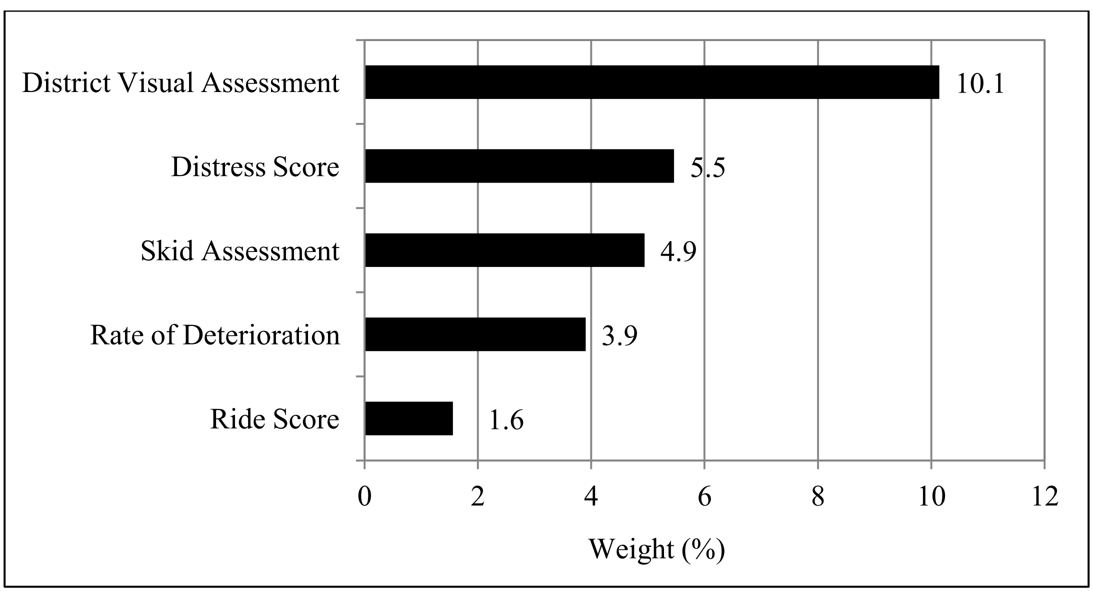


Figure 10. Weights of Pavement Current Condition Indicators for Maintenance Projects.

The importance weights of AADT versus the truck AADT are shown in Figure 11. Truck AADT dominates AADT. Since truck AADT also reflects the economic importance of a roadway corridor, it can be said that the respondents also take this matter into consideration in prioritizing pavement M&R projects.

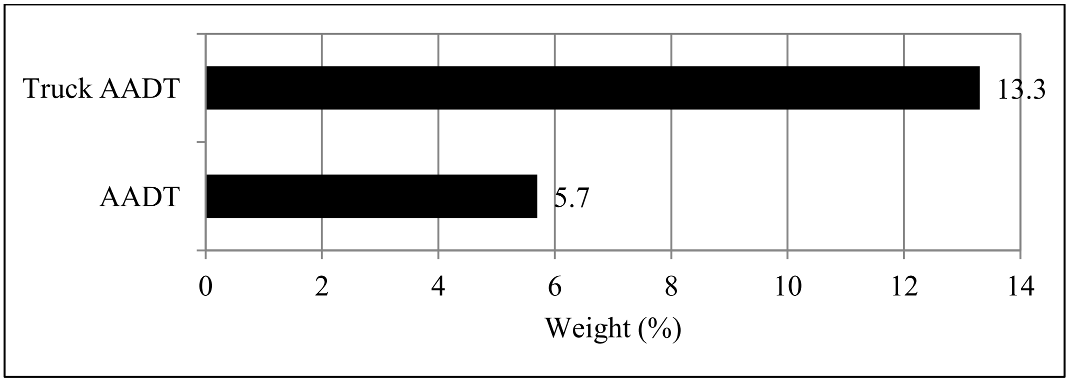


Figure 11. Weights of Current Traffic Volume Factors.

Priority Weights Grouped by District Type

The responses were grouped by district type (metro, urban, and rural) to determine if the priority weights vary among these groups. As discussed earlier, responses have been received from four metro districts, five urban districts, and eight rural districts. The results are shown in Figure 12 through Figure 15. The following observations can be made based on these results:

- Top level categories of factors (Figure 12):
    - The order of priority for urban, rural, and all districts combined is fairly similar (with minor exceptions). However, the magnitudes of the weights vary.
    - For urban and rural districts, pavement current condition and M&R initial cost are the top influencing factors (among factors considered in this study).
    - The order of priority and magnitude of the weights for metro districts are markedly different from those for the other districts.
    - For metro districts, long-term-performance benefits, initial cost, and current traffic volume are the top priorities.
- Factors representing pavement current condition (Figure 13 and Figure 14):
    - District's own visual assessment is the top indicator of pavement current condition for both urban and rural districts. It is followed by distress and condition scores, and to a lesser extent skid resistance.
    - Skid resistance is the top indicator of pavement current condition for metro districts.
    - All district types (metro, urban, and rural) consistently assigned the least weight to ride score as an indicator of pavement current condition.
- Factors representing current traffic volume (Figure 15):
    - All types of districts agree in giving truck AADT higher weight than AADT.

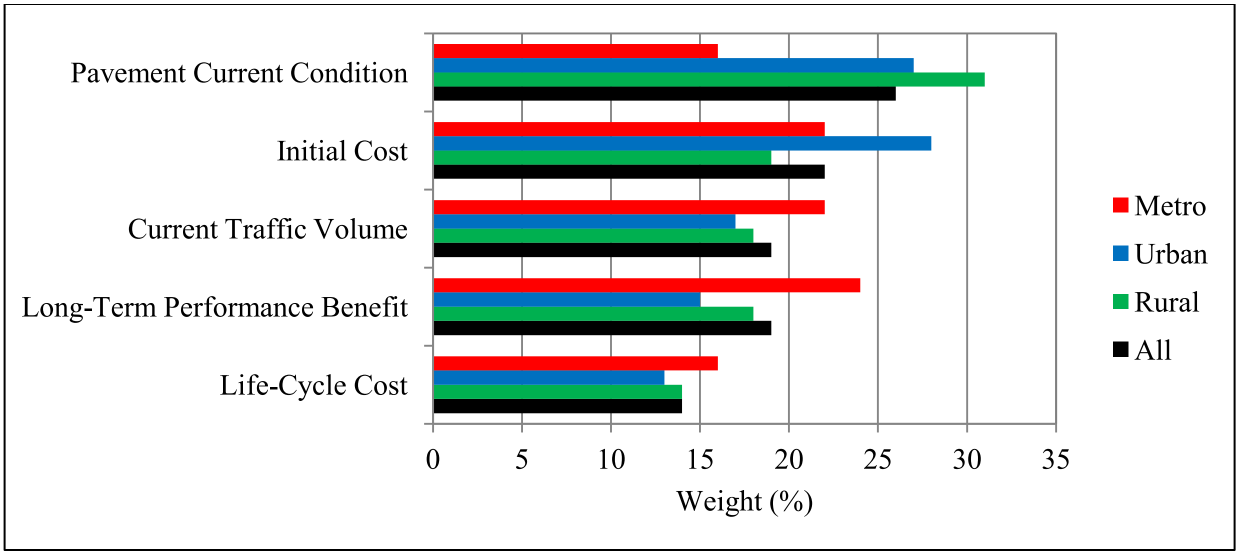


Figure 12. Weights of Short-Term and Long-Term Indicators According District Type.

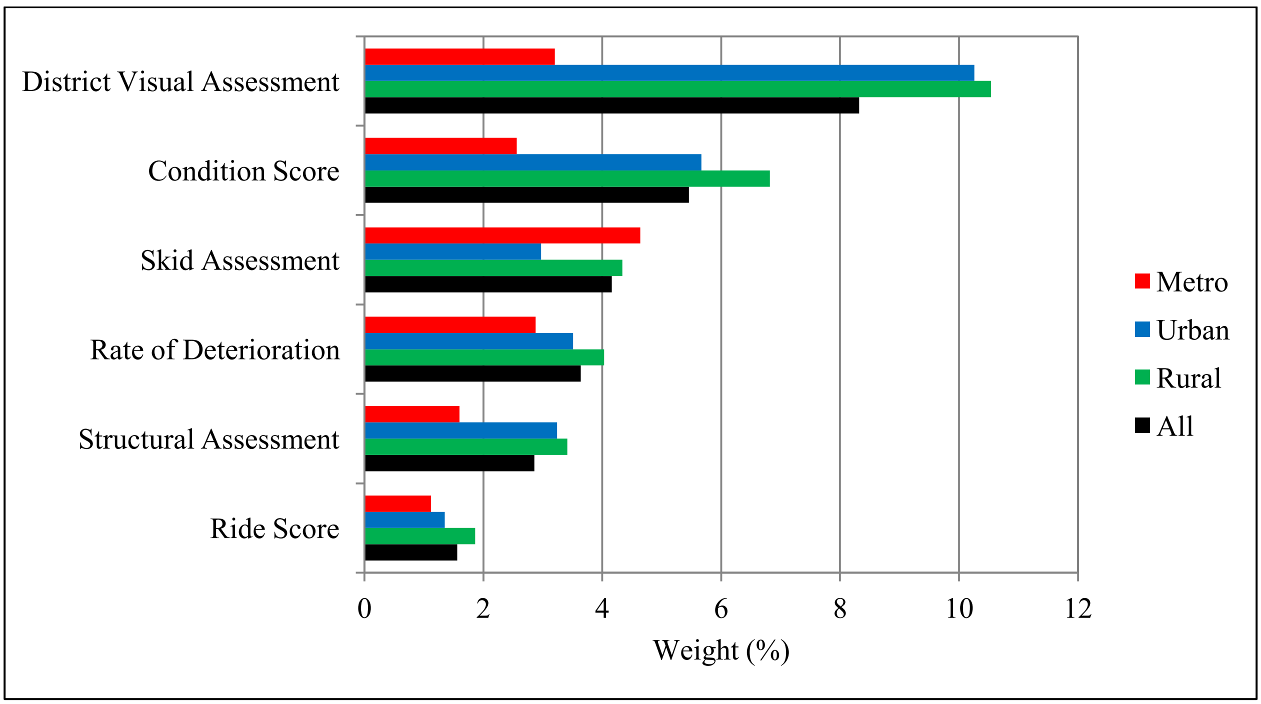


Figure 13. Weights of Pavement Current Condition Indicators (Rehab) According to District Type.

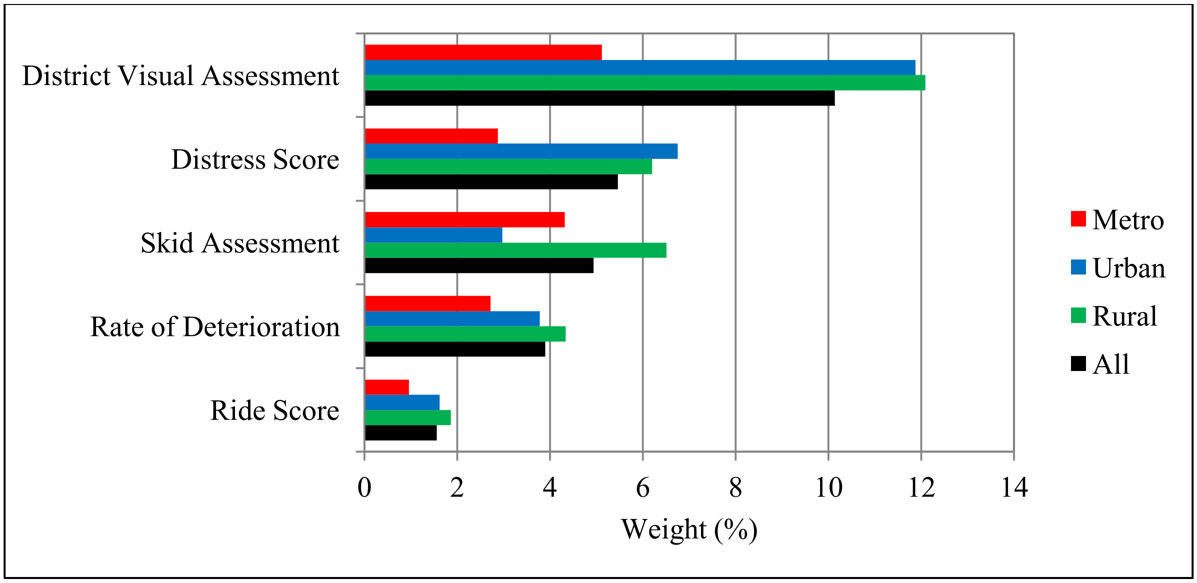


Figure 14. Weights of Pavement Current Condition Indicators (Maintenance) According to District Type.

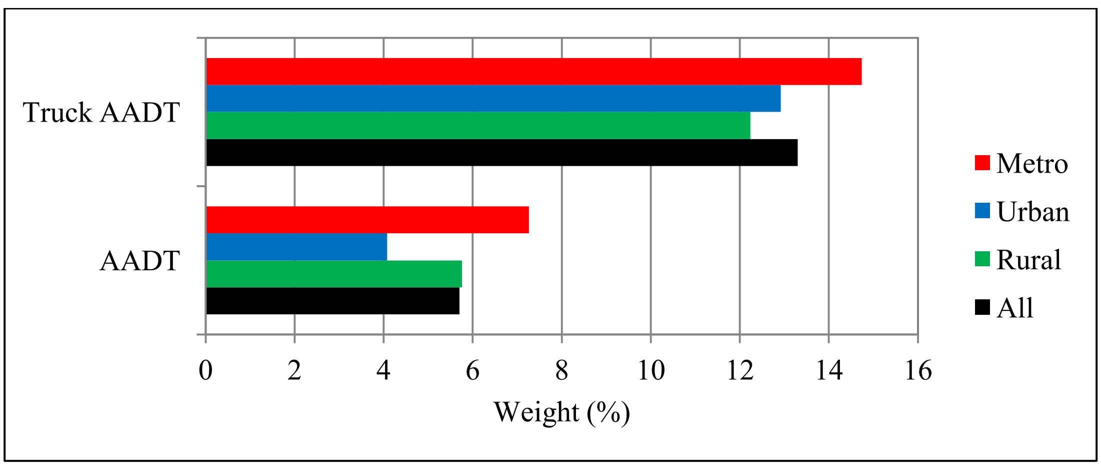


Figure 15. Weights of Current Traffic Volume Factors According to District Type.

Summary of Priority Weights

A summary of the priority weights for the factors considered in the online survey are provided in Table 8 through Table 11, for all districts combined, rural districts, urban districts, and metro districts. These results suggest that there are differences in M&R priorities of the decision makers in these district types. Thus, it would be prudent to enable different district types (or individual districts) to use different priority weights. The weights provided in this study should be considered as default values (or reference points) for TxDOT's districts.

Table 8. Priority Weights Computed Using All Responses.

Influencing Categories and Factors	Weight, %
Pavement Current Condition	26
a. District Visual Assessment (Weight^R = 8.3%, Weight^M= 10.1%)	
b. Condition Score (Weight^R = 5.5%)	
c. Distress Score (Weight^M = 5.5%)	
d. Skid Assessment (Weight^R = 4.2%, Weight^M = 4.9%)	
e. Rate of Deterioration (Weight^R = 3.6%, Weight^M = 3.9%)	
f. Structural Evaluation (Weight^R = 2.9%)	
g. Ride Score (Weight^R = 1.6%, Weight^M = 1.6%)	
Treatment Initial Cost	22
Treatment Life-Cycle Cost	14
Treatment Long-Term Performance Benefits	19
Traffic Volume	19
a. Truck AADT (Weight = 13.3%)	
b. AADT (Weight = 5.7%)	
Total	100

Table 9. Priority Weights Computed Using Rural Districts Responses.

Influencing Categories and Factors	Weight, %
Pavement Current Condition	31
a. District's Visual Assessment (Weight^R = 10.5%, Weight^M= 12.1%)	
b. Condition Score (Weight^R = 6.8%)	
c. Distress Score (Weight^M = 6.2%)	
d. Skid Assessment (Weight^R = 4.3%, Weight^M = 6.5%)	
e. Rate of Deterioration (Weight^R = 4.0%, Weight^M = 4.3%)	
f. Structural Evaluation (Weight^R = 3.4%)	
g. Ride Score (Weight^R = 1.9%, Weight^M = 1.9%)	
Treatment Initial Cost	19
Treatment Life-Cycle Cost	14
Treatment Long-Term Performance Benefits	18
Traffic Volume	18
c. Truck AADT (Weight = 12.2%)	
d. AADT (Weight = 5.8%)	
Total	100

Table 10. Priority Weights Computed Using Urban Districts Responses.

Influencing Categories and Factors	Weight, %
Pavement Current Condition	27
a. District's Visual Assessment (Weight^R = 10.3%, Weight^M= 11.9%)	
b. Condition Score (Weight^R = 5.7%)	
c. Distress Score (Weight^M = 6.8%)	
d. Skid Assessment (Weight^R = 3.0%, Weight^M = 3.0%)	
e. Rate of Deterioration (Weight^R = 3.5%, Weight^M = 3.8%)	
f. Structural Evaluation (Weight^R = 3.2%)	
g. Ride Score (Weight^R = 1.4%, Weight^M = 1.6%)	
Treatment Initial Cost	28
Treatment Life-Cycle Cost	13
Treatment Long-Term Performance Benefits	15
Traffic Volume	17
e. Truck AADT (Weight = 12.9%)	
f. AADT (Weight = 4.1%)	
Total	100

Table 11. Priority Weights Computed Using Metro Districts Responses.

Influencing Categories and Factors	Weight, %
Pavement Current Condition	16
a. District's Visual Assessment (Weight^R = 3.2%, Weight^M= 5.1%)	
b. Condition Score (Weight^R = 2.6%)	
c. Distress Score (Weight^M = 2.9%)	
d. Skid Assessment (Weight^R = 4.6%, Weight^M = 4.3%)	
e. Rate of Deterioration (Weight^R = 2.9%, Weight^M = 2.7%)	
f. Structural Evaluation (Weight^R = 1.6%)	
g. Ride Score (Weight^R = 1.1%, Weight^M = 1.0%)	
Treatment Initial Cost	22
Treatment Life-Cycle Cost	16
Treatment Long-Term Performance Benefits	24
Traffic Volume	22
g. Truck AADT (Weight = 14.7%)	
h. AADT (Weight = 7.3%)	
Total	100

^{R} – indicates that factor is considered in describing pavement current condition for rehabilitation projects only.
^{M} – indicates that factor is considered in describing pavement current condition for maintenance projects only.

CHAPTER 4 − DATA REQUIREMENTS AND AVAILABILITY

This chapter discusses the need and availability of data for use in the proposed PMP methodology. These data are categorized as follows:

- Pavement inventory, condition, work history, and traffic data.
- Unit costs of M&R treatment categories.

PAVEMENT INVENTORY, CONDITION, WORK HISTORY, AND TRAFFIC DATA

Table 12 lists the pavement inventory, condition, work history, and traffic data items required for performing the PMP methodology, along with their source and their specific function within the PMP methodology.

Table 12. Pavement Attribute Data Used in PMP Methodology.

Data Item	Data Source	Purpose
District	PMIS	Identify subgrade and climatic zone for use in performance prediction models
Highway identification (name, roadbed, and direction)	PMIS	Group data collection sections into potential M&R projects
Section Beginning Point [Texas Reference Marker- (TRM) and displacement]	PMIS	Group data collection sections into potential M&R projection sections
Section Ending Point (TRM and displacement)	PMIS	Group data collection sections into potential M&R projects
Section length	PMIS	Calculate project cost and benefit
Number of lanes	PMIS	Calculate project cost
Pavement type	PMIS	Identify pavement family for use in performance prediction models; group data collection sections
Condition score	PMIS	Trigger M&R, calculate performance benefit, prioritize projects
Distress score	PMIS	Trigger M&R, prioritize projects
Ride score	PMIS	Prioritize M&R projects
Rate of deterioration	Computed from condition or distress score	Prioritize M&R projects
Type of prior M&R treatment	Work history or assumed to be heavy rehabilitation	Use in performance prediction models
Year of prior M&R treatment	Work history or estimated from prediction models	Use in performance prediction models
Skid assessment	User defined	Prioritize M&R projects
Structural assessment	User defined	Prioritize M&R projects
Visual assessment by district	User defined	Prioritize M&R projects
Forced projects	User defined	Prioritize M&R projects
AADT	PMIS	Calculate project benefit; prioritize projects; use in performance prediction models
Truck AADT	PMIS	Prioritize M&R projects
Speed limit	PMIS	Use in performance prediction models

Most of the above data items are available in the PMIS database. However, no data were available for skid assessment (SKID), structural condition assessment (STRUCT), and visual assessment (VISUAL). Therefore, a process was designed to allow the users (e.g., district staff) to enter a binary "adequate/inadequate" rating for these pavement condition indicators. The user enters the Beginning Reference Marker (BRM) and displacement and End Reference Marker (ERM) and displacement of the road segments that have been rated for skid resistance, structural capacity, and that have been assessed visually. Then, the user assigns adequate or inadequate SKID, STRUCT, and/or VISUAL ratings for these segments, as follows:

- SKID – an adequate/inadequate rating is entered based on skid resistance tests. A “null” rating is used when a section is not rated.
- STRUCT – an adequate/inadequate rating is entered based on structural capacity tests (e.g., Falling-Weight Deflectometer). A “null” rating is used when a section is not tested.
- VISUAL – an adequate/inadequate rating based on overall visual assessment of pavement condition conducted by district staff. A null rating is used when a section is not evaluated.

As part of past research projects (Projects 0-4322 and 5-4322), TxDOT developed the structural condition index (SCI) as a screening tool to identify pavements that need structural improvement. In this project, the researchers evaluated and improved the SCI procedure and investigated potential associations between SCI and pavement surface condition using 155 pavement sections from the Bryan and Fort Worth Districts. This work is presented in Appendix A. It was found that adequate number of FWD tests should be taken within each pavement section to ensure that the computed SCI is representative of the structural condition of the entire pavement section (e.g., five FWD tests per 0.5-mile pavement section). Thus, it may not be feasible to use SCI as a direct input to the PMP methodology due to the extensive amount of FWD testing that would be needed. Instead, SCI may be used to determine if structural improvement is needed for pavements identified by the PMP methodology as candidate M&R projects.

Year and type of prior M&R treatment were extracted, to the maximum possible extent, from TxDOT’s Design and Construction Information System (DCIS) database. The original DCIS database that was used in this study contained project letting information that was collected between 1984 and 2011, and consisted of 129,080 records along with 155 data columns. However, this database contained information on non-pavement projects (e.g., roadside and bridge projects), which was then excluded from any further analysis in this study. The final database consisted of 44,587 records along with 93 data columns for pavement-related projects. Of these 44,587 records of pavement-related projects, 38,790 (87 percent) can be geographically identified, leaving 5,797 projects with missing beginning and ending reference marker positions. For those DCIS records with missing location information, the beginning and ending reference marker positions were estimated and populated programmatically, as follows:

- Direct extraction from work history spreadsheets: These spreadsheets contain key information (including beginning and ending reference marker positions) on seal coat, overlay, and micro-surfacing projects that were completed in 16 districts between 2001 and 2006. Construction projects were matched and reference marker information was copied from the spreadsheets to the DCIS dataset.
- Estimation from PMIS’s Control Section table: In this method, the locations of project reference markers are estimated from PMIS’s Control Section table through parsing and matching of key words and numerical values.
- Estimation from other available data in DCIS: In this method, the locations of project reference markers are estimated from other populated relevant columns in DCIS such as MILE_POINT, PROJ_LENG, or LIMITS_TO (FROM) through parsing and matching of key words and numerical values.

M&R UNIT COSTS

Accurate unit costs of M&R treatment categories are necessary for estimating budget needs and conducting life-cycle analysis and benefit-cost analysis of pavement M&R alternatives. The researchers analyzed the 2011 PMP project cost data to assess the mean values and variability of unit costs for routine maintenance (RM), preventive maintenance (PM), light rehabilitation (LRH), medium rehabilitation (MRH), and heavy rehabilitation (HRH). This analysis was conducted for asphalt concrete pavement (ACP) and Portland cement concrete pavement (PCCP), separately, and the results are presented as follows.

Asphalt Concrete Pavement Treatments

ACP Routine Maintenance. As shown in Table 13, a total of 1,336 ACP RM projects were analyzed; nearly 50 percent of them are “strip or spot seal.” A histogram of the unit costs of these 1,336 RM projects is shown in Figure 16. The average unit cost for these projects is $13,718 per lane-mile, and the standard deviation is $11,458 per lane-mile.

Level-up is normally used to level (or fill in) pavement depressions, ruts, and settlements. The application of a level-up reshapes the roadway crown and restores cross slope, which improves drainage. Generally, current practices at TxDOT consider level-up as a routine maintenance treatment. However, the unit costs of 2,103 level-up projects were found to be distinctly higher than the other RM treatment types (see Figure 17). The average unit cost of these level-up projects is $26,387 per lane-mile, and the standard deviation is $11,458 per lane-mile. These data suggest that it may not be appropriate to consider level-up as a routine maintenance treatment. From a cost standpoint, level-up appears to fit in the LRH category.

Table 13. ACP Routine Maintenance Projects.

Treatment Type	No. of Projects	%Projects
Asphalt Repair	40	3
Base Repair	52	4
Spot Level-Up	84	6
Crack Seal	91	7
Edge Repair/Seal	83	6
Fog Seal	145	11
Milling	115	9
Seal Coat Preparation	42	3
Strip or Spot Seal	622	47
Other	62	5
Total	1336	100

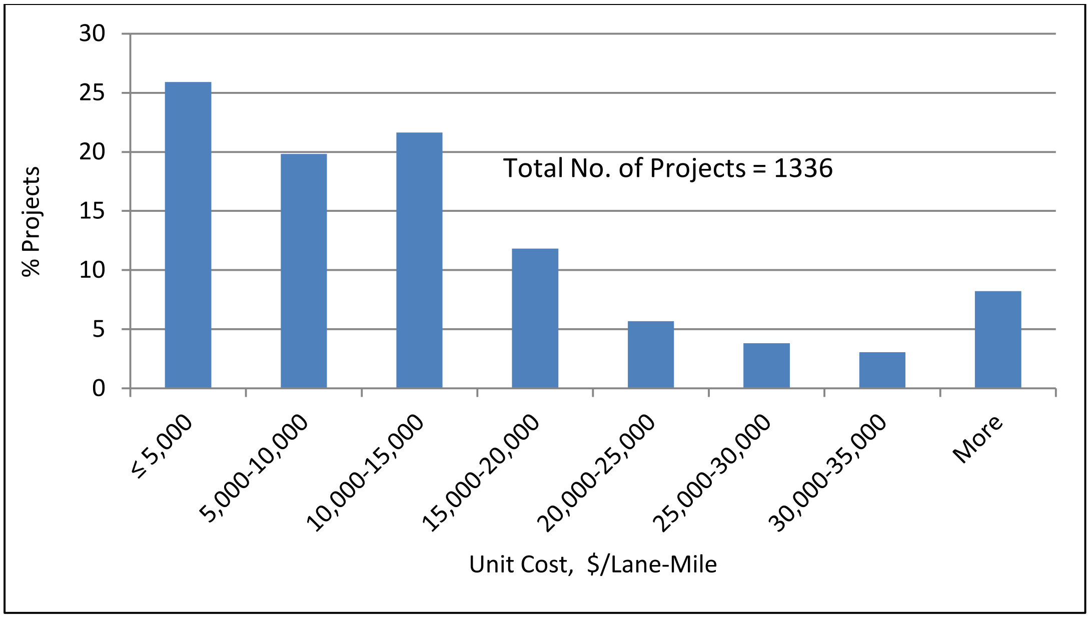


Figure 16. Unit Cost Frequency Distribution for ACP Routine Maintenance Projects (Excluding Level-up).

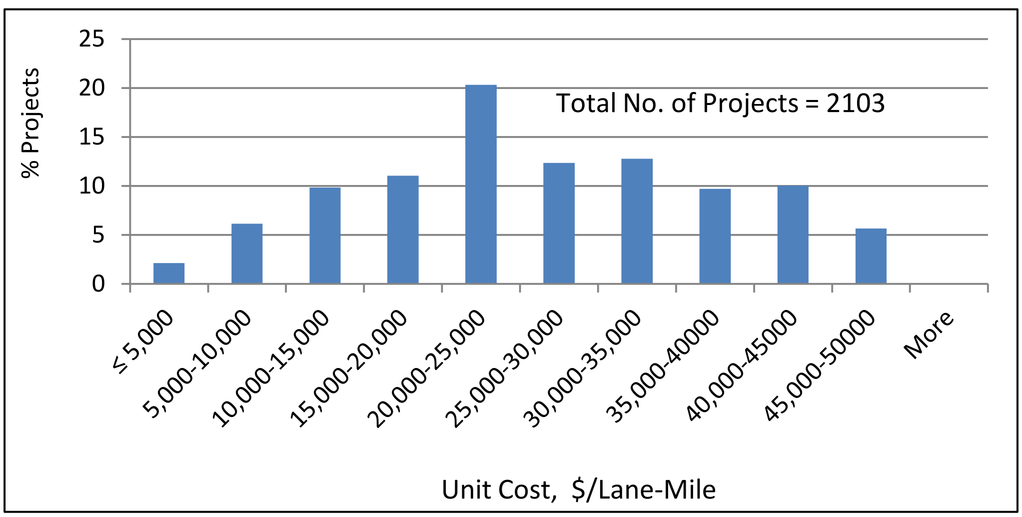


Figure 17. Unit Cost Frequency Distribution for ACP Level-up Projects.

ACP Preventive Maintenance (Seal Coat). PM treatments of ACP are predominantly seal coat, which is generally an application of a single, double, or triple layer(s) of asphalt material covered with aggregate to an existing pavement.

A total of 2,144 seal coat projects were analyzed. As shown in Figure 18, the unit costs of these projects are approximately normally distributed, with an average value of $14,728 per lane-mile and a standard deviation of $8,620 per lane-mile.

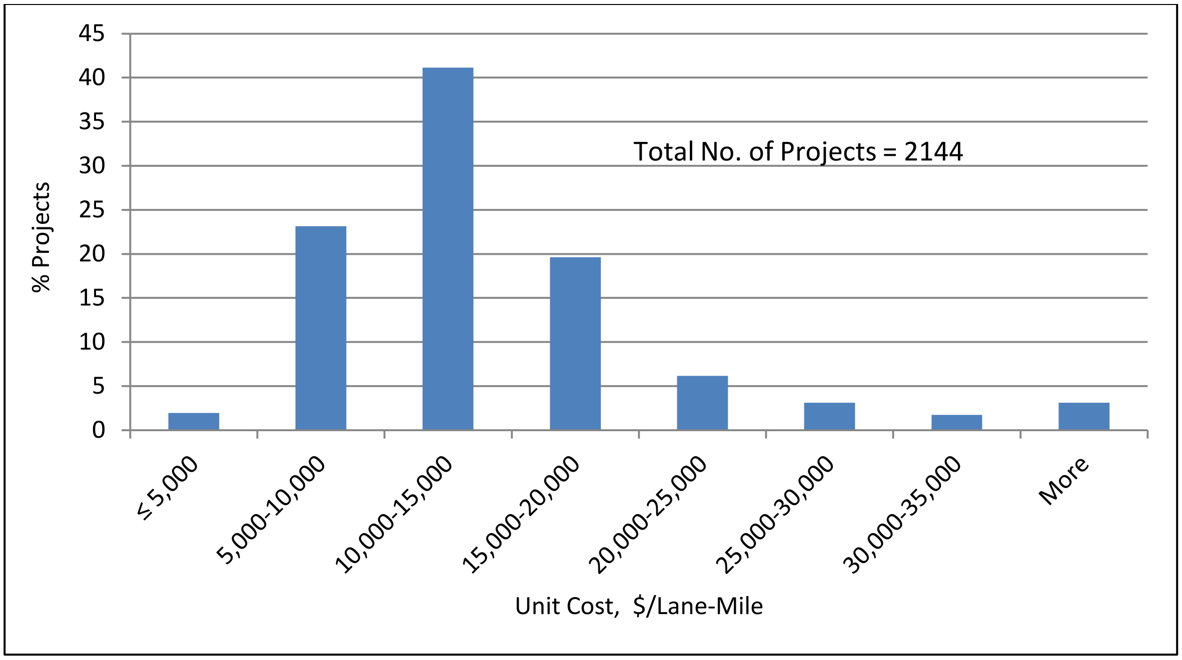


Figure 18. Unit Cost Frequency Distribution for ACP Seal Coat Projects.

ACP Light Rehabilitation. As shown in Table 14, a total of 549 ACP LRH projects were analyzed; nearly 72 percent of them are "base repair, and level-up and/or seal" and "hot-mix asphalt (HMA) overlay." A histogram of the unit costs of these 549 LRH projects is shown in Figure 19, which shows a markedly wide range of unit cost for this M&R category. The average unit cost for these projects is $76,086 per lane-mile, and the standard deviation is $81,121 per lane-mile.

Table 14. ACP Light Rehabilitation Projects.

Treatment Type	No. of Projects	%Projects
Base Repair, and Level Up and/or Seal	188	34
Mill and Inlay	49	9
Mill and Overlay (thickness between 2 and less than 3 inches)	22	4
HMA Overlay (thickness between 2 and less than 3 inches)	211	38
Other	79	14
Total	549	100

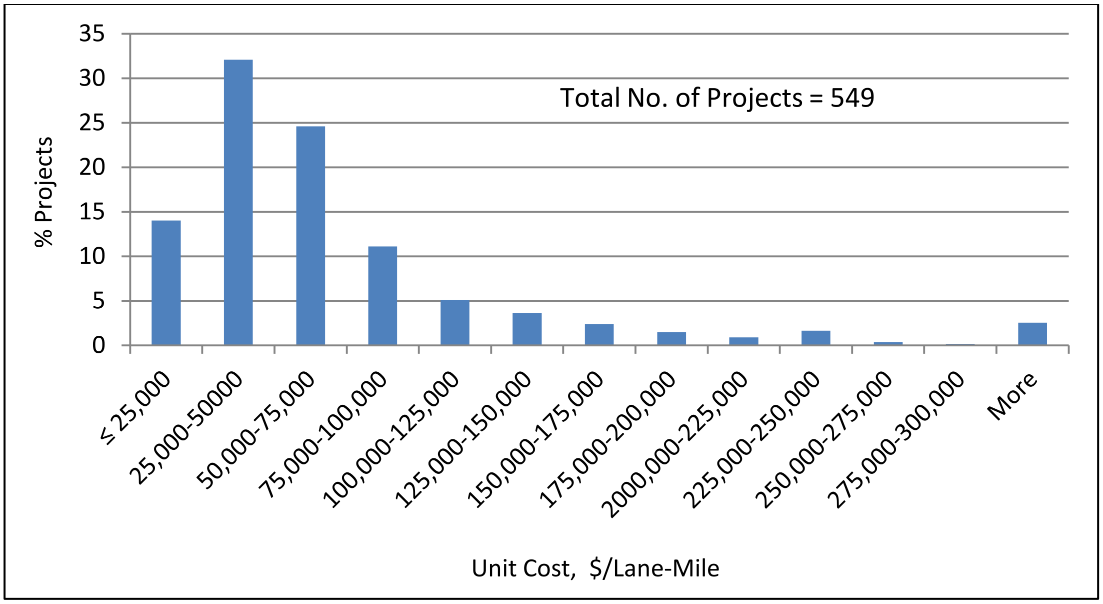


Figure 19. Unit Cost Frequency Distribution for ACP Light Rehabilitation Projects.

ACP Medium Rehabilitation. As shown in Table 15, a total of 329 ACP MRH projects were analyzed; nearly 50 percent of them are "base repair, and level-up and/or seal" and 37 percent are "HMA mill and overlay" or "mill and inlay." A histogram of the unit costs of these 329 MRH projects is shown in Figure 20, which shows high variability in the unit cost of this M&R category. The average unit cost for these projects is $78,429 per lane-mile, and the standard deviation is $87,127 per lane-mile.

Table 15. ACP Medium Rehabilitation Projects.

Treatment Type	No. of Projects	%Projects
Base Repair, and Level Up and/or Seal	162	49
Subgrade repair with Geogrid and Cement	9	3
Mill and Inlay	73	22
Mill and Overlay	48	15
Other	37	11
Total	329	100

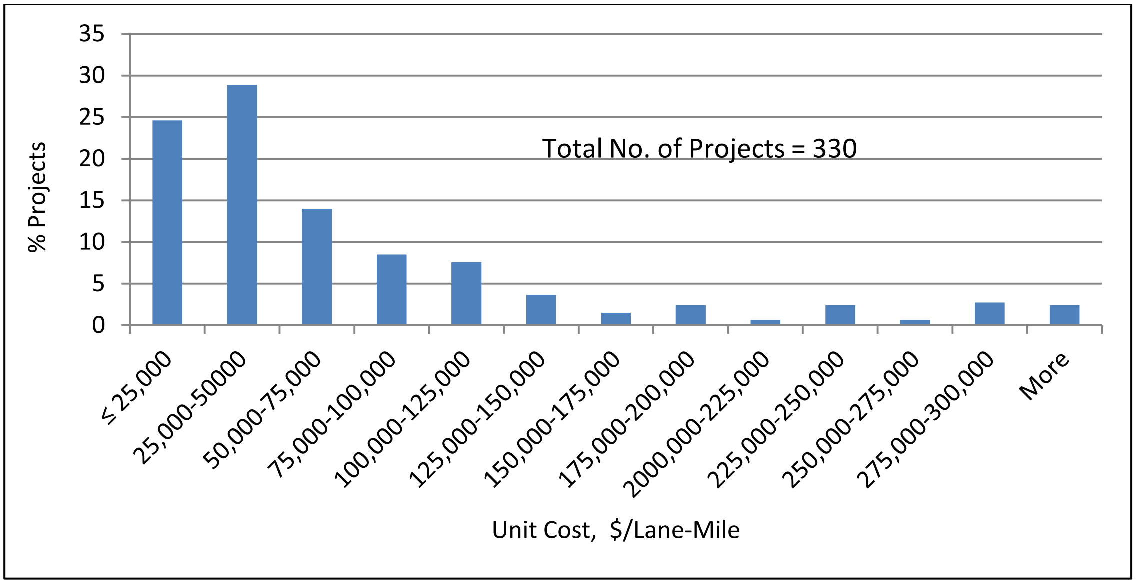


Figure 20. Unit Cost Frequency Distribution for ACP Medium Rehabilitation Projects.

ACP Heavy Rehabilitation. As shown in Table 16, a total of 152 ACP HRH projects were analyzed; 48 percent of them are described as "base repair, rehab, and overlay." These projects are designed to restore the pavement functional and structural condition to nearly original condition. A histogram of the unit costs of these 152 MR projects is shown in Figure 21, which shows high variability in the unit cost of this M&R category (similar to the LRH and MRH categories). The average unit cost for these projects is $133,776 per lane-mile, and the standard deviation is $93,256 per lane-mile.

Table 16. ACP Heavy Rehabilitation Projects.

Treatment Type	No. of Projects	%Projects
Base Repair, Rehab, and Overlay	73	48
Bomag or Scarify, Add base, and Seal/Resurface	28	18
Full Depth Base Repair	21	14
Other	30	20
Total	152	100

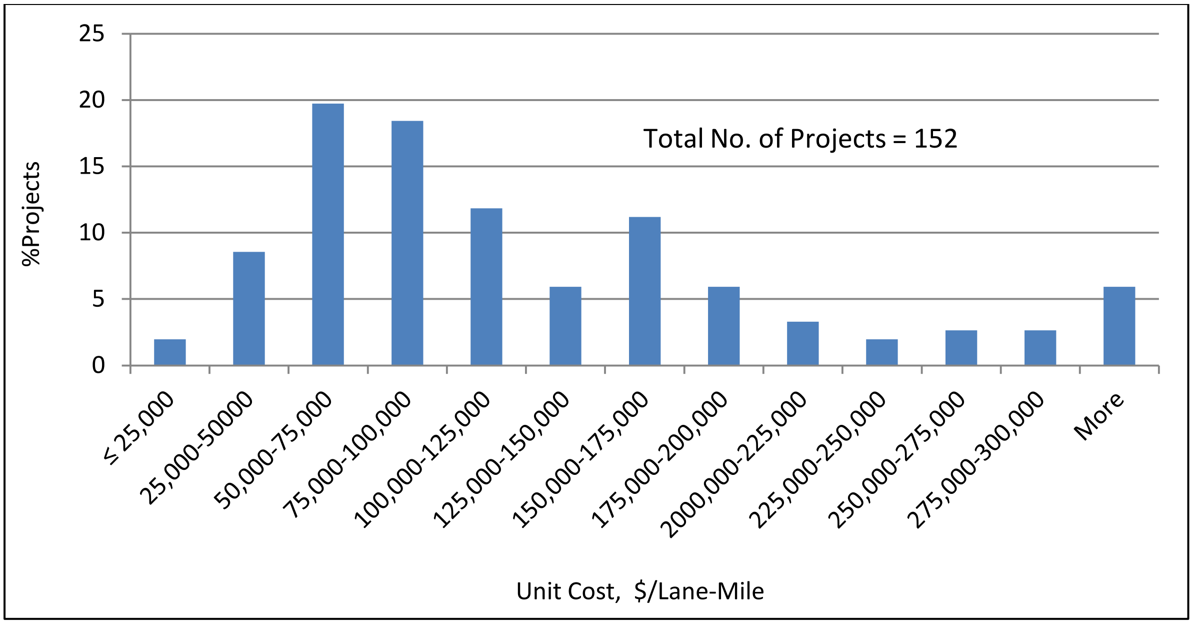


Figure 21. Unit Cost Frequency Distribution for ACP Heavy Rehabilitation Projects.

Portland Cement Concrete Pavement Treatments

PCCP Routine Maintenance. As shown in Table 17, a total of 82 PCCP RM projects were analyzed; 56 percent of them are described as "concrete pavement repair" (i.e., partial-depth patching). A histogram of the unit costs of these 82 RM projects is shown in Figure 22, which shows high variability in the unit cost of this M&R category. The average unit cost for these projects is $16,957 per lane-mile, and the standard deviation is $20,567 per lane-mile.

Table 17. PCCP Routine Maintenance Projects.

Treatment Type	No. of Projects	%Projects
Joint or Crack Seal	8	10%
Concrete Pavement Repair	46	56%
Spall Repair	28	34%
Total	82	100%

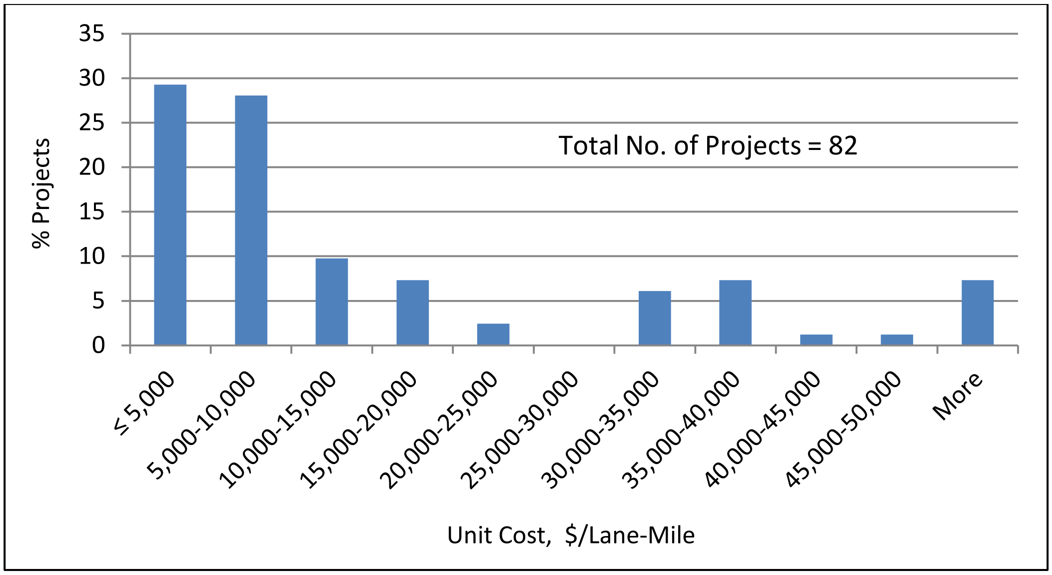


Figure 22. Unit Cost Frequency Distribution for PCCP Routine Maintenance Projects.

PCCP Preventive Maintenance. Only 10 PCCP preventive maintenance projects have sufficient cost data. Nine of these projects are described as patching and one project consists of diamond grinding. The average unit cost for these projects is $20,818 per lane-mile, and the standard deviation is $16,528 per lane-mile.

PCCP Light Rehabilitation. No analysis was performed for this M&R category due to lack of data.

PCCP Medium Rehabilitation. As shown in Table 18, a total of 35 PCCP MRH projects were analyzed; 54 percent of them are described as "full-depth repair," 40 percent are described as a combination of full-depth repair and other treatments (spall repair, slab jacking, or overlay), and the remaining 6 percent are described as "diamond grinding and joint cleaning and sealing." A histogram of the unit costs of these 35 MRH projects is shown in Figure 23, which shows high variability. The average unit cost for these projects is $82,726 per lane-mile, and the standard deviation is $126,566 per lane-mile.

Table 18. PCCP Medium Rehabilitation Projects.

Treatment Type	No. of Projects	%Projects
Full Depth Repair	19	54%
Full Depth and Spall Repair	2	6%
Full Depth Repair, Slab Jacking, and Spall Repair	6	17%
Full Depth Repair and Overlay	6	17%
Diamond Grinding and Clean and Seal Joints	2	6%
Total	35	100%

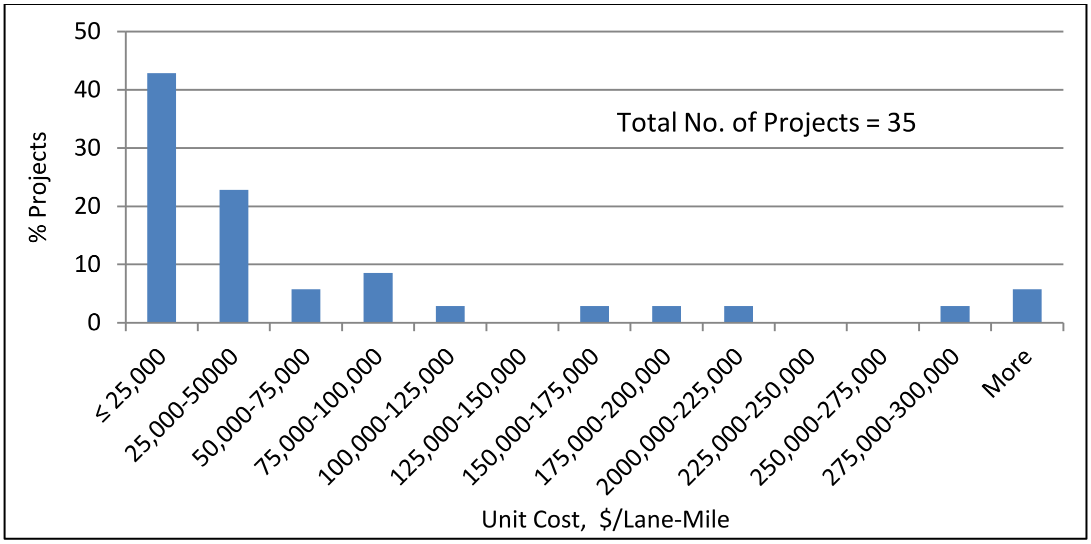


Figure 23. Unit Cost Frequency Distribution for PCCP Medium Rehabilitation Projects.

PCCP Heavy Rehabilitation. No analysis was performed for this M&R category due to lack of data.

Summary of M&R Unit Costs

Table 19 provides a summary of statewide average unit costs for ACP (pavement types 4 to 10), obtained from 2012 Pavement Management Information System (PMIS) data, 2009 PMIS data, and 2011 PMP data (analyzed as part of this study). Similarly, Table 20 provides a summary of statewide average unit costs for PCCP (pavement types 1 to 3). For most cases, the unit costs computed as part of this study lie in between the 2009 and 2012 PMIS unit costs.

Table 19. Unit Costs for ACP M&R Treatment Categories.

M&R Category	Mean, $/Lane-mile (PMIS 2012(1))	Mean, $/Lane-mile (PMIS 2009)	Mean, $/Lane-mile (This Study(2))	Standard Deviation $/Lane-mile (This Study(2))
RM(3)	31,100	9,571	13,718	11,458
PM	31,100	9,571	15,409	8,620
LRH	139,100	33,714	76,086	81,121
MRH	242,700	59,429	78,429	87,127
HRH	504,700	153,143	133,776	93,256

(1) Based on PMIS data for Bryan District.
(2) This study: 2011 PMP data
(3) RM without level-up.

Table 20. Unit Costs for PCCP M&R Treatment Categories.

M&R Category	Mean, $/Lane-mile (PMIS 2012[(1)]))	Mean, $/Lane-mile (PMIS 2009)	Mean, $/Lane-mile (This Study[(2)])	Standard Deviation $/Lane-mile (This Study[(2)])
RM	36,000	NA	16,957	20,567
PM	36,000	6,000	20,818	16,528
LRH	60,000	60,000	NA	NA
MRH	256,000	125,000	82,726	126,566
HRH	651,000	400,000	NA	NA

(1) Based on PMIS data for Bryan District.
(2) This study: 2011 PMP data

CHAPTER 5 – PMP DEVELOPMENT METHODOLOGY

This chapter describes the developed PMP methodology. The discussion is organized into the following sections:

- Overview of PMP methodology.
- Grouping data collection sections into management sections.
- Prediction of pavement performance.
- Measuring long-term performance benefits and life-cycle costs.
- Prioritization of M&R projects.

OVERVIEW OF PMP METHODOLOGY

The developed methodology for preparing a multi-year pavement management plan is illustrated in Figure 24.

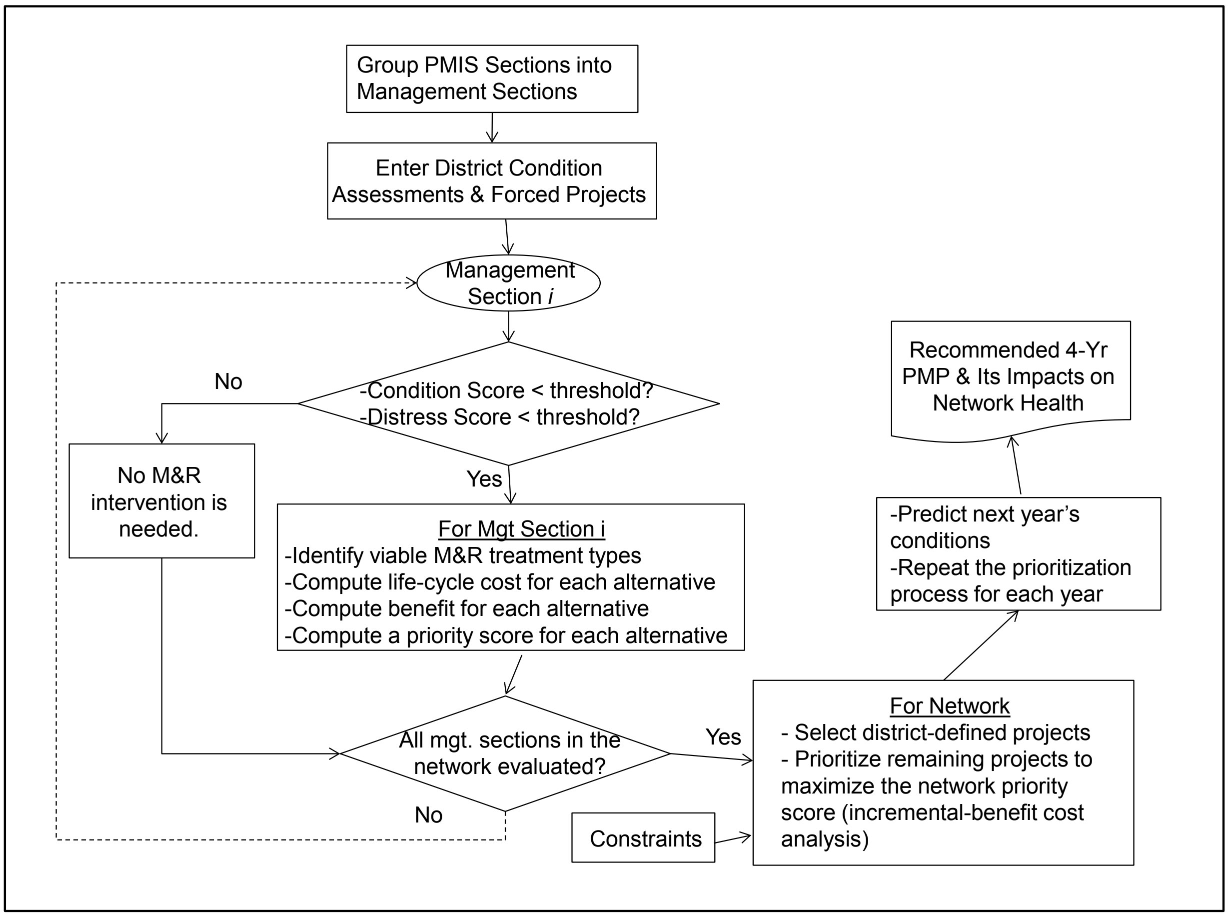


Figure 24. Methodological Framework for Developing PMP.

The algorithm first groups the data collection sections found in the PMIS database into management sections based on the homogeneity of their condition, traffic loading, and pavement type. Districts may then enter additional condition assessments as well as projects that the district is committed to fund (i.e., forced projects).

For every management section formed, the algorithm compares its CS or DS to user-defined M&R trigger value. Sections with CS or DS below the trigger value are considered in need for M&R action, while no intervention is needed for those with CS or DS above the trigger value. For each section needing M&R, viable M&R treatments are identified and their life-cycle cost, performance benefit, and priority score are computed. The combination of management sections and their viable M&R treatments represent candidate M&R projects that should be considered for funding.

The candidate projects are then prioritized using the Incremental Benefit-Cost (IBC) algorithm to generate a list of projects that maximize the total priority score for the given budget. The pavement condition is then projected for the following year, and the process is repeated every year until the end of the planning horizon (i.e., four years). The selected M&R projects constitute the 4-year PMP. Finally, the impact of the PMP on the network condition is analyzed.

GROUPING DATA COLLECTION SECTIONS INTO PAVEMENT MANAGEMENT SECTIONS

The PMIS database contains data on "data collection sections" that are typically 0.5-mile long. In contrast, the districts prioritize and let M&R projects that extend over longer roadway segments typically ranging from 2 to 10 miles. Hence, contiguous data collection sections must be grouped together to form realistic M&R projects. In this step in the PMP methodology, adjacent PMIS data collection sections are grouped into homogeneous "management sections" that can be maintained independently, and thus represent potential M&R projects. Also, the developed algorithm allows for assigning minimum and maximum lengths to facilitate the project letting process.

This section of the report first describes the location referencing system used in PMIS, which is pertinent to project formation. Then, two M&R project formation schemes are presented. The first scheme is the widely used Cumulative Difference Algorithm (CDA), which groups pavement sections based on homogeneity. The second scheme was developed in this study and is called the Proximity to Deficient Areas (PDA) approach, where M&R projects are formed around defective pavements. These schemes are incorporated in the PMP methodology and computational tool.

Location Referencing System in PMIS Database

The TxDOT PMIS locates a data collection section through its unique highway identifier (ID) and Reference Markers (RM). The highway ID contains information on the: (1) route type; (2) highway number; and (3) roadbed on which the data collection section stands. Figure 25 shows an example of a highway ID (Texas Department of Transportation 2010).

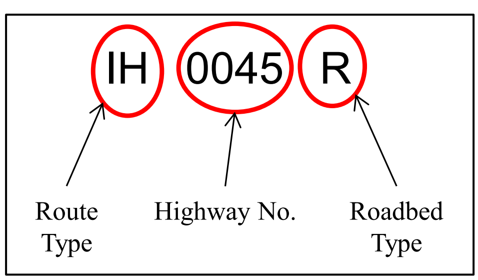


Figure 25. Description of Highway ID Used in PMIS Database.

Table 21 lists the types of routes used by TxDOT (from major to minor) and the corresponding prefixes. Figure 26 illustrates the different types of roadbeds used in the PMIS database (Texas Department of Transportation 2011).

Table 21. Route Types Used in PMIS Database.

Route Description	Prefix
Interstate Highway	IH
US Highway	US
State Highway (includes NASA, OSR)	SH
Business Interstate	BI
Business US Highway	BU
Business State Highway	BS
Farm to Market	FM
Business Farm to Market	BF
Park Road	PR

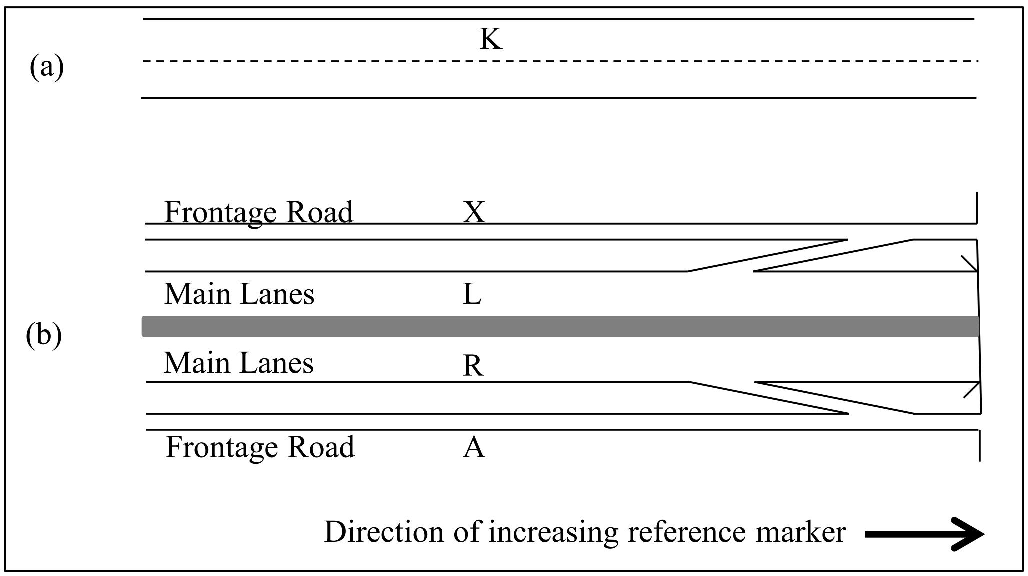


Figure 26. Roadbed Types Used in PMIS Database: a) Single Roadbed, b) Multiple Roadbeds.

Following the highway ID are four reference markers that specify the exact location of the data collection section along the highway. As an example, Figure 27 indicates a data collection section that starts exactly at RM 173 (i.e., "00" miles past the beginning reference marker [BRM]) and ends 0.5 miles past RM 173 (i.e., 0.5 mile past the ending reference marker [ERM]), for a total section length of 0.5 miles.

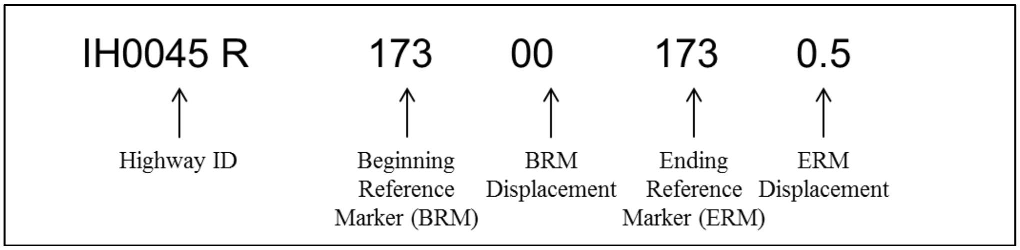


Figure 27. Description of PMIS Reference Markers.

Cumulative Difference Algorithm for Forming M&R Projects

The cumulative difference algorithm can be used to group homogeneous data collection sections into segments that can be maintained independently and thus represent potential M&R projects. In this project formation scheme, data collection sections can only be grouped together if the following conditions are met:

- Sections must belong to the same highway (i.e., same highway ID).
- Sections must be on the same roadbed.
- Sections must be contiguous (as indicated by their RMs).
- Sections must be of the same pavement family (see Table 22).

In addition, this project formation scheme allows for imposing minimum and maximum lengths on the projects formed.

Table 22. PMIS Pavement Families Developed under TxDOT Project 0-6386 (Gharaibeh et al., 2012).

Pavement Family	PMIS Pavement Type	Description
CRCP	1	Continuously-Reinforced Concrete Pavement
JCP	2	Jointed Concrete Pavement, reinforced
	3	Jointed Concrete Pavement, unreinforced ("plain")
A	4	Thick ACP
	5	Intermediate ACP
	9	Overlaid ACP
B	7	Composite Pavement
	8	Concrete Pavement Overlaid with ACP
C	6	Thin ACP
	10	Thin-Surfaced ACP

The example shown in Figure 28 illustrates the CDA segmentation process based on homogeneity in CS. The cumulative difference between each section's CS and a CS threshold value of 70 is plotted. In theory, change-points in the cumulative difference plot indicate boundaries between homogeneous segments. In this example, the seven marked lines indicate boundaries between the eight homogeneous segments *a* to *h*. Assuming that each PMIS section in this case is 0.5-miles long and that a minimum project length of 2 miles is imposed, segments *c*, *d*, *e*, and *g* would be too short to form management sections and thus boundaries 3, 4, and 7 are discounted. Consequently, the CS-based homogeneous segments are delineated by boundaries 1, 2, 5, and 6 (see red lines).

The CDA was also applied using DS and projected cumulative ESALS to produce segments that are homogeneous in both condition and carried truck traffic. The CS and DS segmentation thresholds can be set to delineate stretches of roadways that have acceptable condition (e.g., CS greater than 70 and DS greater than 80) from stretches with unacceptable condition. The ESAL threshold can be set to delineate stretches of roadways that have above-average cumulative design ESALs from stretches that have below-average cumulative design ESALs.

PMIS Section	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
CS	60	60	60	60	90	90	90	90	40	40	40	80	80	40	100	100	100	100	100	100	50	90	90	90	90

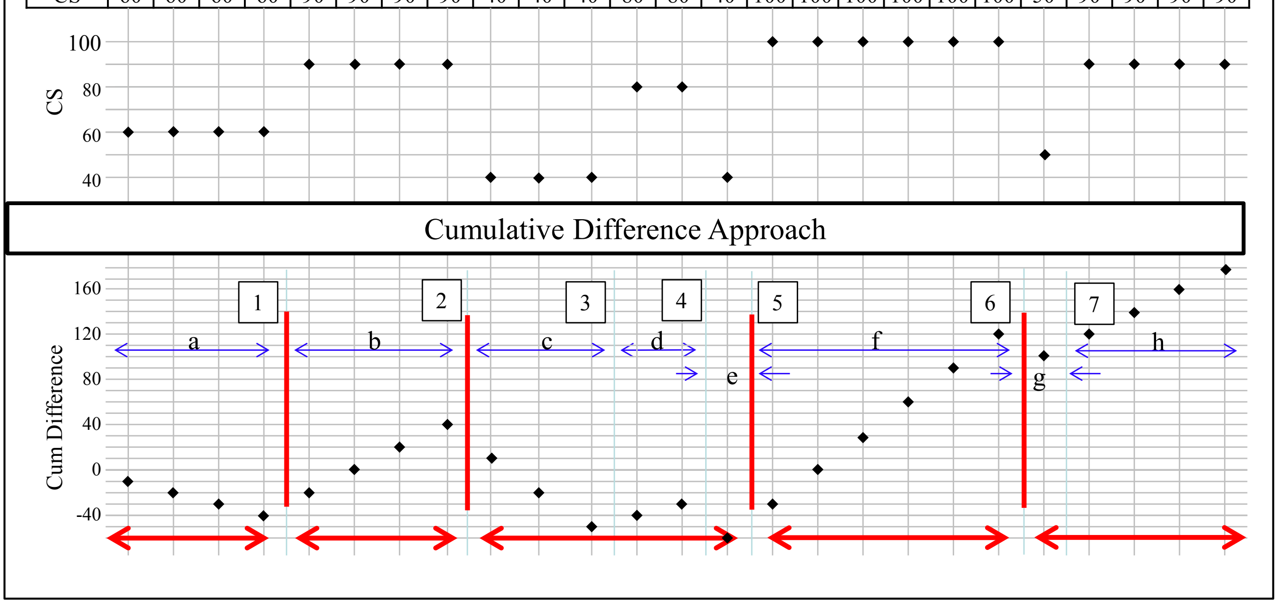


Figure 28. Example of the Cumulative Difference Approach for Forming M&R Projects.

While the CDA approach is widely used by transportation agencies, it can potentially mask local deficient areas due to the averaging effect. Thus, an alternative project formation scheme was developed in this study to overcome this potential drawback, as discussed next.

Proximity to Deficient Areas Approach for Forming M&R Projects

The PDA method was conceptualized after observing that actual M&R project boundaries in the districts PMPs are generally established around localized deficient sections. Therefore, this scheme roughly approximates this apparent practice by the districts. It uses an M&R trigger criteria (e.g., CS < 80) to identify deficient localized areas (i.e., data collection sections that fail to meet a minimum performance threshold). Realistic M&R projects are then formed around these deficient areas by grouping together nearby data collection sections. Similar to the CDA, the following conditions must be met for data collection sections to be grouped together:

- Sections must belong to the same highway (i.e., same highway ID).
- Sections must be on the same roadbed.
- Sections must be contiguous (as indicated by their RMs).
- Sections must be of the same pavement family.

In addition, this project formation scheme allows for imposing minimum and maximum lengths on the projects formed.

Figure 29 displays the same CS data that were used for demonstrating the CDA approach, but the PDA approach is used in this case instead of the CDA approach to delineate project limits. First, sections with attributes falling below the M&R trigger value (i.e., CS of 80) are flagged (see red dots). Segments *a*, *b*, *c*, and *d* are initially formed around these flagged sections. As in the CDA, notice that segments *b*, *c*, and *d* are too short to constitute realistic M&R projects while segment *a* meets the minimum project length limit. In these cases, the algorithm joins short deficient segments with other deficient segments that are less than 2 miles apart (see segments *b* and *c* being joined). When the gap between localized deficient sections is greater than 2 miles, each localized deficient section is expanded by 1 mile of roadway on both sides (see enlarged segment *d*). This approach ensures that independent M&R projects are separated by at least the minimum project length limit 2 miles in this example); the maximum project length limit is applied similar to that in the CDA. Finally, similar to the CDA approach, some segments may still remain shorter than the minimum limit due to exceptional situations (e.g., entire road is too short, an isolated short stretch of a certain pavement family).

PMIS Section	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
CS	60	60	60	60	90	90	90	90	40	40	40	80	80	40	100	100	100	100	100	100	50	90	90	90	90

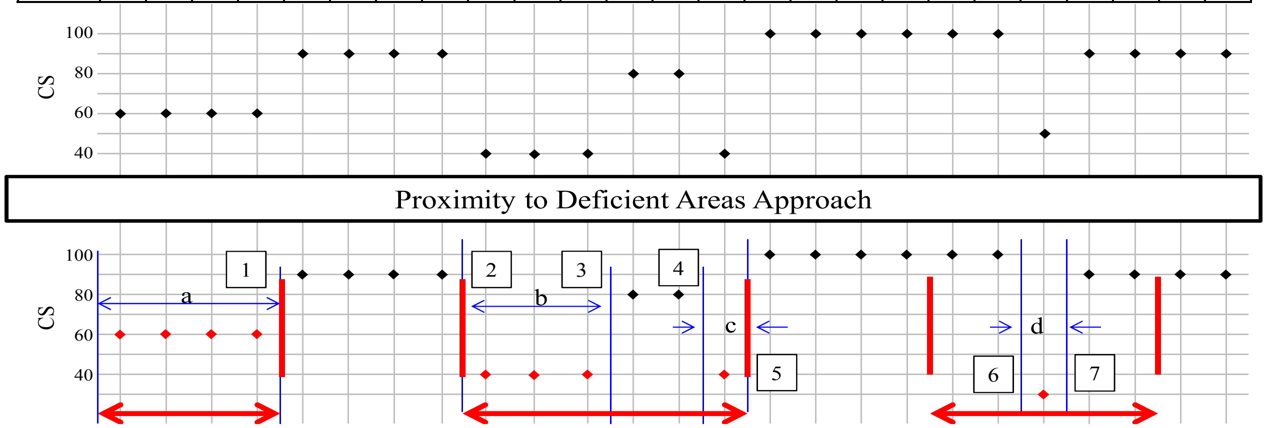


Figure 29. Example of the Proximity to Deficient Areas Approach for Forming M&R Projects.

Reconciling Segmentation Alternatives

Segmenting a roadway based on multiple attributes (i.e., CS, DS, and cumulative ESALs, pavement family, minimum project length, maximum project length) naturally results in different sets of segment boundaries. Furthermore, these sets may not coincide with each other. Consider the diagram in Figure 30 for example. It can be seen that the boundary between segment 1 and 2 coincide for all segmentation criteria. For the other segments, however, the boundaries do not coincide. Theoretically, whenever a boundary is identified from any of the above criteria, a separate segment is formed, as shown in the set labeled "Theoretical Segments." However, this method will inevitably create segments that are too short (e.g., less than 2 miles) such as segments 3, 5, 6, 7, 9, and 10 in this example. To meet the minimum length requirement, a "stitching" rule was devised, as follows:

- When the boundary from CS conflicts with that from DS or ESAL, the boundary from CS is used.
- If the conflict is between DS and ESALs, the DS boundary is used.

The results of applying this stitching rule are shown and labeled as "Final Segments" in Figure 30. In some cases, the segments formed may exceed a required maximum length (e.g., 10 miles). In these cases, the long stretches are divided equally to remain within the maximum length limit. For example, if the maximum length limit is set to 10 miles, a 14-mile segment will be divided into two 7-mile segments. Finally, even after the stitching process is applied, some segments may remain shorter than the minimum length limit (e.g., entire road is too short, an isolated short stretch of a certain pavement family).

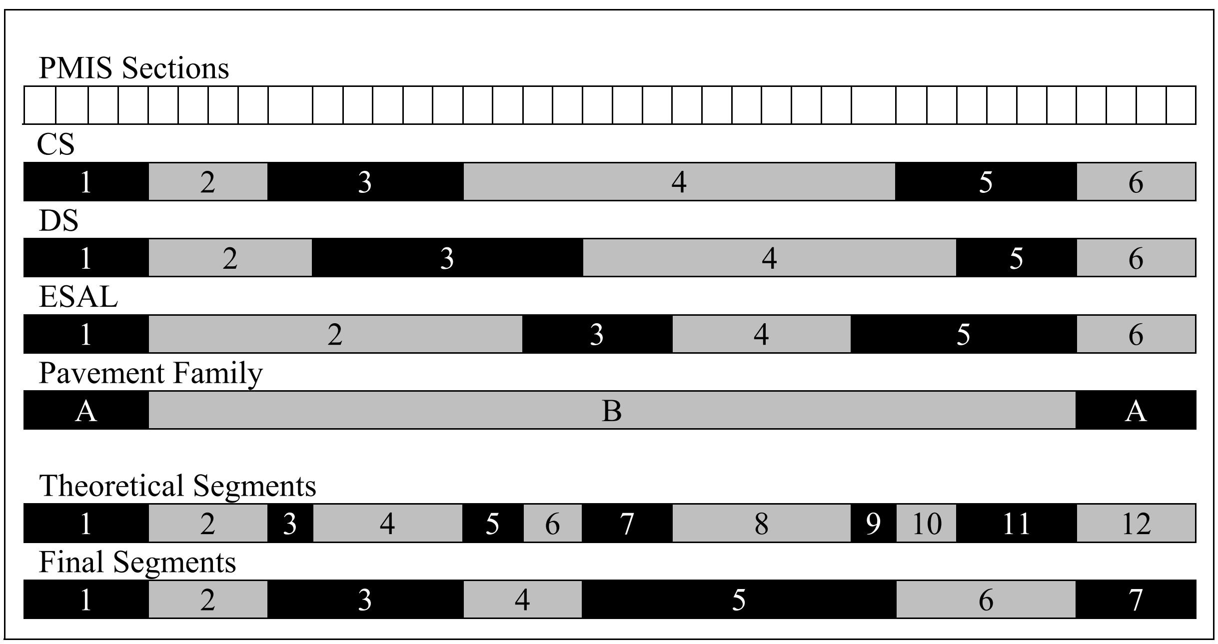


Figure 30. Example of Reconciling Segmentation Alternatives.

Aggregation of Attribute Data

To account for variability within grouped PMIS sections and to reduce the potential for masking localized failures, the attribute data (e.g., CS, DS, AADT) for the management sections are computed as follows:

$$Attribute_R = \bar{x}_w - Z_R \mathrm{sd}_w \qquad \text{Equation 4}$$

where $Attribute_R$ is the segment attribute (e.g., CS, DS, AADT) at reliability level R; $\bar{x}_w$ is the weighted (by length) average of the attribute for the segment; Z_R is the standard normal deviate corresponding to reliability level R; and sd_w is the weighted (by length) standard deviation of attribute values in the segment. The formula for weighted standard deviation, sd_w, is given by Equation 5.

$$sd_w = \sqrt{\frac{\sum_{i=1}^{N} w_i (x_i - \bar{x}_w)^2}{\frac{(N' - 1)\sum_{i=1}^{N} w_i}{N'}}} \qquad \text{Equation 5}$$

where w_i is the weight (section length in this case) for the ith observation and N' is the number of non-zero weights (Heckert and Filliben 2003).

Consider the example shown in Table 23. Assuming a CS trigger value of 80, notice that only Section 5 in this segment needs M&R. When the average CS (i.e., 50 percent reliability) is used to represent the condition of this group of sections, the segment would be deemed not requiring treatment (i.e., CS 87.4 > 80). This is an example when a localized deficiency is obscured by relatively good neighboring sections. However, if the reliability is increased to 80 percent, the segment would be triggered for M&R and will be a candidate M&R project.

Table 23. Example of Applying Reliability in Computing the Condition of a Management Section.

PMIS Section No.	Section Length (mi)	CS
1	0.5	95
2	0.5	96
3	0.5	86
4	0.5	92
5	0.5	58
6	0.5	90
7	0.5	82
8	0.5	96
9	0.5	89
10	0.5	90
Weighted Ave. CS		87.4
Weighted Std. Dev.		11.2
Group CS (50% Reliability)		87.4
Group CS (80% Reliability)		77.9

Processing of User-Defined Skid, Structural, and Visual Assessment Ratings

As discussed earlier, not all pavement condition indicators are available in the PMIS database. Specifically, data on skid assessment, structural assessment, and district visual assessment is either not available or not accessible. Therefore, an additional step was designed to allow district staff to enter binary "adequate/inadequate" ratings for these condition indicators. As discussed earlier, the PMP methodology and software tool allows the district staff to specify the beginning and ending of the road segments that have been rated for skid resistance, structural capacity, and overall visual assessment and then assigns adequate or inadequate ratings for these indicators (called SKID, STRUCT, and VISUAL, respectively).

The Beginning Reference Marker (BRM) and End Reference Marker (ERM) specified by the district staff for SKID, STRUCT, and/or VISUAL may or may not coincide with the segments created by the CDA or PDA algorithms. Thus, a simple rule was used to govern the extrapolation of these ratings to the computed segments: when a portion of a computed segment is rated, the prevailing assessment within that portion is extrapolated to the rest of the group only if that portion represents or exceeds a minimum percentage of the segment length. In this research, the default limit is set to 10 percent of segment length.

Figure 31 provides examples of extrapolating district assessment ratings. In Case 1, eight of the 20 PMIS sections in the management section (i.e., 40 percent) have been assigned inadequate rating. Since this is more than the default limit of 10 percent of the segment length, this rating is extrapolated to the rest of the management section. In Case 2, the prevailing assessment is adequate, hence the management section is rated as adequate. In Case 3, less than 10 percent of the management section has been rated. In this case, the rating is ignored and the segment rating is "Null." A null rating eliminates the effect of the performance indicator on the priority score.

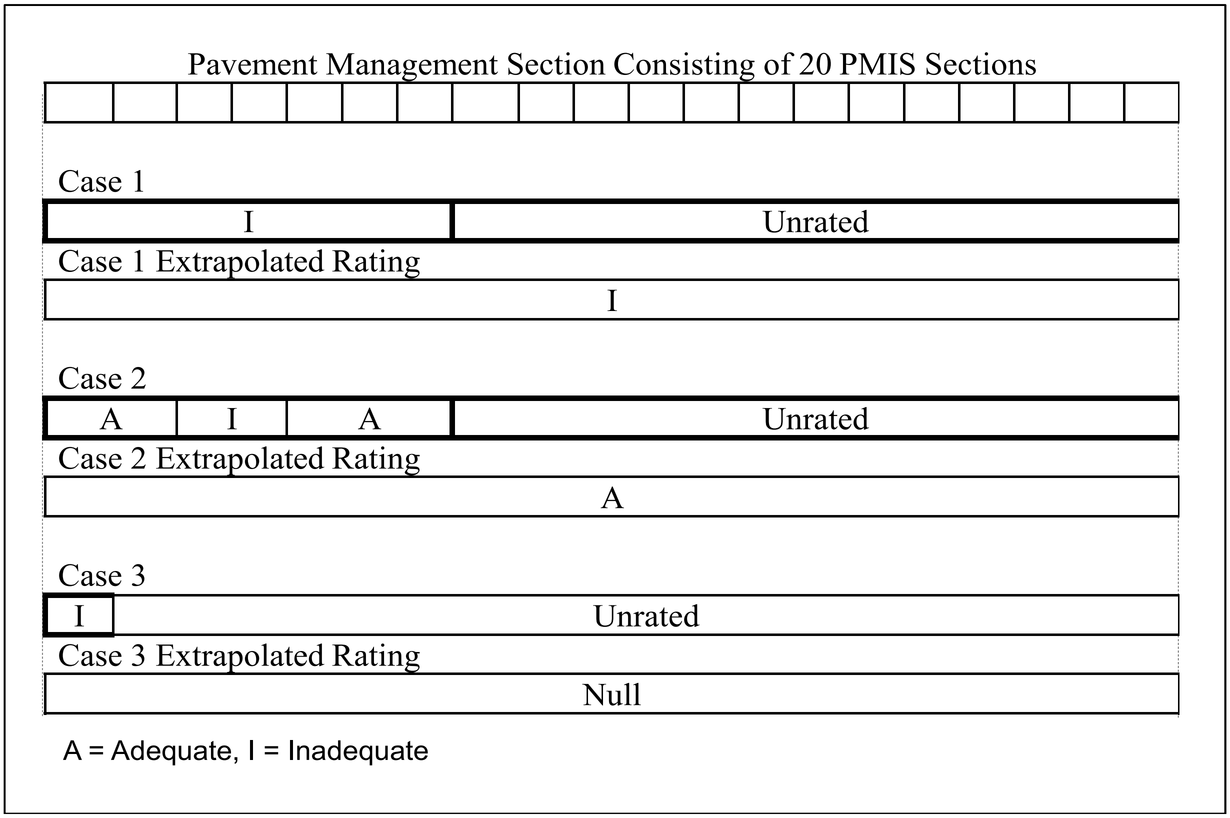


Figure 31. Extrapolation of Partial SKID, STRUCT, or VISUAL Assessments.

Forced Projects

District staff can also enter the boundaries of forced M&R projects. A forced project is defined as a roadway segment that has been assigned an M&R treatment by district staff and is automatically funded; therefore does not undergo the project prioritization process.

The procedure for reconciling the boundaries of a forced treatment with the boundaries of management sections is similar to that used for extrapolating SKID, STRUCT, and VISUAL ratings. However, in this case, the M&R type of the forced project (i.e., PM = Preventive Maintenance, LR = Light Rehabilitation, MR = Medium Rehabilitation, HR = Heavy Rehabilitation) is specified instead of specifying adequate or inadequate. Figure 32 shows three examples of extrapolated forced M&R projects.

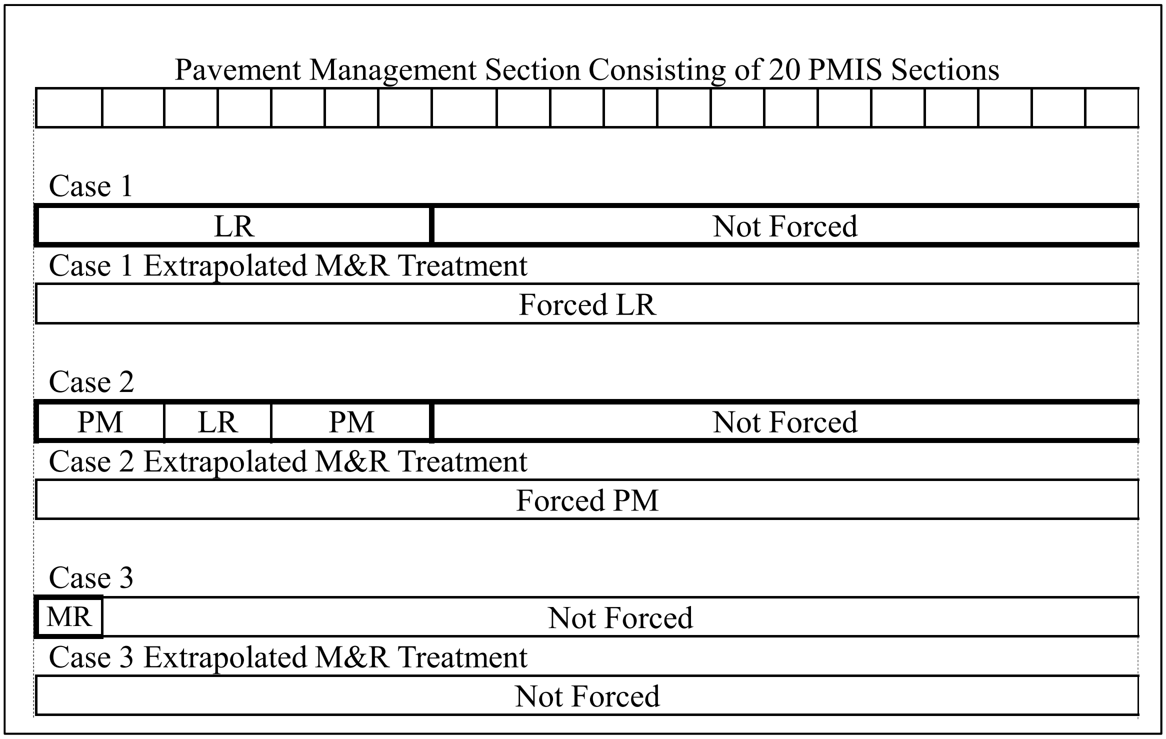


Figure 32. Extrapolation of Forced M&R Treatments.

PREDICTION OF PAVEMENT PERFORMANCE

Performance prediction models are essential for multi-year planning and programming of pavement M&R activities. Models for predicting DS, CS, and RS were derived from distress prediction models that have been recently calibrated by TxDOT under Project 0-6386 (Gharaibeh et al. 2012). The other performance indicators considered in the PMP methodology (i.e., CSRD, SKID, STRUCT, and VISUAL) are used to prioritize projects for the current year only since no models are available for projecting these indicators into the future. Thus, their future values are set to “NULL”; indicating that they are not used for prioritizing M&R projects beyond the first year of the PMP plan.

Equation 6 to Equation 8 are used for computing DS and CS. These equations were developed for Texas in the 1990s (Stampley et al. 1995).

$$U_i = \begin{cases} 1.0 & \text{when } L_i = 0 \\ 1 - \alpha e^{-\left(\frac{\rho}{L_i}\right)^{\beta}} & \text{when } L_i > 0 \end{cases}$$ Equation 6

$$DS = 100 \times \prod_{i=1}^{n} U_i$$ Equation 7

$$CS = U_{Ride} \times DS$$ Equation 8

L_i is the density of individual distress types in the pavement section. It is expressed as quantity of distress per mile, quantity of distress per section area, quantity of distress per 100-ft, etc., depending on the distress type. For asphalt pavements, for example, eight distress types are considered—shallow rutting, deep rutting, failures, block cracking, alligator cracking, longitudinal cracking, transverse cracking, and patching. Ride L_i represents the percent of ride quality lost over time. U_i is a utility value (ranging between zero and 1.0) and represents the quality of a pavement in terms of overall usefulness (e.g., a U_i of 1.0 indicates that distress type i is not present and thus is most useful). Coefficients α (maximum loss factor), β (slope factor), and ρ (prolongation factor) control the shape of the utility curve, including maximum drop, inflection point, and the slope of the curve at that point. As discussed earlier, *DS* is the distress score, which is a composite index that combines multiple U_i*s*. DS has a 1–100 scale (with 100 representing no or minimal distress). *CS* is the condition score, which is a broad composite index that combines DS and ride quality. CS has a 1–100 scale (with 100 representing no or minimal distress and roughness).

To derive models for predicting DS, CS, and RS, TxDOT's most updated performance prediction models were used. These models were calibrated in TxDOT Project 0-6386 based on actual field performance data (Gharaibeh et al. 2012). They predict the densities of individual distress types and loss of ride quality over time (i.e., pavement age) using a sigmoidal curve (S-curve) and are expressed as shown in Equation 9 below:

$$L_i = \begin{cases} 0 & when\ Age = 0 \\ \alpha_i e^{-\left(\frac{A_i}{Age}\right)^{\beta_i}} & when\ Age > 0 \end{cases} \qquad \text{Equation 9}$$

In Equation 9, *Age* is the number of years since last construction or M&R treatment applied to the pavement. α_i is the maximum loss factor that controls the maximum L_i. β_i is the slope factor that controls how steeply L_i increases in the middle of the curve. A_i is the prolongation factor that controls the location of the L_i curve's inflection point. The values of these model factors are documented in Project 0-6386 final report for different combinations of traffic, climate, and subgrade conditions. Figure 33 illustrates the general shape of this curve.

To derive prediction models for DS and CS, the L_i vs. age models were converted to U_i vs. age models through the L_i vs. U_i equation (see Equation 6). Each considered distress has its own U_i vs. age curve. Since DS at any given time is simply the product of 100 and the utility values of all distresses present (see Equation 7), then a DS vs. age curve was derived from the individual utility curves as shown in Figure 34. Finally, a CS vs. age curve was derived by combining the DS curve with the utility curve for ride quality (according to Equation 8) as shown in Figure 35.

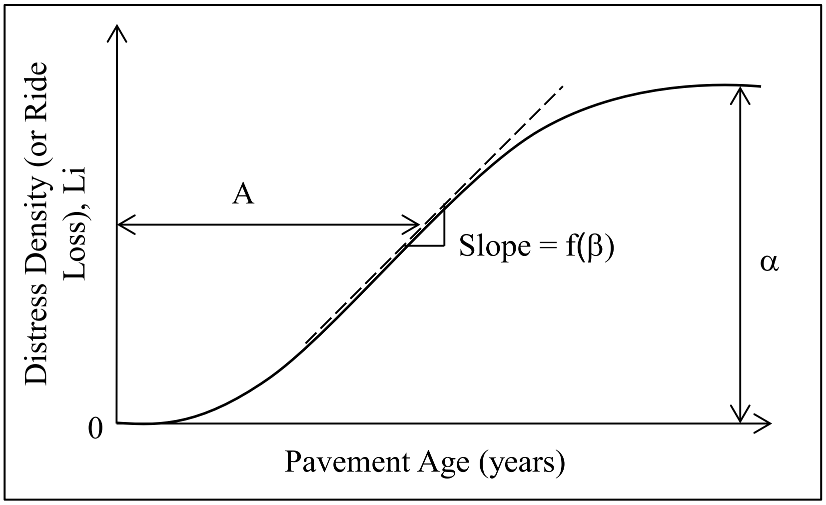


Figure 33. Typical L_i Prediction Curve.

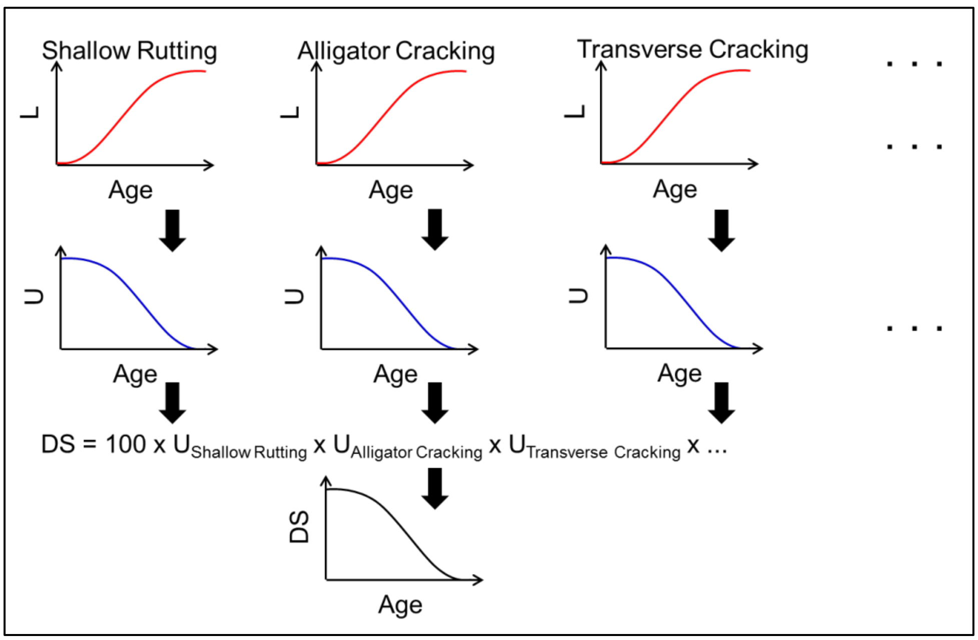


Figure 34. Derivation of DS Prediction Models.

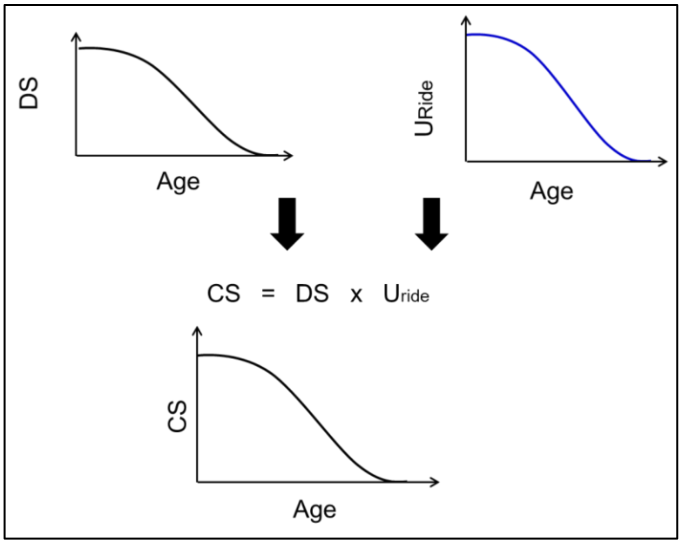


Figure 35. Derivation of CS Prediction Models.

The DS vs. age and CS vs. age curves take the form of a sigmoidal curve and are mathematically expressed in Equation 10 and Equation 11, respectively. In these equations, DS_0 and CS_0 are the DS and CS immediately after construction/maintenance respectively; *Age* is the number of years since last construction/maintenance; β is the slope factor; and ρ is the prolongation factor.

$$DS = DS_0\left[1 - e^{-\left(\frac{\rho}{AGE}\right)^{\beta}}\right]$$

Equation 10

$$CS = CS_0\left[1 - e^{-\left(\frac{\rho}{AGE}\right)^{\beta}}\right]$$

Equation 11

The β and ρ were derived for different combinations of climate-subgrade zone, pavement family, ESAL class, traffic class (AADT × Speed), and M&R type. These groups are summarized next and are discussed in great detail in the final report of TxDOT Project 0-6386.

The four climate-subgrade zones that represent different combinations of subgrade and climate in terms of its effect on pavement performance were formed, as follows:

- Zone 1: This zone represents wet-cold climate, and poor, very poor, or mixed subgrade.
- Zone 2: This zone represents wet-warm climate, and poor, very poor, or mixed subgrade.
- Zone 3: This zone represents dry-cold climate, and good, very good, or mixed subgrade.
- Zone 4: This zone represents dry-warm climate, and good, very good, or mixed subgrade.

These zones are depicted in the color-coded map shown in Figure 36. Counties with mixed climate, and poor or very poor subgrade are assigned to Zone 2. Counties with mixed climate, and good or very good subgrade are assigned to Zone 3. Counties with mixed climate and mixed subgrade are assigned to Zone 2. Only four counties are in this mixed category.

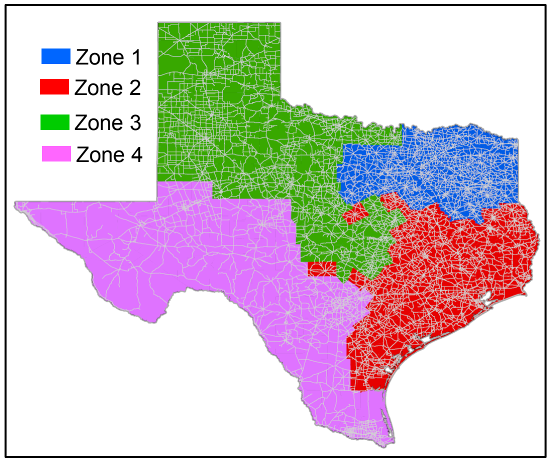


Figure 36. Map of Climate-Subgrade Zones.

The ACP families are as follows:

- Pavement Family A: This pavement family includes thick ACP (PMIS Pavement Type 4), Intermediate ACP (PMIS Pavement Type 5), and overlaid ACP (PMIS Pavement Type 9).
- Pavement Family B: This pavement family includes composite pavement (PMIS Pavement Type 7) and concrete pavement overlaid with ACP (PMIS Pavement Type 8).
- Pavement Family C: This pavement family includes thin ACP (PMIS Pavement Type 6) and thin-surfaced ACP (PMIS Pavement Type 10).

The traffic loading division includes three levels, as follows:

- Low Traffic Loading: This level includes pavement sections that have a 20-year projected cumulative Equivalent Single Axle Load (ESAL) of less than 1.0 million ESALs.
- Medium Traffic Loading: This level includes pavement sections that have a 20-year projected cumulative ESAL greater than or equal to 1.0 million ESALs and less than 10 million ESALs.
- Heavy Traffic Loading: This level includes pavement sections that have a 20-year projected cumulative ESAL greater than or equal to 10 million ESALs.

The traffic class division includes three levels, as follows:

- Low ADT × Speed Limits: 1–27,500.
- Medium ADT × Speed Limits: 27,501–165,000.
- High ADT × Speed Limits: >165,000.

Figure 37 and Figure 38 show the different combinations for which DS and CS models were developed. The DS prediction models for Pavement A, Zone 2, and medium traffic loading are shown in Figure 39, as an example. The CS prediction models for Pavement A, Zone 2, low traffic loading, and low ADT × Speed Limit are shown in Figure 40, as an example.

The β and ρ values for different combinations of climate-subgrade zone, ACP pavement family, ESAL class, traffic class (AADT × Speed), and M&R type are shown in Table 24 through and Table 27 for DS, and in Table 28 through Table 32 for CS. Table 32 and Table 33 present the model coefficients for JCP. These models were tested for an upper-limit prediction period of 15 year and thus should not be extrapolated beyond that prediction period without further testing. No model coefficients are provided for CRCP due to lack of data. Also, the RS prediction models were not calibrated in Project 0-6386; thus the original U_{Ride} prediction models (Stampley et al. 1995) were used instead for deriving the CS prediction models. Cases marked as "NA" indicate that no model coefficients were derived due to lack of data.

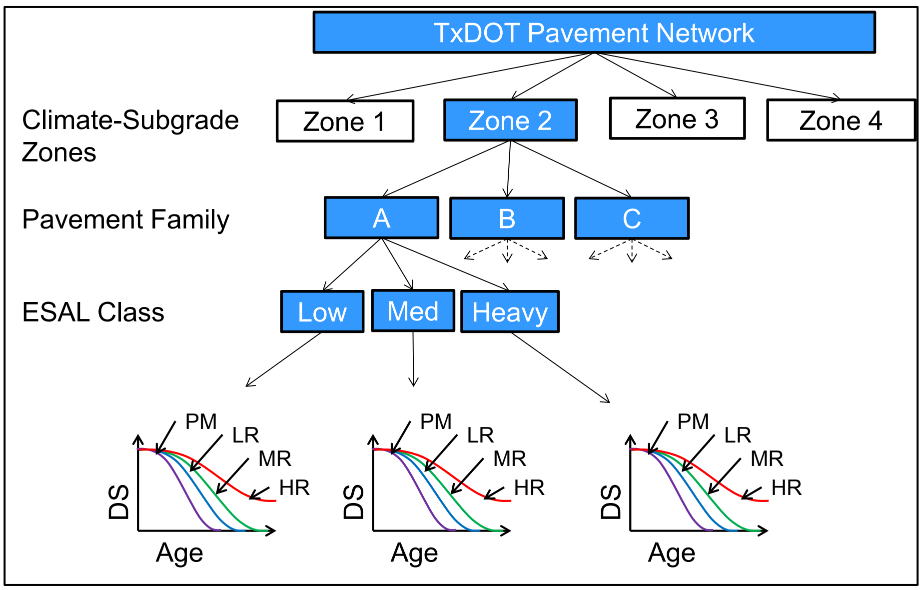


Figure 37. Combinations of Climate-Subgrade Zone, Pavement Family, ESAL Class, M&R Treatment Type for DS Prediction Model.

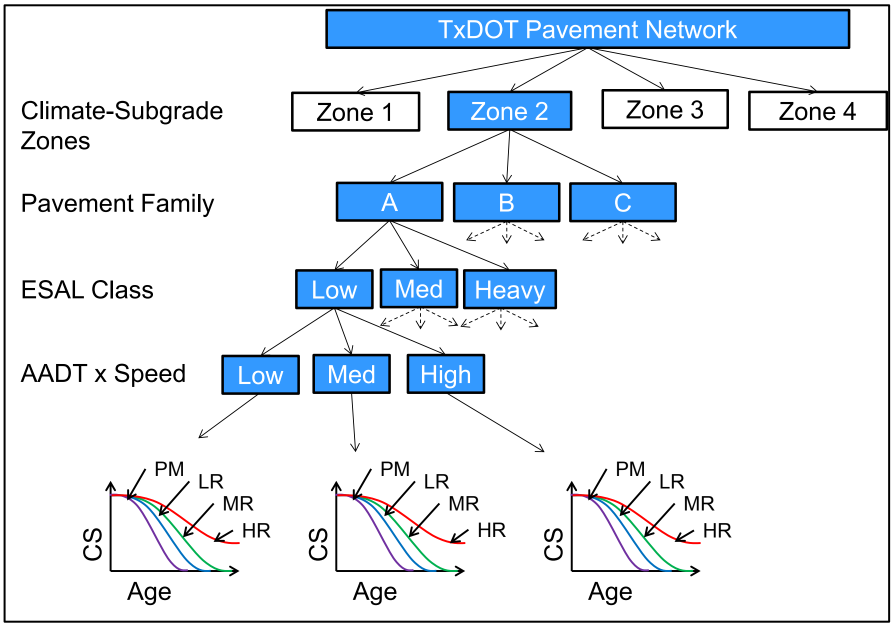


Figure 38. Combinations of Climate-Subgrade Zone, Pavement Family, ESAL Class, Traffic Class, and M&R Treatment Type for CS Prediction Model.

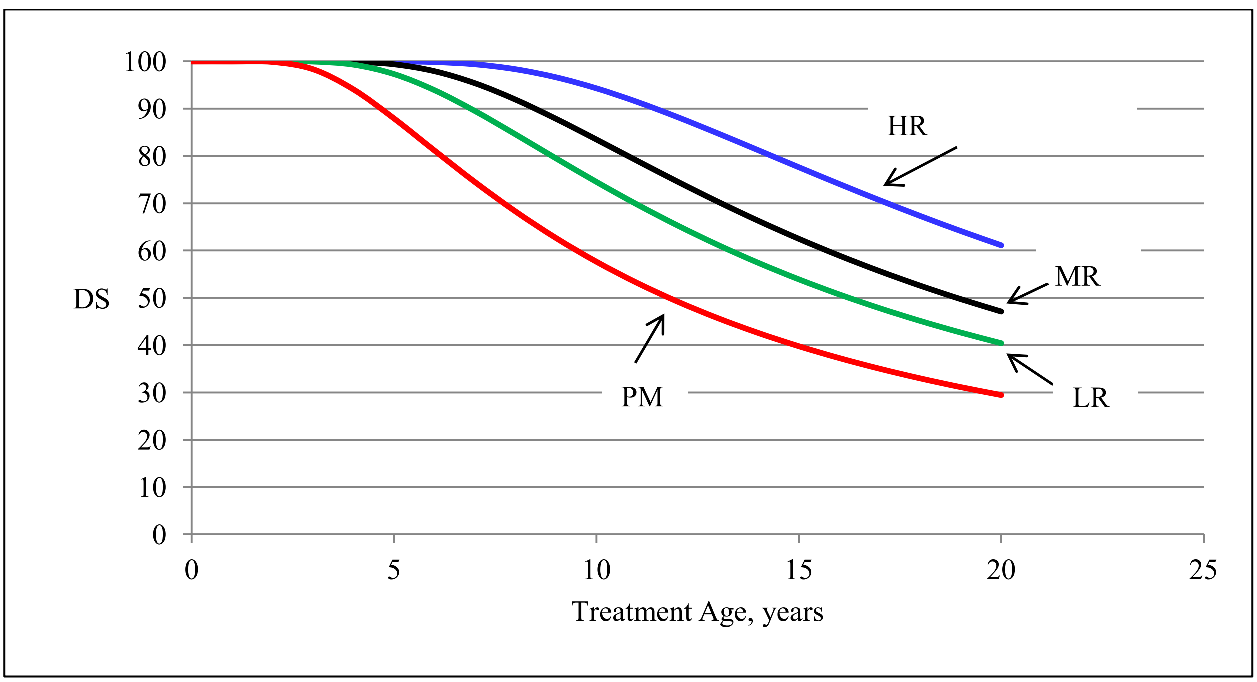


Figure 39. Example DS Prediction Models (Pavement A, Zone 2, and Medium Traffic Loading).

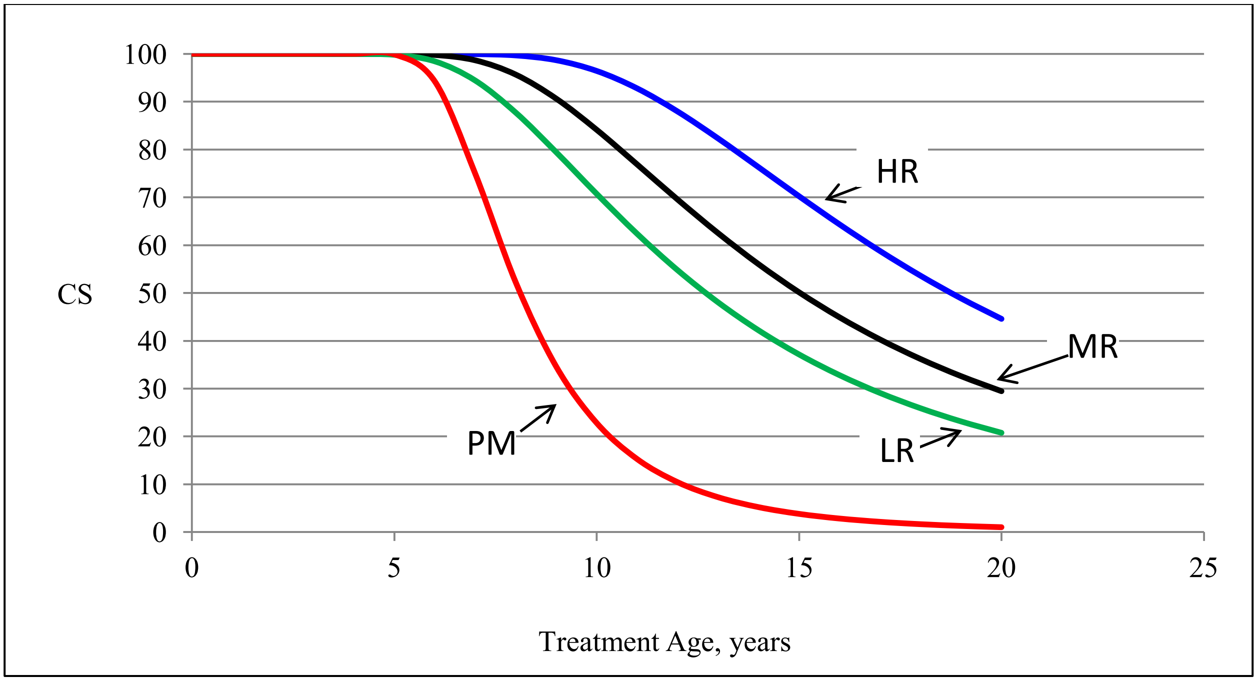


Figure 40. Example CS Prediction Models (Pavement A, Zone 2, Low Traffic Loading, and Low ADT x Speed Limit).

Table 24. ρ and β Coefficients for ACP DS Prediction Models (Climate-Subgrade Zone 1).

Pavement Family — ESAL Class	PM		LR		MR		HR	
	ρ	β	ρ	β	ρ	β	ρ	β
A-Low	11.4	2.1	13.2	2.3	16.6	2.6	19.2	2.6
A-Med	11.1	2.9	12.7	2.8	14.2	2.7	15.7	2.7
A-High	6.9	4.7	7.8	5.8	8.3	5.3	8.5	5
B-Low	9.3	1.2	11.9	1.1	14.6	1.1	16.2	1.2
B-Med	19.3	1.5	25.2	1.3	30.4	1.3	33.7	1.5
B-High	7.2	1.5	8.1	1.6	9.2	1.7	10.2	1.9
C-Low	11.2	1.3	14.8	1.4	19.5	1.2	25.3	1.1
C-Med*	11.2	1.3	14.8	1.4	19.5	1.2	25.3	1.1
C-High*	11.2	1.3	14.8	1.4	19.5	1.2	25.3	1.1

*C-Low Coefficients are used for C-Med and C-High due to lack of data for these groups.

Table 25. ρ and β Coefficients for ACP DS Prediction Models (Climate-Subgrade Zone 2).

Pavement Family — ESAL Class	PM		LR		MR		HR	
	ρ	β	ρ	β	ρ	β	ρ	β
A-Low	9.3	2.3	11	2.3	12.9	2.4	16.1	2.6
A-Med	8.9	1.3	12.5	1.4	14.8	1.5	19.3	1.6
A-High	10.5	1.5	12.5	1.3	14.9	1.1	16.5	1.2
B-Low	9	3	10.2	3.3	12.1	4	14.4	4.6
B-Med	11.9	2.4	13.4	2.3	14.4	2.3	15.4	2.4
B-High*	11.9	2.4	13.4	2.3	14.4	2.3	15.4	2.4
C-Low	14.1	2.1	17	2.4	21.4	2.6	25.2	2.3
C-Med	11.4	1.2	17.4	1.3	21.7	1.5	29.3	1.5
C-High*	11.4	1.2	17.4	1.3	21.7	1.5	29.3	1.5

*B-Med and C-Med Coefficients are used for B-High and C-High due to lack of data for these groups.

Table 26. ρ and β Coefficients for ACP DS Prediction Models (Climate-Subgrade Zone 3).

Pavement Family — ESAL Class	PM		LR		MR		HR	
	ρ	β	ρ	β	ρ	β	ρ	β
A-Low	11.7	2.2	15.5	2.6	19.5	2.6	23.8	2
A-Med	13	1.8	15.5	1.9	18.9	2.1	24.2	2.6
A-High	11.2	3.6	12	3.7	13.4	4	15.8	4.6
B-Low	9.1	1.2	10.2	1.3	11.9	1.6	12.6	1.6
B-Med	21.7	1.5	33.6	1.1	55.2	0.8	61	0.9
B-High	18.3	1.8	16.1	1.6	23.1	1.9	25.6	2.1
C-Low	16	2	21	2.3	29.3	2.2	40.2	1.9
C-Med	9.3	1.9	11.4	1.8	13.7	1.8	15.7	1.8
C-High*	9.3	1.9	11.4	1.8	13.7	1.8	15.7	1.8

*C-Med Coefficients are used for C-High due to lack of data for this group.

Table 27. ρ and β Coefficients for ACP DS Prediction Models (Climate-Subgrade Zone 4).

Pavement Family — ESAL Class	PM		LR		MR		HR	
	ρ	β	ρ	β	ρ	β	ρ	β
A-Low	9.3	1.5	11.4	1.4	14.9	1.4	20.3	1
A-Med	8.4	1.7	10	1.8	11.7	1.9	13.3	2.1
A-High	10.4	1.5	11.7	1.5	12.5	1.3	14	1.2
B-Low	16.2	1.1	23.2	0.9	31.3	0.9	37.8	1
B-Med	9.7	1.7	11.4	1.8	13.5	1.7	16.5	1.7
B-High*	9.7	1.7	11.4	1.8	13.5	1.7	16.5	1.7
C-Low	11	1.7	13.9	1.9	19.2	3.1	27.9	2.3
C-Med	3.2	1.1	5.9	0.9	8.4	0.9	11	1
C-High*	3.2	1.1	5.9	0.9	8.4	0.9	11	1

*B-Med and C-Med Coefficients are used for B-High and C-High due to lack of data for these groups.

Table 28. ρ and β Coefficients for ACP CS Prediction Models (Climate-Subgrade Zone 1).

Pavement Family — ESAL Class — Traffic Class	PM		LR		MR		HR	
	ρ	β	ρ	β	ρ	β	ρ	β
A-Low-Low	8.7	2.6	11.2	2.6	19.8	1.7	22.4	1.7
A-Low-Med	7.5	4	9.8	5.9	19.6	1.7	22.4	1.7
A-Low-High	7.2	4.5	9.5	7	19.4	1.8	22.4	1.7
A-Med-Low	9.4	3.5	10.2	4.1	13.4	3.4	15.3	3.2
A-Med-Med	NA	NA	9.2	5.3	12.6	4.4	15.3	3.2
A-Med-High	8.1	4.9	8.8	5.6	12.2	5	15.3	3.2
A-High-Low	NA	NA	NA	NA	NA	NA	NA	NA
A-High-Med	NA	NA	NA	NA	NA	NA	NA	NA
A-High-High	NA	NA	NA	NA	NA	NA	NA	NA
B-Low-Low	6.9	3.3	8.8	2.6	13.3	1.4	15.2	1.4
B-Low-Med	6.6	6.8	8.3	4.7	13.3	1.4	15.2	1.4
B-Low-High	6.5	7.8	8.2	5.8	13.3	1.4	NA	NA
B-Med-Low	9.4	3.9	16.7	2.1	NA	NA	30.7	1.7
B-Med-Med	8.2	6.5	12.2	4.3	NA	NA	30.7	1.7
B-Med-High	7.9	7.3	11.3	5.9	NA	NA	31.2	1.7
B-High-Low	6.2	3.5	6.9	4.4	7.7	4.8	8.4	4.5
B-High-Med	NA	NA	NA	NA	NA	NA	NA	NA
B-High-High	NA	NA	NA	NA	NA	NA	NA	NA
C-Low-Low	8.5	2	17	1	21.1	1	24.5	1.2
C-Low-Med	7.5	3.3	16.3	1.1	21.1	1	24.5	1.2
C-Low-High	7.2	3.8	NA	NA	21.1	1	24.5	1.2
C-Med-Low*	8.5	2	17	1	21.1	1	24.5	1.2
C-Med-Med*	7.5	3.3	16.3	1.1	21.1	1	24.5	1.2
C-Med-High*	7.2	3.8	NA	NA	21.1	1	24.5	1.2
C-High-Low*	8.5	2	17	1	21.1	1	24.5	1.2
C-High-Med*	7.5	3.3	16.3	1.1	21.1	1	24.5	1.2
C-High-High*	7.2	3.8	NA	NA	21.1	1	24.5	1.2

* C-Low Coefficients are used for C-Med and C-High due to lack of data for these groups.

Table 29. ρ and β Coefficients for ACP CS Prediction Models (Climate-Subgrade Zone 2).

Pavement Family — ESAL Class — Traffic Class	PM		LR		MR		HR	
	ρ	β	ρ	β	ρ	β	ρ	β
A-Low-Low	7.5	4.7	10.9	2.4	12.9	2.4	16.2	2.5
A-Low-Med	7	9.3	10.8	2.5	12.9	2.4	16.2	2.5
A-Low-High	6.9	10.7	10.6	2.7	12.9	2.4	16.2	2.5
A-Med-Low	6.1	4.4	NA	NA	11.5	3.4	NA	NA
A-Med-Med	NA	NA	NA	NA	NA	NA	NA	NA
A-Med-High	NA	NA	NA	NA	NA	NA	NA	NA
A-High-Low	6.5	5.4	8.3	8.3	10	6.8	14.8	1.6
A-High-Med	NA	NA	NA	NA	NA	NA	14.8	1.6
A-High-High	NA	NA	NA	NA	NA	NA	14.8	1.6
B-Low-Low	NA	NA	NA	NA	NA	NA	NA	NA
B-Low-Med	NA	NA	NA	NA	NA	NA	NA	NA
B-Low-High	NA	NA	NA	NA	NA	NA	NA	NA
B-Med-Low	8.2	5.3	14.2	2.1	14.4	2.3	15.2	2.6
B-Med-Med	7.5	11.9	14.1	2.1	14.4	2.3	15.2	2.6
B-Med-High	7.3	13.5	14	2.1	14.4	2.3	15.2	2.6
B-High-Low*	8.2	5.3	14.2	2.1	14.4	2.3	15.2	2.6
B-High-Med*	7.5	11.9	14.1	2.1	14.4	2.3	15.2	2.6
B-High-High*	7.3	13.5	14	2.1	14.4	2.3	15.2	2.6
C-Low-Low	7.1	4	8.4	5.3	11	6.8	13.1	7.2
C-Low-Med	NA	NA	NA	NA	NA	NA	NA	NA
C-Low-High	NA	NA	NA	NA	NA	NA	NA	NA
C-Med-Low	6.1	3.4	9	6.8	11.5	9.4	27.2	1.7
C-Med-Med	NA	NA	NA	NA	NA	NA	NA	NA
C-Med-High	NA	NA	NA	NA	NA	NA	NA	NA
C-High-Low*	6.1	3.4	9	6.8	11.5	9.4	27.2	1.7
C-High-Med*	NA	NA	NA	NA	NA	NA	NA	NA
C-High-High*	NA	NA	NA	NA	NA	NA	NA	NA

*B-Med and C-Med Coefficients are used for B-High and C-High due to lack of data for these groups.

Table 30. ρ and β Coefficients for ACP CS Prediction Models (Climate-Subgrade Zone 3).

Pavement Family — ESAL Class — Traffic Class	PM		LR		MR		HR	
	ρ	β	ρ	β	ρ	β	ρ	β
A-Low-Low	8.8	4.1	13.2	3.3	20	2.4	22.9	2.2
A-Low-Med	8	6.7	11.4	5.3	20.1	2.4	22.9	2.2
A-Low-High	7.8	7.6	10.9	6.8	20	2.4	22.9	2.2
A-Med-Low	8.2	6.5	9.7	13.2	18.5	2.2	NA	NA
A-Med-Med	7.9	29.2	NA	NA	18.4	2.2	NA	NA
A-Med-High	7.9	61.1	NA	NA	18.2	2.3	NA	NA
A-High-Low	9.5	3.4	12.3	2.4	18	1.7	NA	NA
A-High-Med	8.5	5.5	10.6	4.4	16.7	1.9	NA	NA
A-High-High	8.3	6.1	10.2	5.4	15.4	2.3	NA	NA
B-Low-Low	6.4	5.4	7.8	6.8	9.4	7.3	11.4	2.9
B-Low-Med	6.2	26.6	NA	NA	NA	NA	11.2	3.8
B-Low-High	6.1	78	7.5	12	NA	NA	11.2	3.9
B-Med-Low	9.4	4.1	19.7	1.6	11.9	7.9	60.2	0.9
B-Med-Med	8.3	7.1	12.1	4.5	NA	NA	60.3	0.9
B-Med-High	8.1	8.1	11.1	6.3	NA	NA	60.8	0.9
B-High-Low	10.6	2.5	10.3	3.5	24.6	1.7	23.4	2.5
B-High-Med	8.7	3.5	9	4.4	21.5	2	23.4	2.5
B-High-High	8.1	3.8	8.6	4.7	18.6	2.6	23.4	2.5
C-Low-Low	10.2	3.5	14.8	4	19.2	3.8	22.9	4.3
C-Low-Med	8.8	4.7	NA	NA	13.8	12.5	16.7	17.3
C-Low-High	8.4	5.1	NA	NA	13.5	15	16.4	20.5
C-Med-Low	7.9	3	12.9	1.1	16	1.1	17.8	1.2
C-Med-Med	NA	NA	12.7	1.1	16	1.1	17.8	1.2
C-Med-High	NA	NA	12.5	1.2	16	1.1	17.8	1.2
C-High-Low*	7.9	3	12.9	1.1	16	1.1	17.8	1.2
C-High-Med*	NA	NA	12.7	1.1	16	1.1	17.8	1.2
C-High-High*	NA	NA	12.5	1.2	16	1.1	17.8	1.2

*C-Med Coefficients are used for C-High due to lack of data for this group.

Table 31. ρ and β Coefficients for ACP CS Prediction Models (Climate-Subgrade Zone 4).

Pavement Family — ESAL Class — Traffic Class	PM		LR		MR		HR	
	ρ	β	ρ	β	ρ	β	ρ	β
A-Low-Low	6.3	3.5	10.1	1.3	17.5	0.9	26	0.7
A-Low-Med	6.2	13.3	8.8	3.1	15.1	1.1	26	0.7
A-Low-High	6.2	15.8	9.2	15.4	13.9	1.3	26	0.7
A-Med-Low	6.2	4.4	7.4	6.2	9.4	6.9	12.1	5.4
A-Med-Med	NA	NA	NA	NA	NA	NA	12.1	10.9
A-Med-High	NA	NA	NA	NA	NA	NA	12.1	12.1
A-High-Low	7.6	6.7	9.1	5.8	9.7	5.6	10.8	4.1
A-High-Med	NA	NA	NA	NA	NA	NA	11.1	9
A-High-High	NA	NA	NA	NA	NA	NA	11.1	9
B-Low-Low	6	3.2	8.8	7.1	31.6	0.9	41.5	0.9
B-Low-Med	NA	NA	NA	NA	NA	NA	NA	NA
B-Low-High	NA	NA	NA	NA	NA	NA	NA	NA
B-Med-Low	8.2	2.1	10	1.9	14.8	1.3	17.3	1.5
B-Med-Med	7.6	4	8.9	3.4	14.7	1.3	17.3	1.5
B-Med-High	7.5	4.8	8.7	4.4	14.5	1.3	17.3	1.5
B-High-Low*	8.2	2.1	10	1.9	14.8	1.3	17.3	1.5
B-High-Med*	7.6	4	8.9	3.4	14.7	1.3	17.3	1.5
B-High-High*	7.5	4.8	8.7	4.4	14.5	1.3	17.3	1.5
C-Low-Low	7	4.6	9.5	12.1	11.3	11.8	19.6	5.3
C-Low-Med	NA	NA	NA	NA	NA	NA	NA	NA
C-Low-High	NA	NA	NA	NA	NA	NA	NA	NA
C-Med-Low	3.2	1.6	5.6	1	8.1	1	10.9	1.1
C-Med-Med	3.2	2	5.5	1.1	8	1	10.9	1.1
C-Med-High	3.2	2.1	5.5	1.2	7.9	1.1	10.9	1.1
C-High-Low*	3.2	1.6	5.6	1	8.1	1	10.9	1.1
C-High-Med*	3.2	2	5.5	1.1	8	1	10.9	1.1
C-High-High*	3.2	2.1	5.5	1.2	7.9	1.1	10.9	1.1

*B-Med and C-Med Coefficients are used for B-High and C-High due to lack of data for these groups.

Table 32. ρ and β Coefficients for DS Prediction Models for JCP.

Climate-Subgrade Zone	ESAL Class	PM		LR		HR	
		ρ	β	ρ	β	ρ	β
1	Low	4.1	0.7	26.5	0.7	NA	NA
1	Medium	1.7	0.9	23.6	0.6	NA	NA
1	High	1.6	0.9	20.5	0.6	NA	NA
2	Low	6.9	0.9	30.6	0.6	NA	NA
2	Medium	5.5	0.9	NA	NA	NA	NA
2	High	3.8	0.9	22.1	0.6	NA	NA
3	Low	9.3	0.8	18.2	0.8	NA	NA
3	Medium	8.4	0.8	NA	NA	NA	NA
3	High	6.3	0.8	14.9	0.7	NA	NA
4	Low	9.3	0.8	18.2	0.8	NA	NA
4	Medium	8.4	0.8	NA	NA	NA	NA
4	High	6.3	0.8	14.9	0.7	NA	NA

*No MR because JCP with HMA overlay is considered in the ACP families.

Table 33. ρ and β Coefficients for CS Prediction Models for JCP.

Climate-Subgrade Zone	ESAL Class	PM		LR		HR	
		ρ	β	ρ	β	ρ	β
1	Low	4.1	0.7	26.5	0.7	NA	NA
1	Medium	1.7	0.9	23.6	0.6	NA	NA
1	High	1.6	0.9	20.5	0.6	NA	NA
2	Low	6.9	0.9	30.6	0.6	NA	NA
2	Medium	5.5	0.9	NA	NA	NA	NA
2	High	3.8	0.9	22.1	0.6	NA	NA
3	Low	9.3	0.8	18.2	0.8	NA	NA
3	Medium	8.4	0.8	NA	NA	NA	NA
3	High	6.3	0.8	14.9	0.7	NA	NA
4	Low	9.3	0.8	18.2	0.8	NA	NA
4	Medium	8.4	0.8	NA	NA	NA	NA
4	High	6.3	0.8	14.9	0.7	NA	NA

*No MR because JCP with HMA overlay is considered in the ACP families.

IDENTIFYING VIABLE M&R TREATMENT ALTERNATIVES

After the network is segmented (i.e., data collection sections are grouped into management sections), segments that need M&R are identified based on a CS or DS trigger value defined by the agency. In this study, a CS trigger value of 80 is used. That is, management sections with CS (at user-specified reliability level) less than 80 are identified as candidate M&R project and compete for available funding. Note that while TxDOT's policy goal of 90 percent of its roads to have CS values greater than or equal to 70 (threshold for good condition), the trigger value is set 10 points higher. This was done to guard against pavements that are approaching the threshold and might fall below it within a short time.

For each roadway segment that is identified as a candidate M&R project, four possible M&R treatment types are evaluated: (1) Preventive Maintenance; (2) Light Rehabilitation; (3) Medium Rehabilitation; and (4) Heavy Rehabilitation. However, depending on the project's condition, not all of the four treatment types may be viable alternatives. The immediate gains in pavement condition due to applying the four M&R types are shown in Table 34 (Texas Department of Transportation 2011).

Table 34. Immediate Effects of Treatments on Pavement Condition.

Treatment Type	Reduction in Distress Rating[1]	Gain in Ride Score
PM	Set distress L_i to zero	Increase Ride Score by 0.5[2]
LR	Set distress L_i to zero	Increase Ride Score by 1.5[2]
MR	Set distress L_i to zero	Set Ride Score to 4.8
HR	Set distress L_i to zero	Set Ride Score to 4.8

[1]L_i=0.0 and U_i = 1.0
[2]Without exceeding the maximum practical ride score value of 4.8

To compute the corresponding gain in CS, the RS is converted to L_r (percent of ride quality lost) using Equation 12 through Equation 14 (Texas Department of Transportation 2011).

For "Low" AADT × Speed Class:

$$L_r = 100 \times \left(\frac{2.5 - Ride\,Score}{2.5} \right) \quad \text{Equation 12}$$

For "Medium" AADT × Speed Class:

$$L_r = 100 \times \left(\frac{3.0 - Ride\,Score}{3.0} \right) \quad \text{Equation 13}$$

For "High" AADT × Speed Class:

$$L_r = 100 \times \left(\frac{3.5 - Ride\,Score}{3.5} \right) \quad \text{Equation 14}$$

where, where L_r is the percent of ride quality lost (compared to perfectly smooth pavement). When calculated L_r is less than or equal to zero, it is set to zero.

Once the post-treatment ride score is converted to L_r, it can then be converted to a utility value (U_{Ride}) as explained previously. Finally, the post-treatment DS and U_{Ride} are combined to determine the post-treatment CS.

To determine the viability of an M&R treatment and at the same time to guard against the potential for repetitive treatments (i.e., a recently repaired project being triggered again for M&R in the following year), the following criteria were used in the proposed PMP methodology:

- Trigger + 5 Rule: In general, a treatment is counted as a viable alternative if it is able to raise the project's average CS to at least five points above the M&R trigger value (i.e., at least 85 for a CS trigger value of 80). The five-point limit was imposed to prevent repetitive M&R work on the same roadway.
- Minimum CS Rule: While a certain treatment may be regarded as viable based on its effect on average condition, it may still be disqualified from consideration if the minimum CS of the management section (i.e., the lowest CS among the individual data collection sections within the management section) is lower than a certain value (see Figure 41). Table 35 shows the default values for this rule. These value were determined based on TxDOT CS boundary values between "Fair" and "Poor" (i.e., CS = 50) and between "Poor" and "Very Poor" (i.e., CS = 35) (Texas Department of Transportation 2011). Note that since MR and HR reset the scores to perfect condition, they would always be viable alternatives.

Table 35. M&R Treatment Viability Criteria Based on Minimum CS.

Treatment Type	Default Values for Minimum CS Rule
PM	Min. individual CS of the segment ≥ 50
LR	Min. individual CS of the segment ≥ 35
MR	No restriction
HR	No restriction

While the conditions in Table 35 guard against repetitive projects, they may, on the other hand, overprovide for parts of the management section that are in relatively good condition and consequently result in higher needs estimates due to replacing a light treatment (e.g., PM) with a heavier one (e.g., LR). Thus, the concept of "hybrid projects" is introduced. A hybrid project consists of two M&R treatment types (e.g., a PM and LR) applied to different parts of the management section according to its pavement condition. The management section in Figure 41, for example, qualifies as a hybrid PM/LR project where the LR performance prediction model is used to predict its future performance but the project's total cost is computed using the unit costs of LR and PM. Table 36 explains the possible hybrid project types.

Table 36. Possible Hybrid Project Types.

Hybrid Treatment Type	Applicable Performance Model	Scenarios when Used
PM/LR	LR	PM is viable based on average CS but unviable based on segment Min CS (35≤ Min CS<50)
PM/MR	MR	PM is viable based on average CS but unviable based on segment Min CS (Min CS<35)
LR/MR	MR	LR is viable based on average CS but unviable based on segment Min CS (Min CS<35)

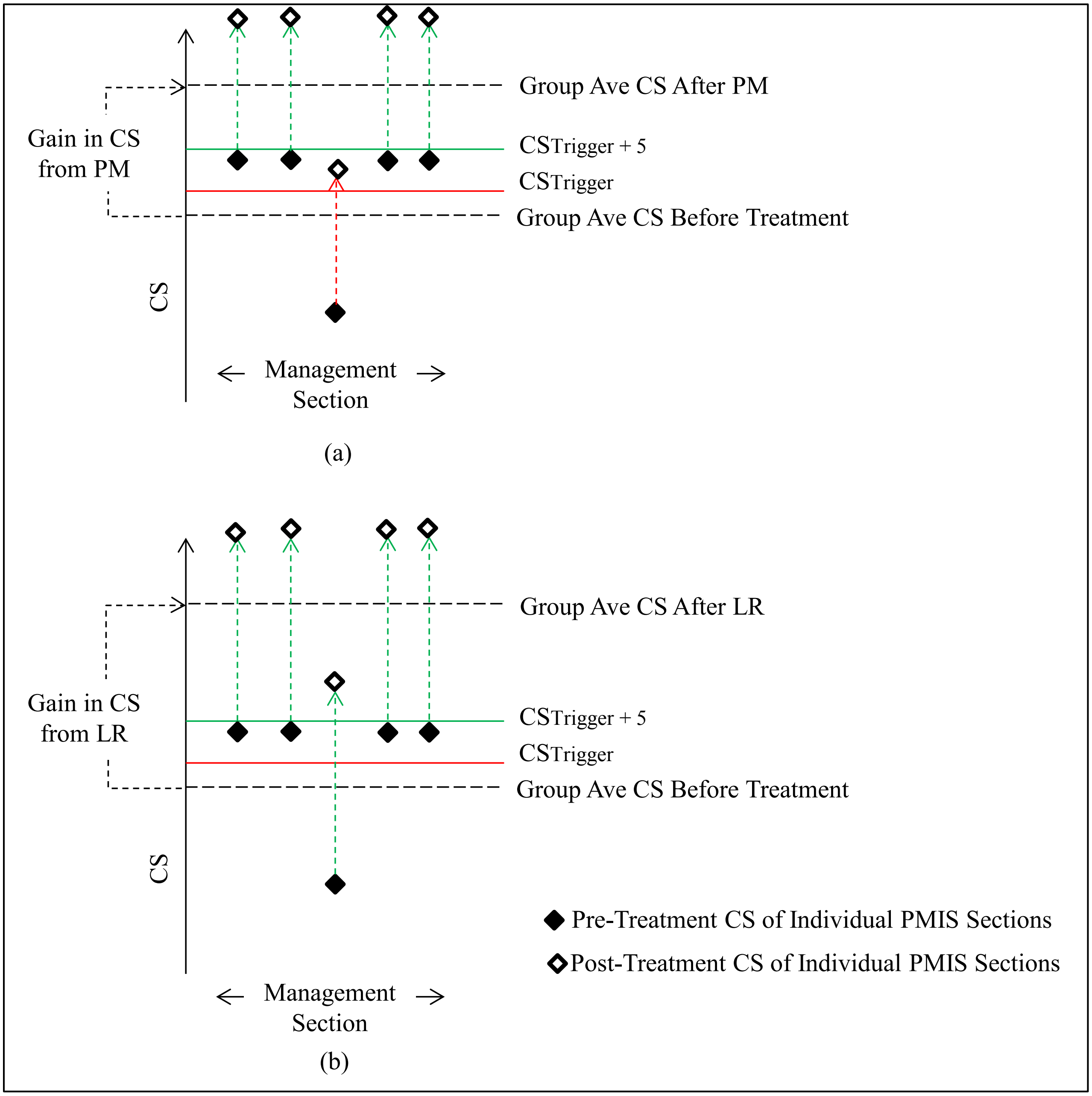


Figure 41. Illustration of the Treatment Disqualifier Criterion: a) PM Is Disqualified due to Violating the Minimum CS Rule, b) LR Replaces PM as a Viable Treatment.

MEASURING LONG-TERM PERFORMANCE BENEFIT AND LIFE-CYCLE COST

The long-term performance benefit (LTPB) and life-cycle cost (LCC) of each viable M&R alternative are computed. The LTPB for each viable M&R alternative is computed using the Area Under the Performance Curve (AUPC) method, where AUPC is defined as the area between the CS performance curve and an agency-defined threshold value (see Figure 42). This parameter quantifies the performance benefit of applying a certain M&R type by considering both the condition improvement caused by the treatment and the life of the treatment. In this research, a CS threshold value of 70 was used for AUPC computation. While the trigger value was set at CS=80 as mentioned previously, a pavement with CS of, say 75, is considered useful (i.e., with benefit). The AUPC shown in Figure 42 represents the benefit of applying a particular M&R treatment (i.e., PM, LR, MR, or HR). Thus, the total benefit is the sum of these areas throughout the analysis period (e.g., 20 years). This quantity is then divided by the number of years (n) in the analysis period (e.g., 20) and multiplied by the annual traffic ($AADT \; x \; 365$), number of lanes (N), and length of the segment (L) to account for the effect of usage and project size on benefit, as follows:

$$AnnualBenefit = (AUPC / n) \times AADT \times 365 \times N \times L \qquad \text{Equation 15}$$

The annualized benefit represents the LTPB, which is used as one of the decision factors that influence the prioritization of projects (as discussed earlier in Chapter 3).

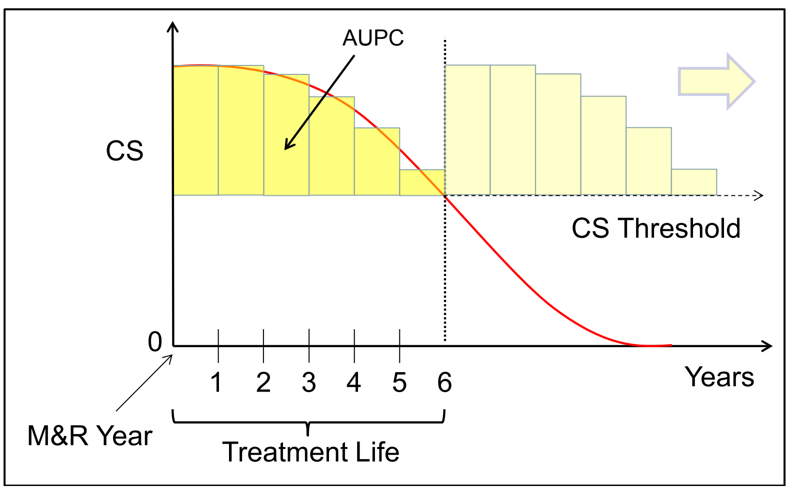


Figure 42. Illustration of the Area under the Performance Curve (AUPC) Concept.

The unit costs of M&R treatment types were discussed earlier in Chapter 4. The initial cost of M&R alternative j on project i, is computed as follows:

$$Treatment\,Cost_{ij} = UC_j \; x \; D_i \; x \; N_i \qquad \text{Equation 16}$$

where UC_j is the treatment unit cost; D_i is the length of project i; and N_i is the number of lanes.

For hybrid projects, the treatment cost is computed as follows:

$$Treatment\,Cost_{i\,j/k} = UC_j \;x\; D_i \;x\; N_i \;x\; P_j + UC_k \;x\; D_i \;x\; N_i \;x\; P_k \qquad \text{Equation 17}$$

where D_i and N_i are project length and number of lanes, respectively; UC_j is the treatment unit cost of the lighter M&R treatment *j*; P_j is the proportion of project lane-miles for which treatment *j* is applied; UC_k is the treatment unit cost of the heavier M&R alternative *k*; and P_k is the proportion of project lane-miles for which treatment *k* is applied (i.e., $P_k = 1.00 - P_j$).

Knowing the treatment life and cost of each M&R alternative, their corresponding life-cycle cost can be computed by assuming that the same M&R treatment is repeatedly applied on the pavement throughout the analysis period. Figure 43 shows the life-cycle cost of example M&R treatment type over a 20-year analysis period. The salvage value occurs at the end of the analysis period and is computed as follows:

$$Salvage\,Value = \frac{Treatment\ Remaining\ Life}{Treatment\ Expected Life} \times Treatment\,Cost \qquad \text{Equation 18}$$

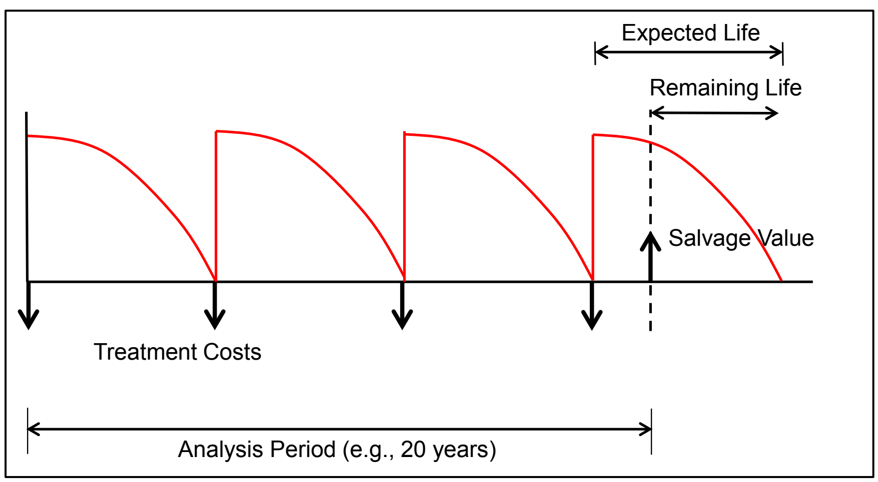


Figure 43. Illustration of Life-Cycle Costs.

The net present worth value (PWV) is computed and then converted into an Equivalent Uniform Annual Cost (EUAC) value as follows:

$$\text{PWV} = \text{Initial Cost} + \sum_{k=1}^{j} \text{Future Cost}\left[\frac{1}{(1+i)^{n_k}}\right] \quad \text{Equation 19}$$

$$\text{EUAC} = \text{PWV} * \text{i} * \left[\frac{(1+i)^m}{(1+i)^m - 1}\right] \quad \text{Equation 20}$$

where i is the discount rate; n is the number of year to the year of expenditure; k is the total number of cost items used in the analysis, $k = 1$ to j; and m is the number of years in the analysis period.

EUAC is used as one of the decision factors that influence the prioritization of projects (as discussed earlier in Chapter 3).

PRIORITIZATION OF PROJECTS

Candidate M&R projects are prioritized based on the decision factors deemed important by TxDOT districts. These factors and their weights were discussed earlier in Chapter 3 of this report. These factors are organized in the hierarchy presented in Figure 44. The top of the hierarchy represents the goal of the decision problem, which is determining the priority or rank of each candidate M&R project considering the factors included in the hierarchy.

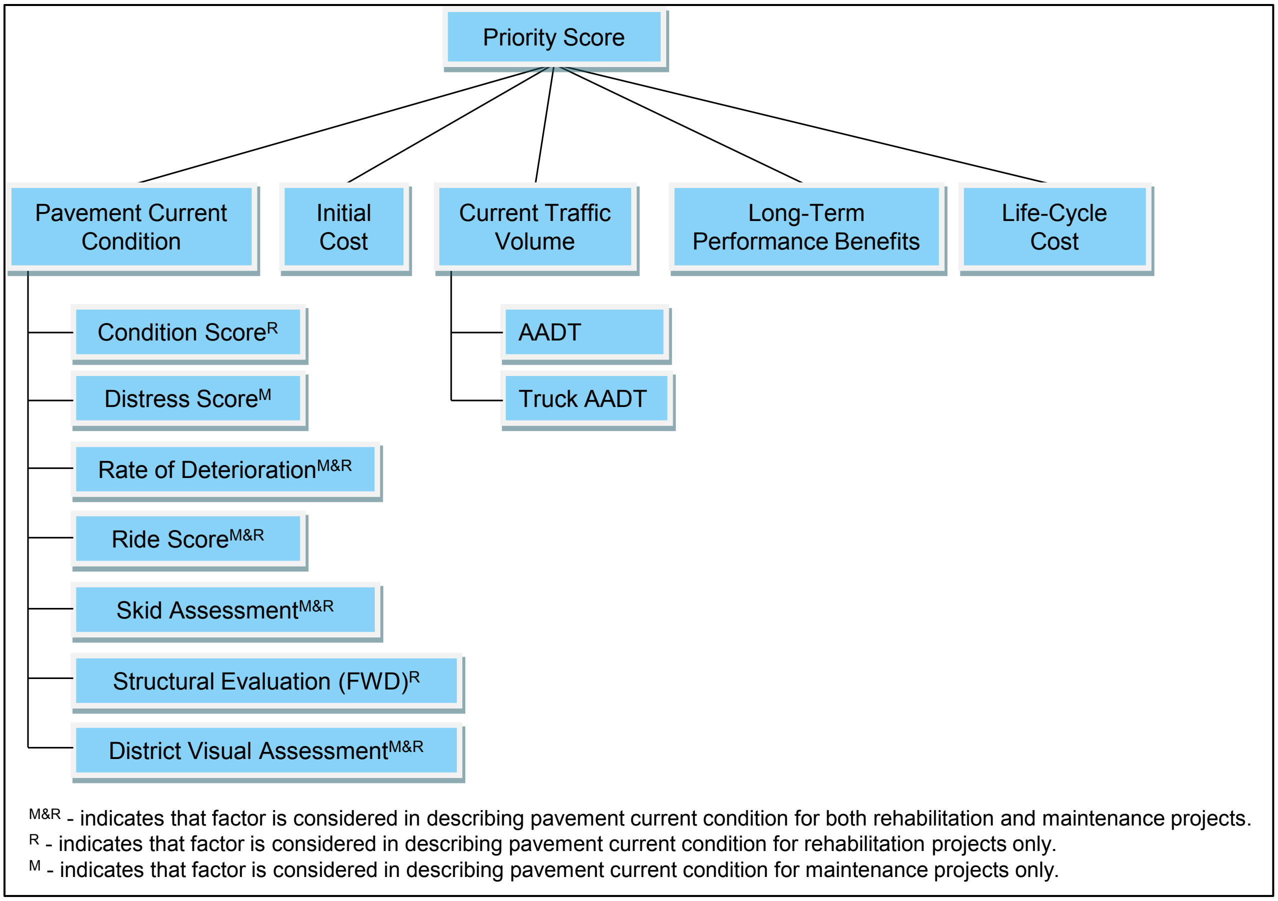


Figure 44. Hierarchy of Possible Factors Influencing the Prioritization of Pavement M&R Projects.

At this stage of the flow of the PMP methodology, each candidate M&R project has values for these factors. Indicators of pavement current condition (CC) (i.e., CS, DS, and RS) are extracted from PMIS. CSRD is computed from CS values. SKID, STRUCT, and VISUAL assessments are entered by the districts. Current traffic volume (CTV) factors, which include AADT and Truck AADT (TAADT), are obtained from the PMIS database. Initial cost (IC) is estimated using user-defined unit cost data (default values are available), and finally, long-term benefits and costs (i.e., LTPB and LCC) are computed.

These decision factors have different units of measurement (e.g., CS is unit-less, AADT is in vehicles per day, IC is in dollars) and different scale (e.g., CS ranges from 0 to 100; SKID can be 0,1, or NULL; AADT ranges from 0 to tens of thousands). Hence, these values must be converted to 0–1 utility values to facilitate comparison and to allow for computing an overall priority score for each candidate project.

Raw values of these decision factors were converted to 0–1 utility values through linear normalization. Figure 45a shows the first type of decision factors where the higher the value, the lower the priority. For instance, high CS, DS, and RS values indicate good condition; thus, the higher the values of these factors are, the lower the need for M&R would be. Conversely, Figure 45b shows the second type of decision factors where the higher the value, the higher the priority.

For instance, a high CSRD suggests rapid deterioration and thus, the urgency to apply M&R is high.

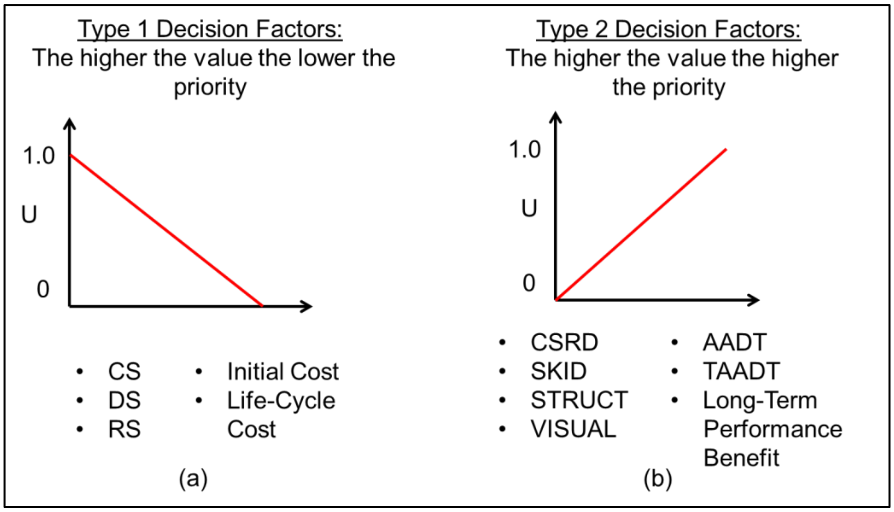


Figure 45. Normalizing the Decision Factors.

Computing the Priority Score

The normalized decision factors (i.e., utility values) are used to compute the priority score for each candidate M&R project. Figure 46 illustrates this process through an example. The utility values are shown in the left side of the figure, followed by the hierarchy of decision factors. The numbers in parentheses represent the weights of each decision factor. Note that the weights of the main factors (CC, CTV, IC, LTPB, and LCC) and the sub-factors under CC (CS, RS, CSRD, SKID, STRUCT, VISUAL) and CTV (AADT, TAADT) must sum to 100 percent. The priority score is computed by multiplying the utility values with their corresponding weights and summing the products as shown in Figure 46 example.

Forced projects (i.e., projects committed by the agency) are identified beforehand and are excluded from the prioritization process, as they are funded first. Candidate projects identified by the PMP methodology compete for the remaining funds.

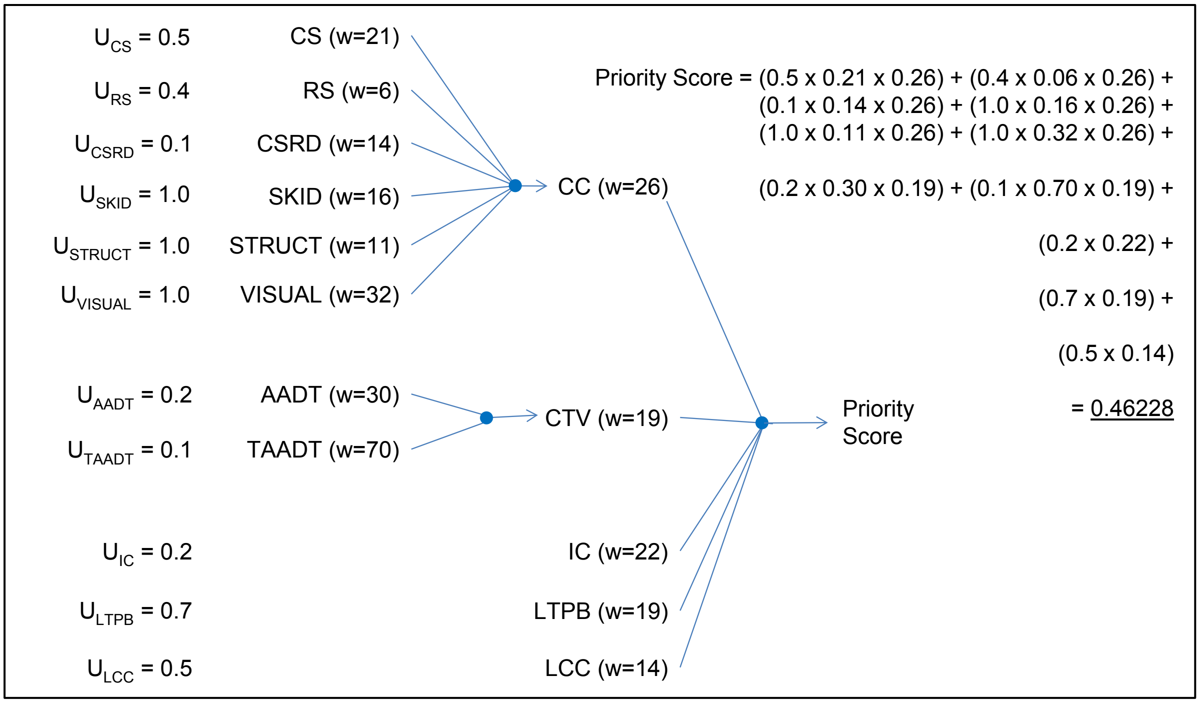


Figure 46. Calculation of the Priority Score (Example).

Incremental Benefit-Cost Analysis

Once the viable M&R alternatives for each candidate project are identified and their respective priority scores are computed, all combinations of project and M&R alternative are prioritized using the IBC algorithm for any given budget.

In the case of roadway segments that need treatment, the viable M&R alternatives are sorted in increasing order of priority score (see Figure 47). The algorithm first recommends the most cost-effective alternative (i.e., highest priority score per dollar) and if the budget permits, the recommended treatment may be replaced by the next heavier (with higher priority score) alternative. At the network level, candidate projects that yield the greatest IBC ratios are initially prioritized and if there is still available budget, the M&R treatments of the initially prioritized projects may be replaced by heavier (with higher priority score) treatments. This algorithm effectively produces the list of projects that maximizes the total priority score for a given budget (see Figure 48).

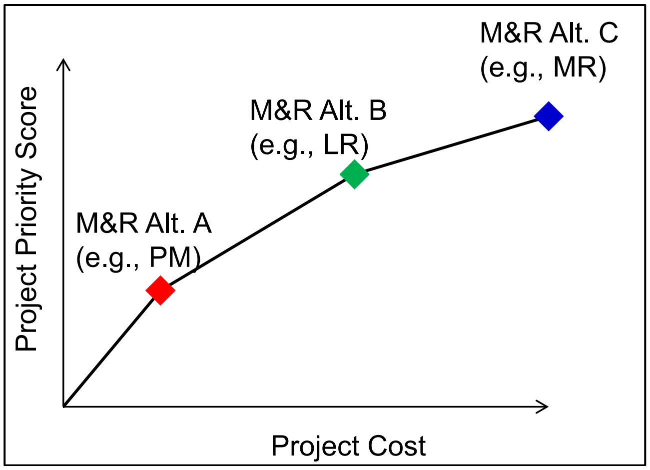


Figure 47. Ranking of Viable M&R Alternatives at the Management Section Level.

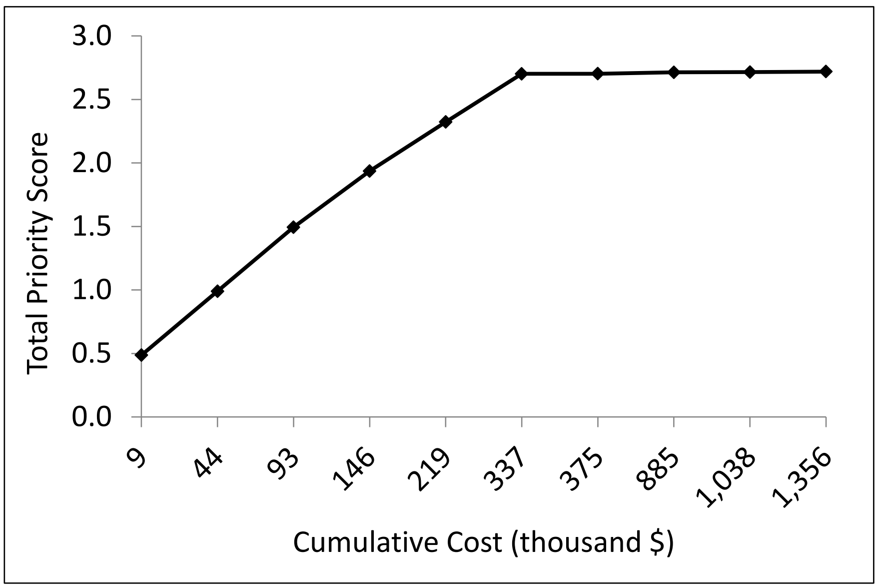


Figure 48. Maximization of the Total Priority Score Using the IBC Algorithm.

Table 37 shows an example of project prioritization using the IBC algorithm with six candidate projects. In the first column, the number indicates a unique management section while the two-letter code indicates the M&R alternative (e.g., PM for Preventive Maintenance). Note that for instance, management sections 2, 5, and 6 have two viable M&R alternatives each (i.e., PM and MR). These are arranged in a decreasing order of their final IBC ratios.

Table 37 shows that for a budget of $219,000, Projects 1-PM, 2-PM, 3-PM, 4-PM, and 5-PM should be funded while Project 6 is left untreated. If the budget is increased to $337,000, all projects can be treated with PM. If the budget is further increased to $375,000, the budget is now large enough to apply MR to Project 1 instead of PM as originally recommended. As the budget increases even more, more projects are assigned MR. This demonstrates the capability of the IBC algorithm to maximize the priority score of the set of projects selected by allowing the replacement of previously considered low-priority score alternatives with a high-priority score alternative whenever the budget permits (Farid et al. 1996).

Table 37. Hypothetical Example of Project Prioritization Using the IBC Algorithm.

M&R Alterna-tive	Initial Cost, ($K)	Priority Score	Final IBC Ratio	Cum. Cost, ($K)	Selected Projects					
					1	2	3	4	5	6
1-PM	9	0.4864	0.0550	9	PM					
2-PM	35	0.5037	0.0142	44	PM	PM				
3-PM	49	0.5039	0.0104	93	PM	PM	PM			
4-PM	53	0.4420	0.0083	146	PM	PM	PM	PM		
5-PM	74	0.3864	0.0052	219	PM	PM	PM	PM	PM	
6-PM	118	0.3797	0.0032	337	PM	PM	PM	PM	PM	PM
1-MR	47	0.4873	2.32E-05	375	MR	PM	PM	PM	PM	PM
6-MR	627	0.3901	2.05E-05	885	MR	PM	PM	PM	PM	MR
1-LR	46	0.4870	1.6E-05	*						
2-MR	188	0.5057	1.3E-05	1038	MR	MR	PM	PM	PM	MR
5-MR	392	0.3903	1.22E-05	1356	MR	MR	PM	PM	MR	MR

Projecting Pavement Condition to the Next Year

The IBC algorithm generates the list of projects (i.e., management sections along with their treatment type) recommended for the first year of the PMP. With this information, network condition for the following year is forecasted using the DS and CS prediction models discussed earlier. As discussed earlier, in the PDA segmentation method, the CS and DS prediction models are used to predict the condition of each data collection section. In contrast, in the CDA segmentation method, the models are used to predict the condition of each management section.

For projects that have been selected for treatment, their DS and CS immediately after treatment (DS_0 and CS_0) are first computed. This is done by applying the gains in rating (shown earlier in Table 34). Then, Equation 10 and Equation 11 are used to predict the condition for the following year. In this case, *Age* would be equal to one since the condition one year after treatment is being computed. The coefficients ρ and β would now be based on the M&R treatment applied (see Figure 49a).

For management sections that have not been selected for treatment, their DS and CS in the following year is projected by using expressed in Equation 10 and Equation 11, respectively. DS_0 and CS_0 would be their current DS and CS, *Age* would be the computed theoretical age (using the DS-based theoretical age in Equation 10 and the CS-based theoretical age in Equation 11), and ρ and β would be those from the HR model under the assumption that the last treatment received by the management section is HR (see Figure 49b).

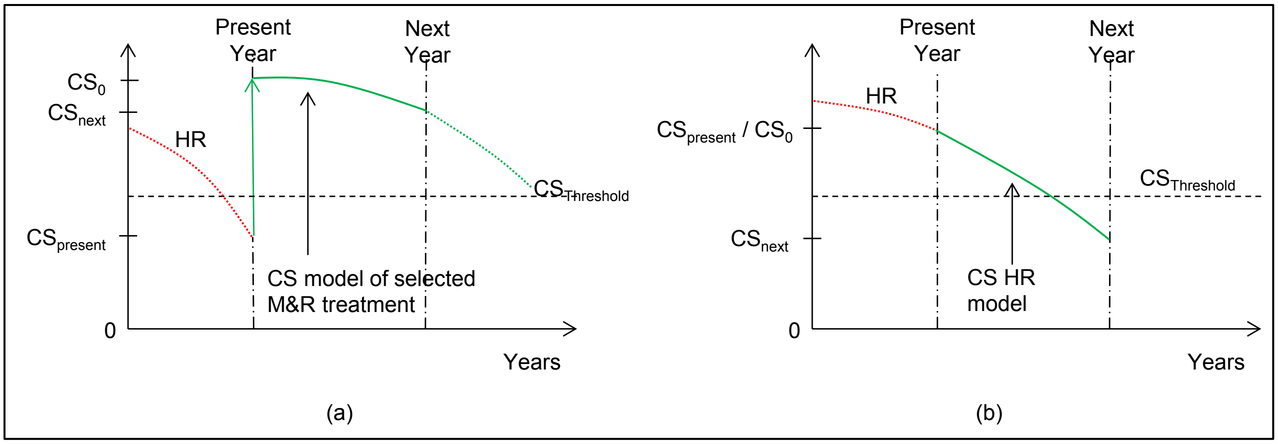


Figure 49. Projecting CS to the Next Year.

The ride score is computed as a function of the projected CS and DS using Equation 8, Equation 12, Equation 13, Equation 14, as discussed earlier. The other condition indicators (CSDR, SKID, STRUCT, and VISUAL) are used to prioritize projects for the current year only due to lack of models for projecting their values (i.e., adequacy/inadequacy of district assessments) into the future. Thus, their values for the following years are set to NULL.

Once the projected pavement condition (i.e., CS, DS, and RS) has been computed, the long-term performance benefit, life-cycle cost, and IBC computations are repeated for the next year. This loop continues until the end of the PMP planning horizon (i.e., four years) to generate the yearly list of M&R projects that constitute the 4-year pavement management plan.

CHAPTER 6 –TESTING AND VALIDATING THE PMP DEVELOPMENT METHODOLOGY

This chapter describes the results of testing and validating the PMP methodology (described in Chapter 5 of this report). The developed methodology has been tested and demonstrated by developing pavement management plans for Bryan, Fort Worth, and Lubbock Districts for the period 2012–2015. Additionally, the developed methodology has been implemented in a web-based software tool for evaluation by TxDOT personnel. Currently, the tool has 2011 PMIS data for Bryan, Lubbock, Fort Worth, and San Antonio only and it will be available until May 2014. TxDOT personnel interested in testing this tool can contact the research team and TxDOT project personnel to obtain username and password to access to this tool. This tool can potentially be used in the future by TxDOT engineers to generate 4-year PMPs for individual districts and the statewide network.

VALIDATION OF PMP METHODOLOGY WITH DISTRICT DATA

The 2012–2015 PMPs for Bryan, Fort Worth, Lubbock, and San Antonio Districts were obtained from TxDOT. The M&R projects used in validating and testing the PMP methodology are summarized in Table 38. This summary includes M&R projects for asphalt concrete pavement (ACP) only. Additionally, only projects with clear definition and boundaries are used in this analysis. Bare concrete pavement sections were not included in this analysis because of inconsistencies in their performance prediction models. Bare concrete sections represent approximately 2 percent, 20 percent, and 4 percent of the network in Bryan, Fort Worth, and Lubbock, respectively.

Table 38. Summary of M&R Projects Listed in District PMPs and Used in Methodology Validation and Testing.

District	Year	No. of M&R Projects Used in Methodology Validation and Testing	Lane-Miles	Estimated Cost
Bryan	2012	51	486	$12,500,000
	2013	72	882	$27,500,000
	2014	81	839	$26,000,000
	2015	61	791	$22,500,000
			4-Year Average	≈$22,000,000
Fort Worth	2012	64	690	$19,500,000
	2013	153	1,241	$33,000,000
	2014	92	882	$28,000,000
	2015	68	737	$15,500,000
			4-Year Average	≈$24,000,000
Lubbock	2012	56	750	$19,000,000
	2013	97	1,330	$40,000,000
	2014	108	1,565	$45,500,000
	2015	112	1,449	$31,500,000
			4-Year Average	≈$34,000,000

The cost values shown in Table 38 were estimated by multiplying the lane-miles of each M&R project listed in the district's PMP by its corresponding unit cost and then adding these projects costs for each year. The unit costs (see Table 39) were computed in this study using data extracted from on the districts' 2011 PMPs (see Chapter 2).

Table 39. Average Unit Costs for ACP M&R Categories.

ACP M&R Category	Unit Cost, $/lane-mile
PM	$15,409
LRH	$76,086
MRH	$78,429
HRH	$133,776

As discussed earlier in Chapter 5 of this report, the PMIS database contains data on "data collection sections" that are typically 0.5-mile long. Thus, the PMP methodology combines adjacent PMIS data collection sections into "management sections" that can be maintained independently, and thus represent potential M&R projects. This functionality is implemented in the PMP methodology using the Cumulative Differences Algorithm (CDA) and the Proximity to Deficient Areas (PDA) method. In both methods, grouped sections must be adjacent and have the same highway ID, roadbed, and pavement family. The testing and validation of the developed methodology was conducted using both of these project formation methods.

The districts' 2012–2015 PMPs were compared to those generated by the developed methodology as follows:

- Overall agreement in selected projects.
- Agreement in project boundaries for PMP initial year.
- Impact on network condition.

The results of above comparisons are discussed next.

Overall Agreement in Selected Projects

Maps of selected M&R projects for the 4-year period (2012–2015) were generated to visually assess the overall agreement between the methodology's PMPs and the districts' PMPs. Figure 50 shows these maps for the Bryan District. The highlighted roadway segments represent M&R projects selected by the proposed methodology (using budgets shown earlier in Table 38) and projects listed in the district's PMP. Generally, the PMPs developed by the proposed methodology tend to have more projects (especially preventive maintenance projects) than the district's PMP. To quantify the agreement between these PMPs in terms of project boundaries, a detailed analysis was performed on projects planned for the first year of the PMP (i.e., 2012) for all studied districts (Bryan, Fort Worth, and Lubbock), as discussed next.

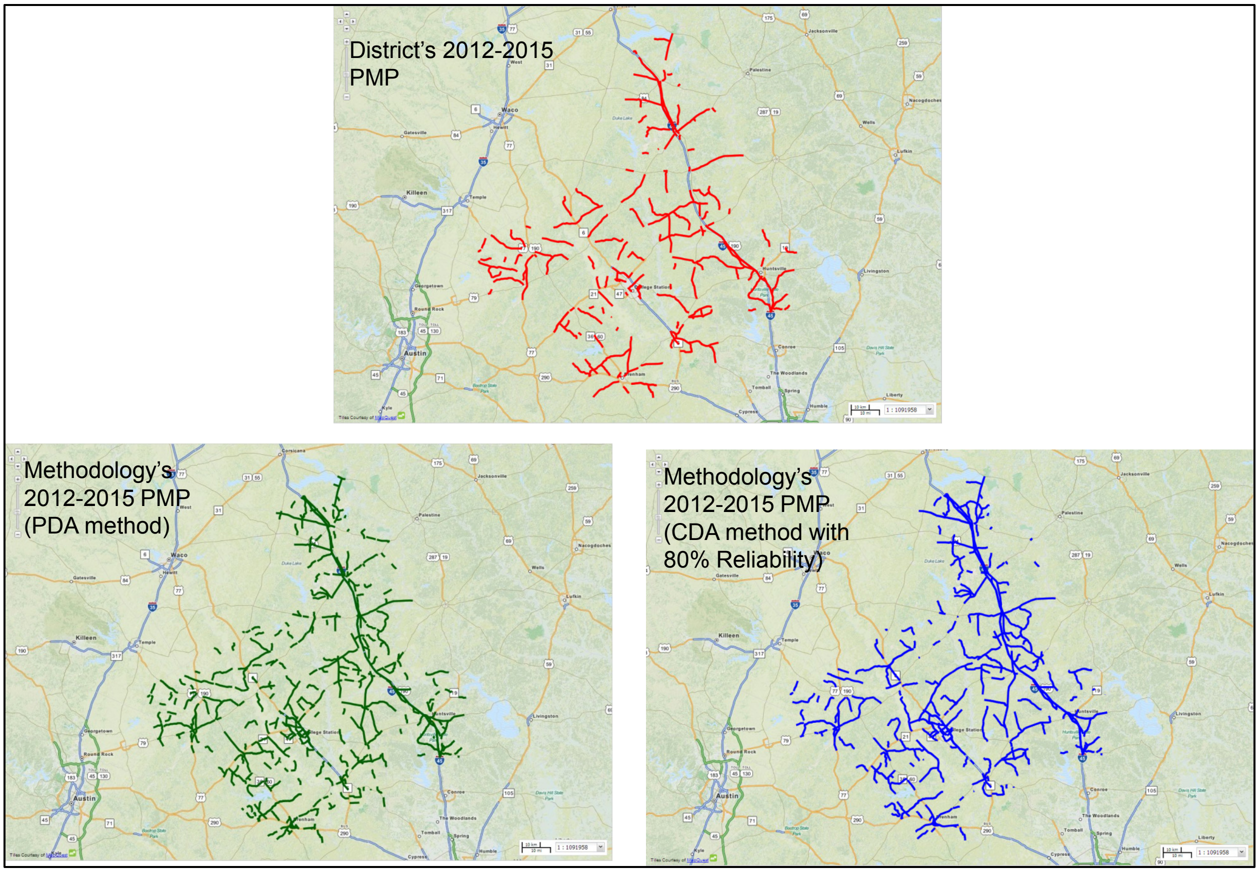


Figure 50. Visual Comparison of Methodology's PMP and Bryan District's PMP (M&R Projects in All 4 Years of the 2012–2015 PMP).

Agreement in Project Boundaries for First Year of the PMP

The agreement between projects planned for 2012 (i.e., the first year in the PMP) was quantified in this analysis. Only projects planned for the first year of the PMP are compared to eliminate the compounding effect of initial mismatches on projects selected for subsequent years. Also, unlimited budget was used in the proposed methodology so that every pavement section recommended for M&R in the district's PMP should, ideally, appear in the methodology's PMP; but not every pavement section in the methodology's PMP should be found on the district's PMP. This comparison represents the best case scenario for agreement between the districts' PMPs and the methodology's PMPs.

The level of agreement between projects selected by the proposed methodology and those listed in the districts PMPs was quantified by the percentage of True Positives (TP) and False Negatives (FN), as follows:

- True Positive: M&R project is selected by the proposed methodology and exists in the district's PMP.
- False Negative: M&R project is not selected by the proposed methodology, but it exists in the district's PMP.

Table 40 shows the results of this comparison. The higher the TP and the lower the FN, the higher the agreement between the two PMPs would be. As a caveat, the word *true* in *True* Positive does not imply that the project listed in the district's PMP is the *right* project choice or that it was indeed implemented. In the same way, a *False* Negative does not imply that the methodology *wrongly* identifies a road segment needing no M&R action. TP and FN are simply indicators of agreement between the PMP developed by the district and the corresponding PMP generated by the methodology.

Table 40. Agreement between the Districts' PMPs and Methodology's PMPs in Terms of Projects Selected for Year 2012.(1)

District	Project Formation Scheme	TP	FN
Fort Worth	CDA (at 80% Reliability)	50%	50%
	PDA	55%	45%
Bryan	CDA (at 80% Reliability)	55%	45%
	PDA	62%	38%
Lubbock	CDA (at 80% Reliability)	40%	60%
	PDA	50%	50%

[1]TP and FN are computed based on 690, 486, and 750 lane-miles of actual projects in Fort Worth, Bryan, and Lubbock, respectively.

To examine the cause of discrepancies between the PMPs generated by the proposed methodology and the PMPs generated by the district, the 51 M&R projects listed in the district's PMP for 2012 were analyzed in detail. The boundaries of each project were compared with the boundaries of the closest CDA- and PDA-formed projects. The methodology was run using unlimited budget to eliminate the potential for leaving out some projects due to limited funding. Analysis revealed four ways by which CDA- and PDA-formed project boundaries may match/mismatch the project boundaries listed in the district's PMP. These four cases are illustrated in Figure 51, where the FPs represent pavement sections adjacent to projects listed in the district's PMP but were selected by the proposed methodology. The TPs and FNs are as defined earlier.

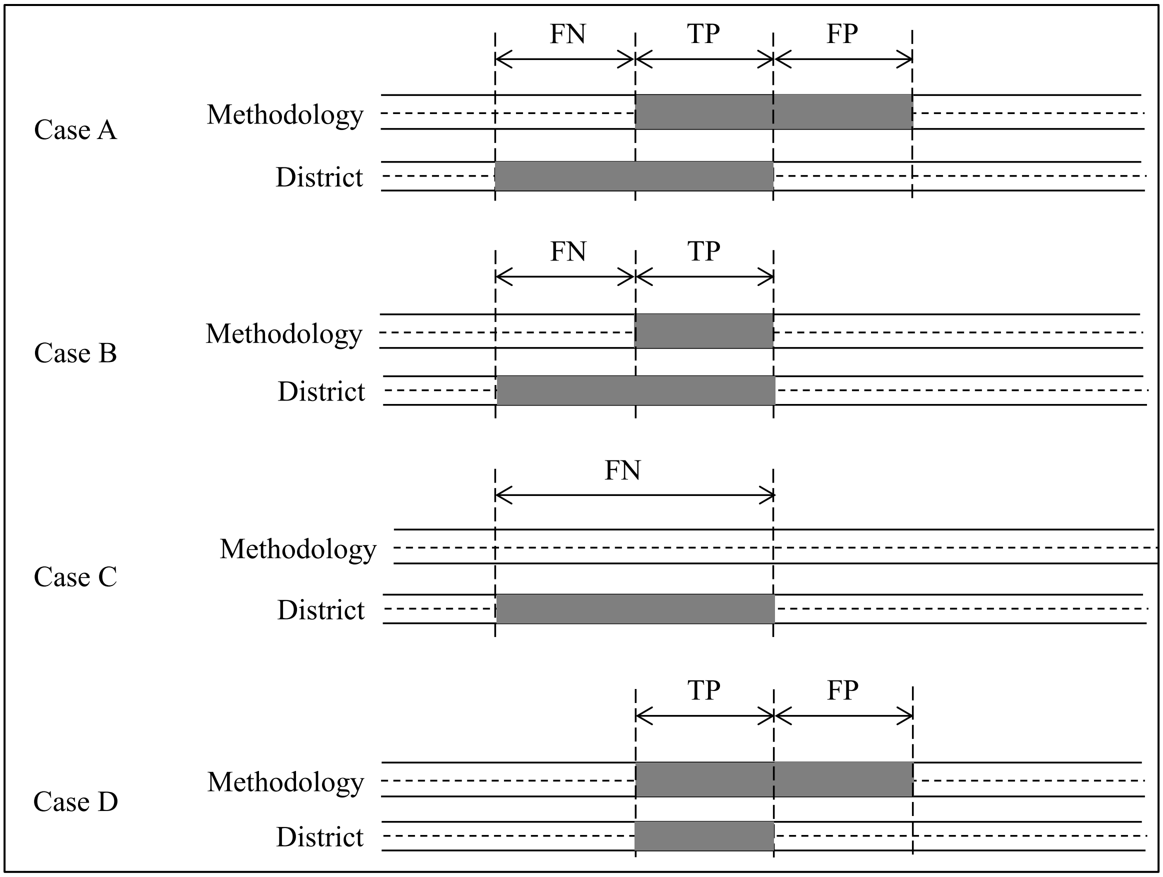


Figure 51. Four Cases of Match/Mismatch between Project Boundaries (Projects Listed in the District's PMP vs. Projects Identified by the Proposed Methodology).

Table 41 shows the average CS of the sections that fall under each mismatching case depicted in Figure 51. The results are explained as follows:

- Case A: The average CS for FP sections (75-84 for the CDA method and 75-79 for the PDA method) is lower than that for the FN sections (92-98 for the CDA method and 95-99 for the PDA method). Thus, the methodology's logic for not selecting these FN sections for M&R and selecting the FP sections instead is justifiable from a CS standpoint.
- Case B: The average CS for FN sections (91-94 for the CDA method and 95-99 for the PDA method) indicates very good condition. Thus, the methodology's logic not to select these sections for M&R is justified from a CS standpoint.
- Case C: Similar to Case B, the average CS for FN sections is indicative of very good condition. Thus, not selecting them for M&R is again justified.
- Case D: The average CS for FP sections is close to that of the TP sections, suggesting that the selection of these FP sections for M&R by the proposed methodology is justified.

The above discussion shows that while there are indeed mismatches in project boundaries, the methodology's project limits are justifiable based on the pavement's CS values.

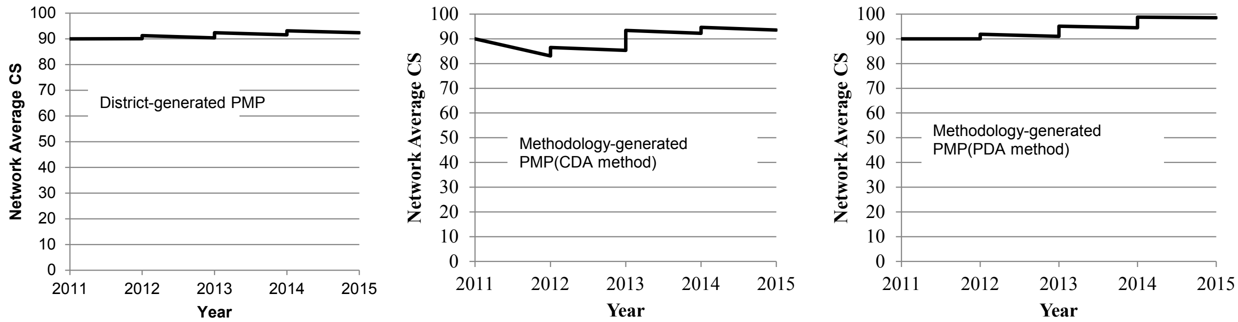
Table 41. Average CS for Each Type of Match/Mismatch Depicted in Figure 51.

District	Match/Mismatch Case	CDA (80% Reliability)			PDA		
		TP	FN	FP	TP	FN	FP
Bryan	A	74	92	79	78	95	75
	B	81	94	NA	79	96	NA
	C	NA	97	NA	NA	99	NA
	D	69	NA	67	68	NA	71
	All Cases	72	95	71	74	96	72
Fort Worth	A	71	96	84	73	95	78
	B	77	91	NA	75	95	NA
	C	NA	94	NA	NA	96	NA
	D	72	NA	74	70	NA	77
	All Cases	71	94	77	72	95	77
Lubbock	A	77	98	75	80	99	79
	B	63	94	NA	72	98	NA
	C	NA	97	NA	NA	99	NA
	D	68	NA	83	68	NA	68
	All Cases	68	97	78	72	98	74

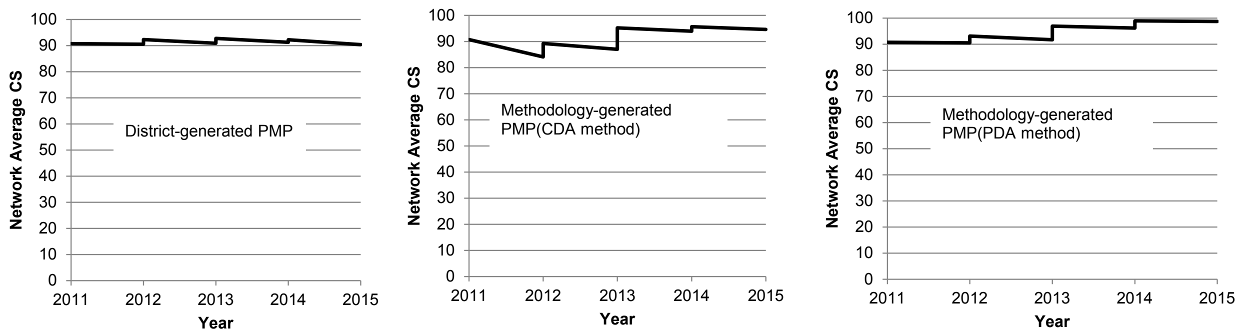
Impact on Network Condition

In this analysis, the district's PMPs are compared to those generated by the methodology in terms of impact on network condition throughout the plan period (2012–2015). The budgets shown earlier in Table 38 were used in running the methodology to facilitate proper comparison.

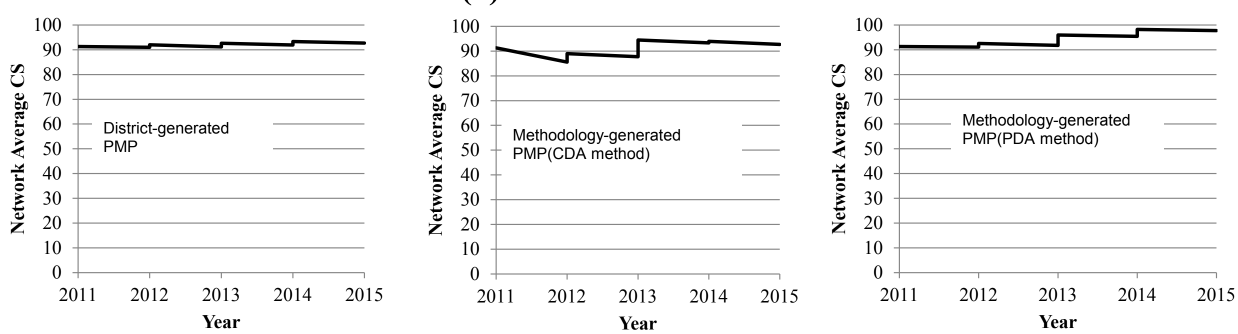
As shown in Figure 52, the average condition score brought about by the district's PMP and the PMPs generated by the proposed methodology are generally comparable. However, the methodology's PMPs are more effective in attaining the goal of having 90 percent of network lane-miles in "good" or better condition, as shown in Figure 53. The methodology's PMPs are predicted to exceed this goal by 2013 while the actual PMP remains at this target throughout 2012–2015. This indicates that, for the same budget, the methodology is allocating funds to projects that have greater impact on improving network condition score.



(a) Bryan District

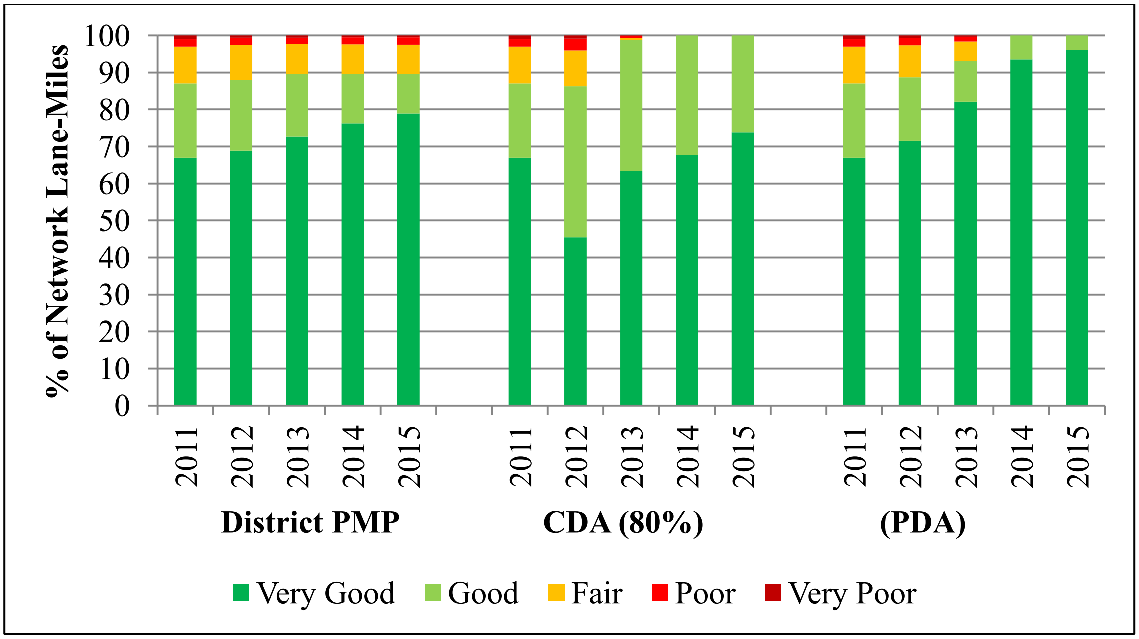


(b) Fort Worth District

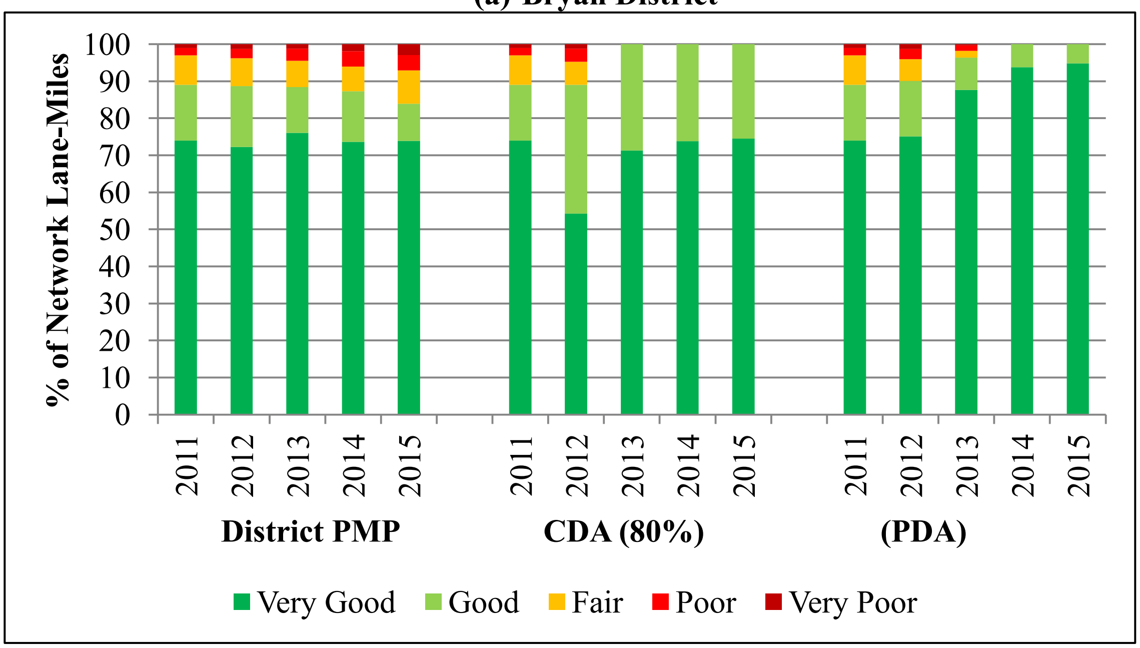


(c) Lubbock District

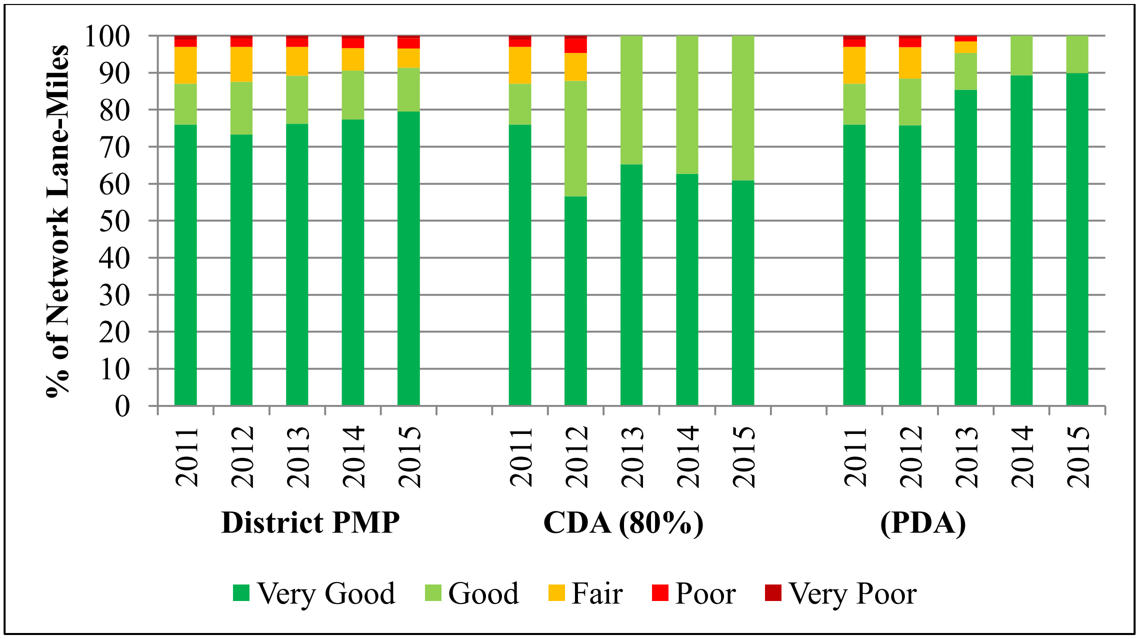
Figure 52. Average Network CS Predicted for the District-Generated, CDA-Generated (80 Percent Reliability), and PDA-Generated PMPs for (a) Fort Worth, (b) Bryan, and (c) Lubbock Districts.



(a) Bryan District



(b) Fort Worth District



(c) Lubbock

Figure 53. Network Condition Predicted for the District's, CDA-Generated, and PDA-Generated PMPs for (a) Bryan, (b) Fort Worth, and (c) Lubbock Districts.

The above analysis suggests that, while mismatches exist between the districts' PMPs and the methodology's PMPs, the methodology's manner of allocating resources appears to be slightly more effective in attaining the statewide goal of having 90 percent of the state-maintained pavement lane-miles in "good or better" condition (measured in terms of CS). These results highlight the potential of the developed methodology for aiding TxDOT in developing cost-effective PMPs that incorporate the districts' priorities.

IMPLEMENTATION OF PMP METHODOLOGY IN AN ONLINE SOFTWARE TOOL

To facilitate the evaluation of the developed PMP methodology by TxDOT's personnel, it was implemented in a web-based software tool. This tool can be accessed by authorized TxDOT personnel via the internet (see Figure 54). Currently, the tool has 2011 PMIS data for Bryan, Lubbock, Fort Worth, and San Antonio Districts only. TxDOT personnel at the Maintenance Division and the Bryan District have conducted preliminary testing of this tool. Additional TxDOT personnel interested in testing this tool can contact the research team and TxDOT project personnel to obtain a username and password to access. The domain name of this tool will remain valid until May 2014. The availability of this tool beyond that date is contingent upon renewing its domain name and web hosting services.

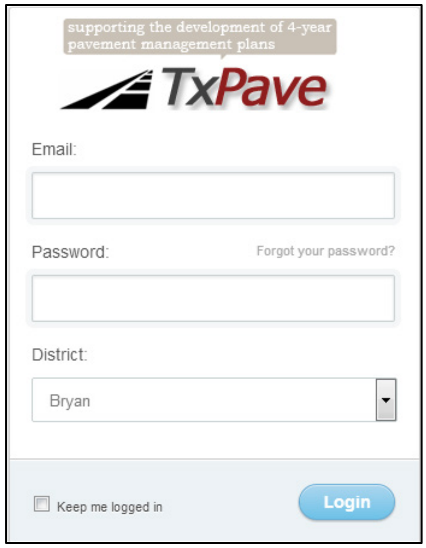


Figure 54. Login to the PMP Tool.

The user begins by segmenting the network using either the CDA or PDA method. The inputs to these methods are shown in Figure 55 (Method 1 is CDA and Method 2 is PDA). A sample output (i.e., resulting pavement management sections) is shown in Figure 56.

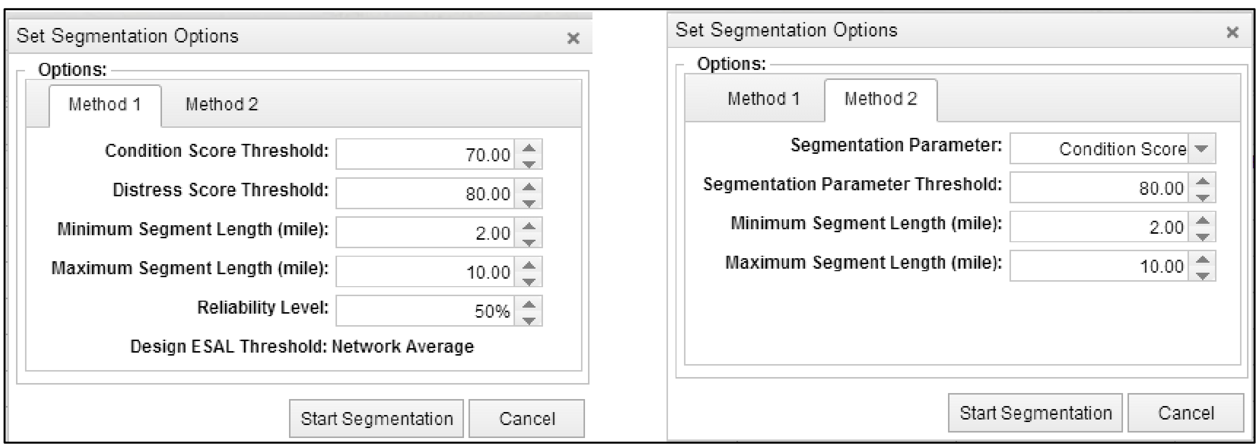
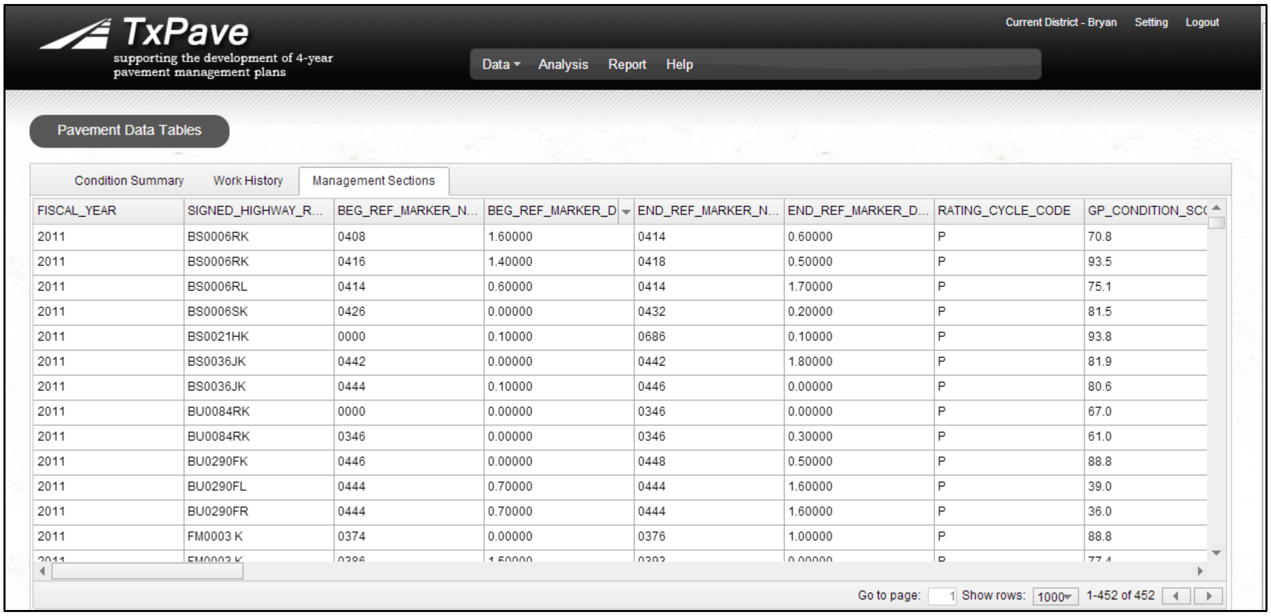


Figure 55. Inputs of the CDA (Left) and PDA (Right) Roadway Segmentation Methods.



FISCAL_YEAR	SIGNED_HIGHWAY_R...	BEG_REF_MARKER_N...	BEG_REF_MARKER_D	END_REF_MARKER_N...	END_REF_MARKER_D...	RATING_CYCLE_CODE	GP_CONDITION_SC(
2011	BS0006RK	0408	1.60000	0414	0.60000	P	70.8
2011	BS0006RK	0416	1.40000	0418	0.50000	P	93.5
2011	BS0006RL	0414	0.60000	0414	1.70000	P	75.1
2011	BS0006SK	0426	0.00000	0432	0.20000	P	81.5
2011	BS0021HK	0000	0.10000	0686	0.10000	P	93.8
2011	BS0036JK	0442	0.00000	0442	1.80000	P	81.9
2011	BS0036JK	0444	0.10000	0446	0.00000	P	80.6
2011	BU0084RK	0000	0.00000	0346	0.00000	P	67.0
2011	BU0084RK	0346	0.00000	0346	0.30000	P	61.0
2011	BU0290FK	0446	0.00000	0448	0.50000	P	88.8
2011	BU0290FL	0444	0.70000	0444	1.60000	P	39.0
2011	BU0290FR	0444	0.70000	0444	1.60000	P	36.0
2011	FM0003 K	0374	0.00000	0376	1.00000	P	88.8

Figure 56. Sample Output of the PDA and CDA Roadway Segmentation Methods.

Once the network is segmented, the user can enter the district's condition assessments (structural, skid, and visual) as well as forced projects (see Figure 57).

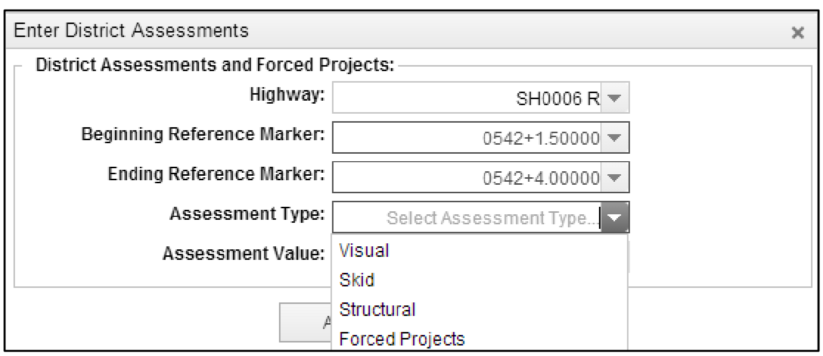


Figure 57. Entry of District's Condition Assessments and Forced Projects.

Next, the user enters appropriate values (or accept the default values) for the analysis parameters. These parameters include the priority weights (see Figure 58), performance prediction models (see Figure 59), benefit measures (see Figure 60), unit costs (see Figure 61), and other parameters (see Figure 62).

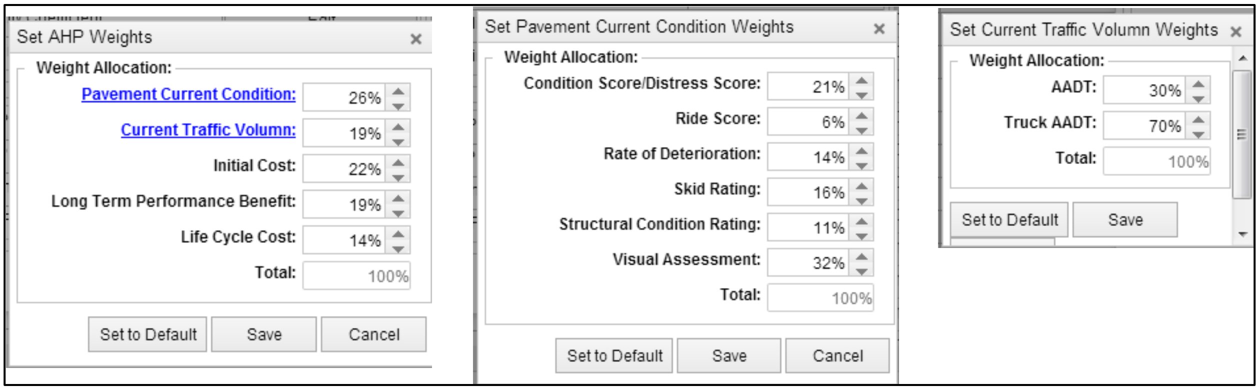
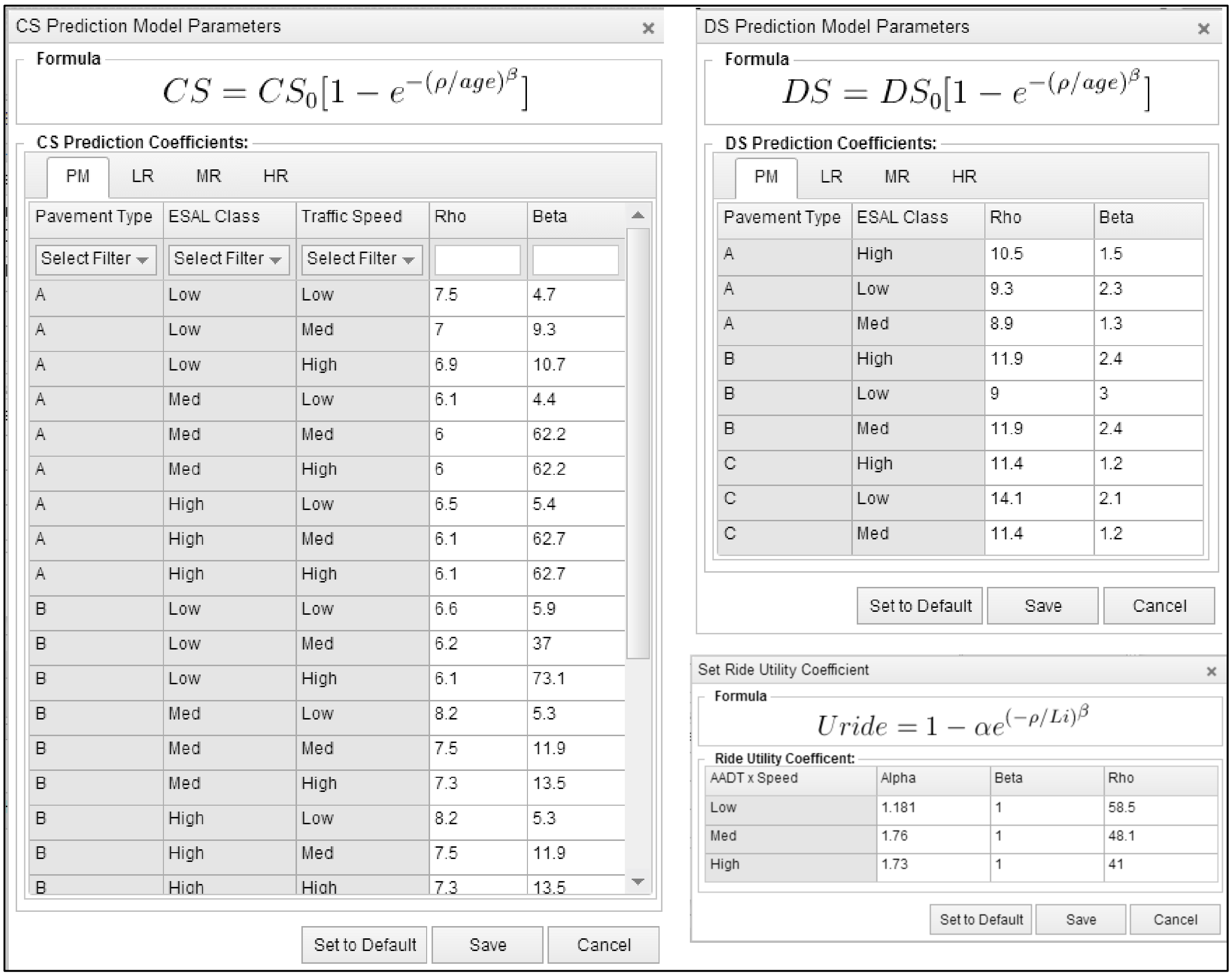


Figure 58. Priority Weights.



Pavement Type	ESAL Class	Traffic Speed	Rho	Beta
Select Filter	Select Filter	Select Filter		
A	Low	Low	7.5	4.7
A	Low	Med	7	9.3
A	Low	High	6.9	10.7
A	Med	Low	6.1	4.4
A	Med	Med	6	62.2
A	Med	High	6	62.2
A	High	Low	6.5	5.4
A	High	Med	6.1	62.7
A	High	High	6.1	62.7
B	Low	Low	6.6	5.9
B	Low	Med	6.2	37
B	Low	High	6.1	73.1
B	Med	Low	8.2	5.3
B	Med	Med	7.5	11.9
B	Med	High	7.3	13.5
B	High	Low	8.2	5.3
B	High	Med	7.5	11.9
B	High	High	7.3	13.5

Pavement Type	ESAL Class	Rho	Beta
A	High	10.5	1.5
A	Low	9.3	2.3
A	Med	8.9	1.3
B	High	11.9	2.4
B	Low	9	3
B	Med	11.9	2.4
C	High	11.4	1.2
C	Low	14.1	2.1
C	Med	11.4	1.2

AADT x Speed	Alpha	Beta	Rho
Low	1.181	1	58.5
Med	1.76	1	48.1
High	1.73	1	41

Figure 59. Pavement Performance Prediction Models.

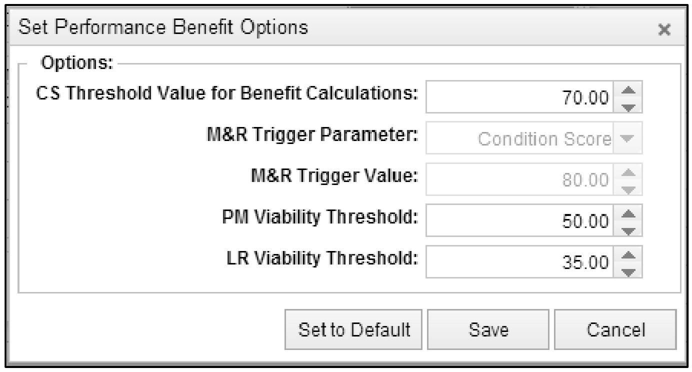
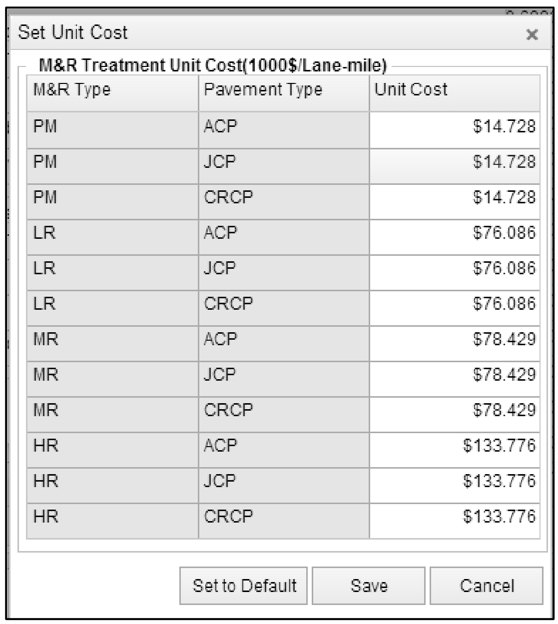


Figure 60. Benefit Parameters.



M&R Type	Pavement Type	Unit Cost
PM	ACP	$14.728
PM	JCP	$14.728
PM	CRCP	$14.728
LR	ACP	$76.086
LR	JCP	$76.086
LR	CRCP	$76.086
MR	ACP	$78.429
MR	JCP	$78.429
MR	CRCP	$78.429
HR	ACP	$133.776
HR	JCP	$133.776
HR	CRCP	$133.776

Figure 61. M&R Unit Costs ($/lane-mile).

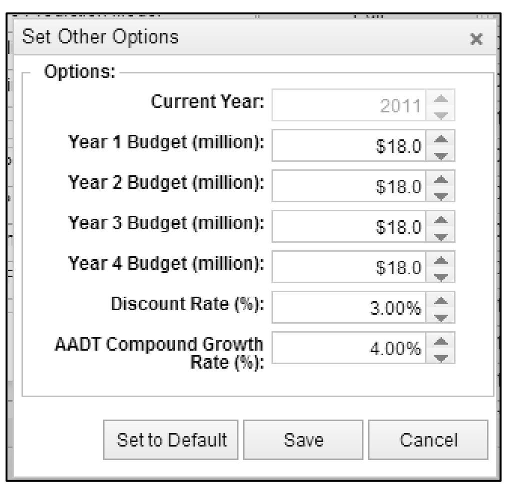
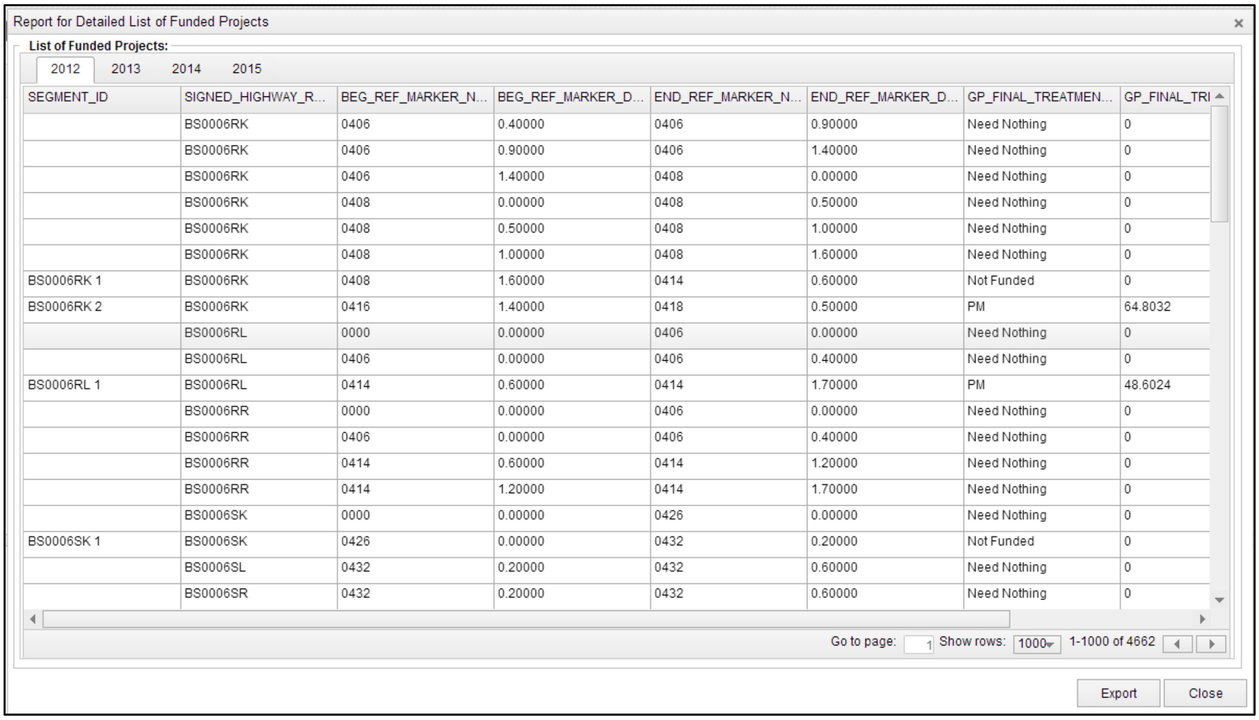


Figure 62. Other Analysis Parameters.

The analysis results are presented in several ways, including a table of selected projects for the 4-year period (see Figure 63), average network CS over the PMP period (see Figure 64), average network DS over the PMP period (see Figure 65), percent lane-miles in various CS levels over the PMP period (see Figure 66), and backlog over the PMP period (see Figure 67).


Report for Detailed List of Funded Projects

List of Funded Projects:

2012 2013 2014 2015

SEGMENT_ID	SIGNED_HIGHWAY_R...	BEG_REF_MARKER_N...	BEG_REF_MARKER_D...	END_REF_MARKER_N...	END_REF_MARKER_D...	GP_FINAL_TREATMEN...	GP_FINAL_TRI
	BS0006RK	0406	0.40000	0406	0.90000	Need Nothing	0
	BS0006RK	0406	0.90000	0406	1.40000	Need Nothing	0
	BS0006RK	0406	1.40000	0408	0.00000	Need Nothing	0
	BS0006RK	0408	0.00000	0408	0.50000	Need Nothing	0
	BS0006RK	0408	0.50000	0408	1.00000	Need Nothing	0
	BS0006RK	0408	1.00000	0408	1.60000	Need Nothing	0
BS0006RK 1	BS0006RK	0408	1.60000	0414	0.60000	Not Funded	0
BS0006RK 2	BS0006RK	0416	1.40000	0418	0.50000	PM	64.8032
	BS0006RL	0000	0.00000	0406	0.00000	Need Nothing	0
	BS0006RL	0406	0.00000	0406	0.40000	Need Nothing	0
BS0006RL 1	BS0006RL	0414	0.60000	0414	1.70000	PM	48.6024
	BS0006RR	0000	0.00000	0406	0.00000	Need Nothing	0
	BS0006RR	0406	0.00000	0406	0.40000	Need Nothing	0
	BS0006RR	0414	0.60000	0414	1.20000	Need Nothing	0
	BS0006RR	0414	1.20000	0414	1.70000	Need Nothing	0
	BS0006SK	0000	0.00000	0426	0.00000	Need Nothing	0
BS0006SK 1	BS0006SK	0426	0.00000	0432	0.20000	Not Funded	0
	BS0006SL	0432	0.20000	0432	0.60000	Need Nothing	0
	BS0006SR	0432	0.20000	0432	0.60000	Need Nothing	0

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Export Close

Figure 63. Table of Funded and Unfunded Projects, and "Need Nothing" Segments.

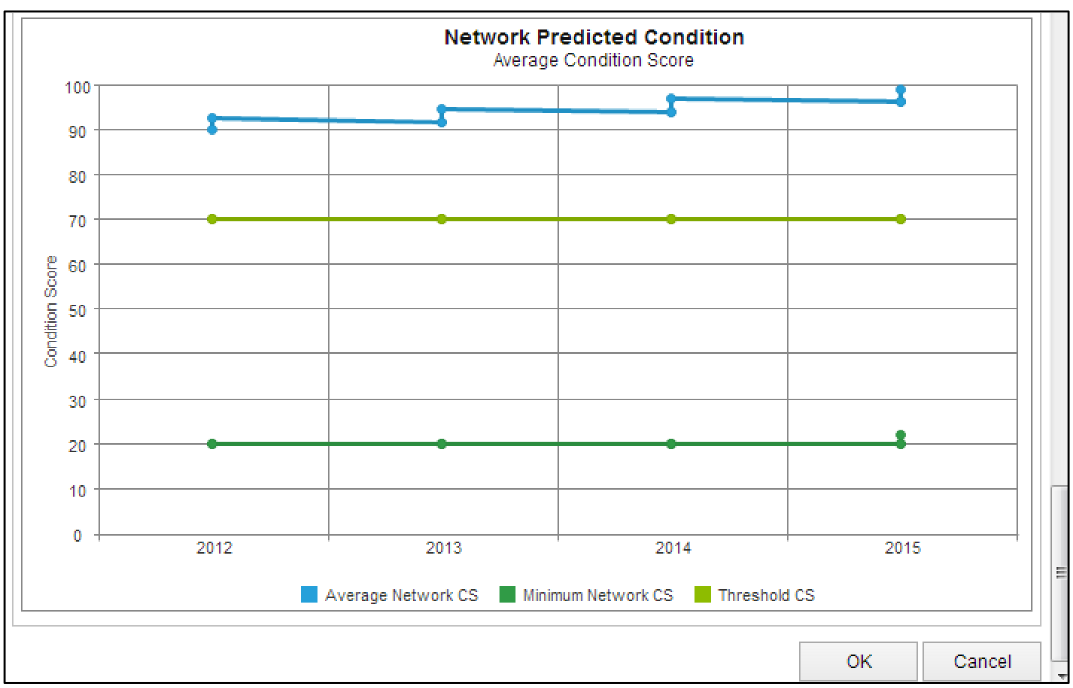

Figure 64. Average and Minimum Network CS over the PMP Period.

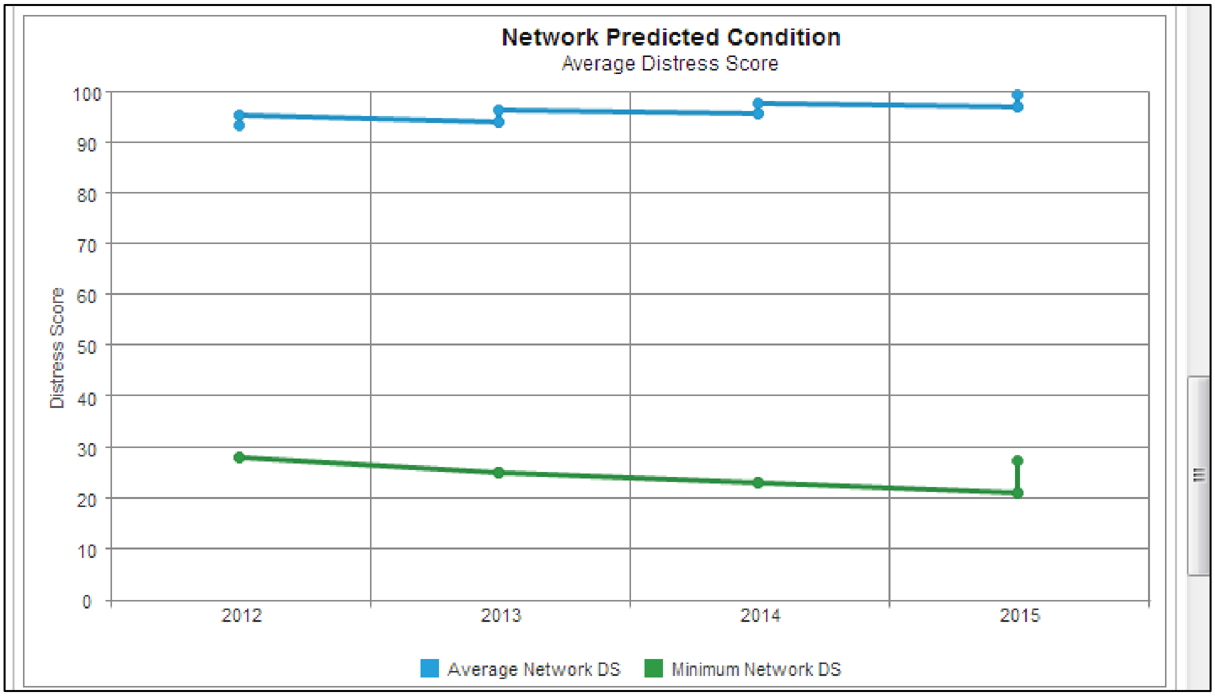

Figure 65. Average and Minimum Network DS over the PMP Period.

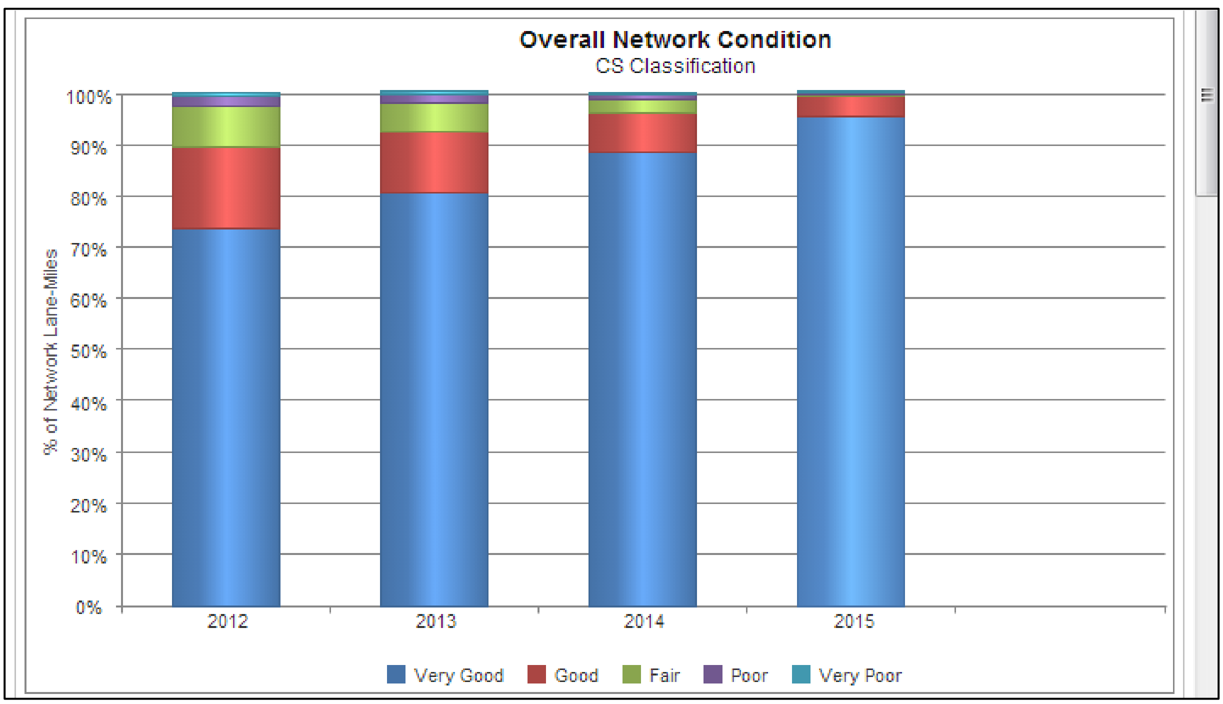

Figure 66. Percent Lane-Miles in Various CS Levels over the PMP Period.

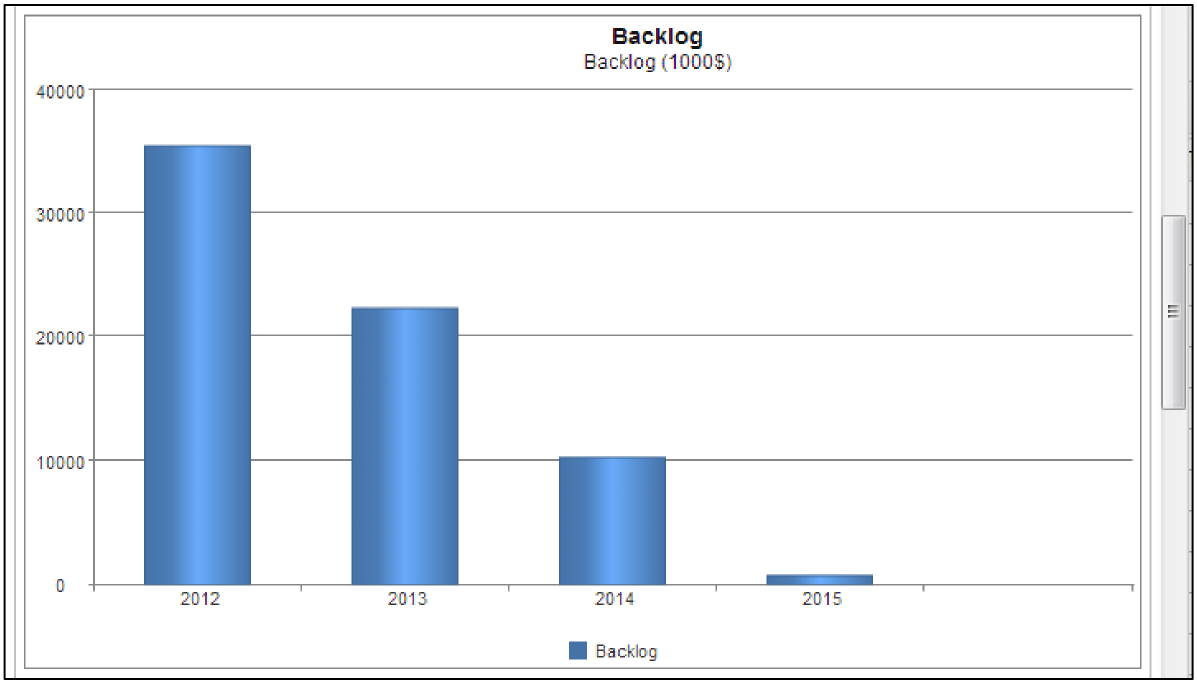

Figure 67. Backlog (in Thousand Dollars) over the PMP Period.

CHAPTER 7 − SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A systematic methodology for forming and prioritizing pavement M&R projects was developed. TxDOT can use this methodology to generate defensible and cost-effective 4-year pavement management plans. The developed methodology was implemented in a web-based software tool for evaluation by TxDOT personnel. This tool can potentially be used in the future by TxDOT engineers to generate 4-year PMPs for individual districts and the statewide network.

OVERVIEW OF THE DEVELOPED METHODOLOGY

The PMP methodology first groups data collection sections found in the PMIS database into management sections based on current condition and pavement types. Districts may then enter additional condition assessments as well as forced projects (i.e., M&R projects that the district is committed to fund). Management sections with condition score or distress score below a user-defined trigger value are considered in need for M&R action. For each management section needing M&R, viable M&R treatments are identified. The combination of management sections and their viable M&R treatments represent potential M&R projects considered for funding. A priority score is computed for each potential M&R project based on factors deemed important by TxDOT districts. These factors and their weights were identified based on a survey of TxDOT's districts. The potential projects are then prioritized using the Incremental Benefit-Cost (IBC) algorithm to generate a list of projects that maximize the total priority score for the given budget. The pavement condition is then projected for the following year, and the process is repeated every year until the end of the planning period (i.e., four years). The selected M&R projects constitute the 4-year PMP. Finally, the impact of the PMP on the network condition is analyzed.

CONCLUSIONS RELATED TO PROJECT PRIORITIZATION FACTORS AND WEIGHTS

A set of factors that are deemed important by TxDOT districts when prioritizing pavement M&R projects for the 4-year PMP were identified based on a survey of TxDOT's districts. Twenty-seven individuals responded to the survey, representing 17 districts (68 percent district response rate). These districts include four metro districts, five urban districts, and eight rural districts. The following conclusions can be made based on the results of this survey.

- For urban and rural districts, pavement current condition and M&R initial cost are considered the most important factors.
- For metro districts, long-term-performance benefits, M&R initial cost, and current traffic volume are considered the most important factors.
- For urban and rural districts, district's own visual assessment is the top indicator of pavement current condition. It is followed by distress and condition scores, and to a lesser extent skid resistance.
- For metro districts, skid resistance is the top indicator of pavement current condition. It is followed by district's own visual assessment.
- All district types (metro, urban, and rural) consistently assigned the least weight to ride score as an indicator of pavement current condition.

CONCLUSIONS RELATED TO DATA AVAILABILITY AND REQUIREMENTS

Available data on pavement inventory, condition, M&R cost, and traffic were evaluated to determine possible sources of data for the PMP methodology and computational tool. Key conclusions of these evaluations are as follows:

- Sources of data for the PMP methodology and tool are:
  - PMIS: CS, DS, RS, ADT, 20-year ESAL, speed limit.
  - Direct entry by users (e.g., district personnel): skid assessment, structural condition assessment, and visual assessment.
  - Defaults: unit costs, decision criteria weights.
- No comprehensive database is available for skid resistance, structural condition assessment, and district visual assessment. Therefore, a process was designed to allow the users (e.g., district personnel) to enter a binary adequate/inadequate rating for these pavement condition indicators.
- Some M&R categories showed high variability in unit cost. This may be attributed to the inherent variability in construction costs (which can be influenced by many factors, such as economic condition, project location, etc.) and the wide range of treatment types combined under each M&R category.

CONCLUSIONS RELATED TO TESTING AND VALIDATING THE DEVELOPED PMP METHODOLOGY

The developed PMP methodology was tested and validated for Bryan, Fort Worth, and Lubbock Districts. Pavement management plans for 2012–2015 were developed for these districts using the PMP methodology with data from PMIS. The resulted PMPs were compared to the 2012–2015 PMPs developed by the districts. Since PMIS does not contain data on district visual assessment, skid assessment, structural assessment, and forced projects, these factors were not considered in these testing and validation efforts. The following conclusions can be made based on the results of this work.

- In terms of project boundaries, the PMPs developed by the districts and those generated through the PMP methodology agreed 50 to 62 percent of the time.
- Mismatches between the PMPs developed by the districts and those generated through the PMP methodology can be attributed to the influence of district visual assessment, skid assessment, structural assessment, and forced projects on the districts PMPs.
- The CDA project formation scheme is prone to obscuring localized deficient sections, which may lead to grossly underestimating network needs. This can be corrected by increasing the reliability level when computing a project's aggregated condition. An 80 percent reliability is recommended.
- For the same budget, the methodology allocates funds to projects that have greater impact on improving network condition score. For example, given the same budget, the PMPs generated through the PMP methodology are predicted to exceed the statewide goal (i.e.,

90 percent of pavement lane-miles in "good or better" condition) by 2013, whereas the districts' PMPs remain at (or slightly above) this target throughout 2012–2015.

These results highlight the potential of the developed methodology to support the 4-year pavement management process by incorporating district priorities, producing cost-effective pavement management plans, and providing insights into the impact of these plans on the network condition.

RECOMMENDATIONS

The following recommendations are provided for TxDOT's considerations.

- Fine-tune, calibrate, and implement the developed PMP methodology and computational tool at pilot districts.
- Upload the most recent PMIS dataset for all districts to the PMP tool.
- Provide TxDOT's personnel with hands-on training on using the PMP tool and on applying its underlying concepts and methods.
- Quantify and incorporate uncertainty in key inputs (e.g., unit costs and initial condition) and performance prediction models into the PMP methodology.

REFERENCES

Abaza, K. A. (2006). "Iterative Linear Approach for Nonlinear Nonhomogenous Stochastic Pavement Management Models." *Journal of Transportation Engineering*, 132(3), 244-256.

Bemanian, S., Polish, P., and Maurer, G. (2005). "Pavement Management System Based on Financial Consequence." Transportation Research Record: Journal of the Transportation Research Board, 1940(1), 32-37.

Cambridge Systematics, Parsons, B., System Metrics Group. (2005). Analytical Tools for Asset Management. National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.

Chen, D-H, Bilyeu, J., Lin, H-H, and Murphy, M. (2000). Temperature Correction on Falling Weight Deflectometer Measurements, *Journal Transportation Research Record: Journal of the Transportation Research Board*. No. 1716, pp. 30-39.

Dessouky, S., Krugler P., Freeman, T., and Papagiannakis, A.T. (2011). *Review of Best Practices for the Selection of Rehab and Preventative Maintenance Projects*. Report FHWA/TX-11/0-6586-1, University of Texas at San Antonio, Texas Transportation Institute, Texas A&M University System, and Texas Department of Transportation.

Farid, F., D. W. Johnston, B. S. Rihani, and C. J. Chen. Feasibility of Incremental Benefit-Cost Analysis for Optimal Budget Allocation in Bridge Management Systems. (1996). In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1442, Transportation Research Board of the National Academies, Washington, D.C., pp. 77-87.

Farid, F., Johnston, D. W., Laverde, M., and Chen, C. J. (1994). "Application of Incremental Benefit-Cost Analysis for Optimal Budget Allocation to Maintenance, Rehabilitation, and Replacement of Bridges" *Transportation Research Record*, (1442), 88-100.

Federal Highway Administration, and Office of Asset Management. (2008). Pavement Management Systems: the Washington State Experience. Federal Highway Administration, Office of Asset Management, Washington, D.C.

Federal Highway Administration, Office of International Programs. (2005). "Transportation Asset Management in Australia, Canada, England, and New Zealand." http://purl.access.gpo.gov/GPO/LPS107322; http://purl.access.gpo.gov/GPO/LPS107322 (02/2012, 2012).

Ferreira, A., Antunes, A., and Picado-Santos, L. (2002). "Probabilistic segment-Linked Pavement Management Optimization Model." *Journal of Transportation Engineering*, 128(6), 568-577.

Gharaibeh, N. G., Zou, Y., and Saliminejad, S. (2010). "Assessing the Agreement among Pavement Condition Indexes." *Journal of Transportation Engineering*, 136(8), 765-772.

Gharaibeh, N., T. Freeman, S. Saliminejad, C. Chang-Albitres, J. Weissman, A. Weissman, A. Wimsatt, and C. Gurganus. (2012). *Evaluation and Development of Pavement Scores, Performance Models and Needs Estimates for the TxDOT Pavement Management Information System*. Report No. FHWA/TX-12/0-6386-3. Texas Transportation Institute, Texas A&M University System, 2012.

Golabi, K., Kulkarni, R. B., and Way, G. B. (1982). "A Statewide Pavement Management System." *Interfaces*, 6(12), 5-21.

Hawker, L. and Hattrell, D. (2001). "The New Generation Data Collection Regime for Pavements for Major Roads in England." *Proceedings of the 5th International Conference on Managing Pavements*, Paper No. 57, Seattle, WA.

Keeney, R. L., and Raiffa, H. (1976). Decisions with Multiple Objectives: Preferences and Value Tradeoffs. John Wiley & Sons Inc., New York.

Kulkarni, R. B., Miller, D., Ingram, R. M., Wong, C. W., and Lorenz, J. (2004). "Need-Based Project Prioritization: Alternative to Cost-Benefit Analysis." *Journal of Transportation Engineering*, 130(2), 150-158.

Li, Y., Cheetham, A., Zaghloul, S., Helali, K., and Bekheet, W. (2006). "Enhancement of Arizona Pavement Management System for Construction and Maintenance Activities." *Transportation Research Record: Journal of the Transportation Research Board*, (1974), 26-36.

Liu, W., Jaipuria, S., Murphy, M., and Zhang, Z. (2012). *A Four-Year Pavement Management Plan (FY 2011-FY 2014): Updated Analysis Report*. Report No. 5-9035-01-P6. University of Texas at Austin. Center for Transportation Research (CTR), Austin, Texas.

Ouyang, Y., and Madanat, S. M. (2004). "Optimal Scheduling of Rehabilitation Activities for Multiple Pavement Facilities: Exact and Approximate Solutions." *Transportation Research Part A: Policy and Practice*, 38(5), 347-365.

Ozbay, K., Jawad, D., Parker, N. A., and Hussain, S. (2004). "Life-Cycle Cost Analysis: State of the Practice versus State of the Art." *Transportation Research Record: Journal of the Transportation Research Board*, (1864), 62-70.

Papagiannakis, A. T., Gharaibeh, N. G., Weissmann, J., and Wimsatt, A. J. (2009). "Pavement Scores Synthesis." Rep. No. FHWA/TX-09/0-6386-1, Texas Transportation Institute and Texas Dept. of Transportation, Austin, TX.

Peddibhotla, S. S. S., Murphy, M., and Zhang, Z. (2011). Validation and Implementation of the Structural Condition Index (SCI) for Network-level Pavement Evaluation. Rep. No. FHWA/TX-11/5-4322-01-1, Center for Transportation Research and Texas Dept. of Transportation, Austin, TX.

Peng, F., and Ouyang, Y. (2010). "Pavement Program Planning based on Multi-Year Cost-Effectiveness Analysis." No. Research Report ICT-10-067, Illinois Center for Transportation, University of Illinois at Urbana-Champaign, Illinois.

Pilson, C., Hudson, W. R., and Anderson, V. (1999). “Multiobjective Optimization in Pavement Management by Using Genetic Algorithms and Efficient Surfaces.” *Transportation Research Record: Journal of the Transportation Research Board*, (1655), 42-48.

Saaty, T. L. (1980). *The Analytic Hierarchy Process*. McGraw-Hill Professional Publishing, New York, NY.

Saaty, T. L. (1990). “How to Make a Decision: the Analytic Hierarchy Process.” *European Journal of Operational Research*, 48(1), 9-26.

Sinhal, R., Abell, R., and Ramdas, V. (2001). “Use of Whole Life Costs in network Level Assessments of Road Maintenance Budgets.” *Proc., 5th International Conference on Managing Pavements*, Seattle, WA.

Smilowitz, K., and Madanat, S. M. (2000). “Optimal Inspection and Maintenance Policies for Infrastructure Networks.” *Computer-Aided Civil and Infrastructure Engineering*, 15(1), 5-13.

Stampley, B. E., Miller, B., Smith, R. E., and Scullion, T. (1995). Pavement Management Information System Concepts, Equations, and Analysis Models. Report No. TX-96/1989-1, Texas Transportation Institute and Texas Department of Transportation.

Texas 2030 Committee (2011). *It’s About Time: Investing in Transportation to Keep Texas Economically Competitive.*

Texas Department of Transportation. (2011). *PMIS Technical Manual*. Materials and Pavements Section of the Construction Division.

Vatn, J. (1997). “Maintenance optimisation from a decision theoretical point of view.” *Reliability Engineering & System Safety*, 58(2), 119-126.

Wang, F., Zhang, Z. M., and Machemehl, R. B. (2003). “Decision-Making Problem for Managing Pavement Maintenance and Rehabilitation Projects.” Transportation Research Record, (1853), 21-28.

Zimmerman, K. A. (1995). Pavement Management Methodologies to Select Projects and Recommend Preservation Treatments. Synthesis of Highway Practice No. 222, NCHRP, Transportation Research Board, Washington, D.C.

APPENDIX A: TXDOT DISTRICTS SURVEY

4-year Pavement Management Plan (PMP)

Research Project 0-6683: Develop a Pavement Project Evaluation Index to Support the 4-Year Pavement Management Plan

The purpose of this survey is to gather information from TxDOT districts about the processes used in developing their 4-year Pavement Management Plans (PMPs). This information will be used to develop a decision-support methodology that can be used by TxDOT districts to analyze available data and prioritize pavement projects for their 4-year PMPs.

Your response to this survey by March 2, 2012 will be appreciated by TxDOT and the TTI/UT-SA research team.

General

Q1. Please provide your contact information below:

Name *(required)*	
District	
Title	
Telephone	
E-mail	

Q2. Who are the key personnel involved in developing the 4-year pavement management plan (PMP) for your district?

1) Name and Title	
2) Name and Title	

3) Name and Title	
4) Name and Title	
5) Name and Title	
6) Name and Title	

Q3. In what month of the year does your district establish the initial list of potential projects for the annual 4-year PMP?

Month

Q4. Past TxDOT research used the following definitions for pavement treatment categories. Do you use these categories and definitions in your district? If a category is not used in your district, please select "N/A".

	Yes	No	N/A
Routine Maintenance (RM): Includes crack sealing, edge maintenance, patching (pothole repair), level-up, strip/spot seals, milling, joint repair, localized base repairs, localized concrete repairs. If your answer is NO, please provide a simple definition (or common work types):	○	○	○
Preventive Maintenance (PM): Includes seal coats (chip seals), thin overlays (less than 2 inches), and micro-surfacing treatments for HMA pavement and diamond grinding for PCC pavement. If your answer is NO, please provide a simple definition (or common work types):	○	○	○
Light Rehabilitation (LR): Includes HMA overlay with thickness between 2 and less than 3 inches; pavement widening and application of full width seal coat, base repair and seal; milling, sealing and thin overlay. If your answer is NO, please provide a simple definition (or common work types):	○	○	○
Medium Rehabilitation (MR): Includes mill and inlay; mill, stabilize base and seal; level up and overlay; widen pavement, level up and overlay or seal coat; 3- to 5-inch HMA overlay; thick overlay (without any other activity such as milling); mill, patch, underseal and inlay; base repair, spot seal, edge repair and overlay; mill, cement stabilize base and overlay or seal. If your answer is NO,	○	○	○

please provide a simple definition (or common work types): [ ]

Heavy Rehabilitation (HR): Includes reconstruction of the base and surface, milling and thick overlay or similar activities that restore the pavement functional and structural condition to nearly original conditions. If your answer is NO, please provide a simple definition (or common work types): [ ] ○ ○ ○

Q5. What types of projects are included in the 4-year PMP (please select all that apply)?

- ☐ Routine maintenance projects
- ☐ Preventive maintenance projects
- ☐ Rehabilitation projects
- ☐ Other - Please describe: [ ]

Q6. What are the primary sources of data for developing the initial list of candidate projects for the 4-year PMP in your district (please check all that applies)?

- ☐ PMIS
- ☐ Visual inspection by district personnel
- ☐ TxMAP
- ☐ MMIS
- ☐ Structural evaluation using falling weight deflectometer
- ☐ Other - Please describe [ ]

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Importance Levels for Factors Influencing the Prioritization of Pavement Projects

This section of the survey asks the responder to assign a relative degree of importance on a 1-9 scale for several factors, one pair at a time, according to their influence on the prioritization of pavement maintenance and rehabilitation (M&R) projects.

1=Equal Importance	3=Somewhat Greater Importance
5=Strong Importance	7=Very Strong Importance
9=Absolute Importance	2,4,6,8=Intermediate

The comparisons will appear like this:

	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Factor A	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Factor B

For example:

If Factor A has absolute importance compared to Factor B, click the "9" button on the left (near Factor A)

If Factor B has strong importance compared to Factor A, click the "5" button on the right (near Factor B)

If Factors A and B have equal importance, click the "1" button at the center

If Either Factor A or Factor B or Both factors are not considered by your district, do not click any buttons (ie. leave the buttons blank).

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Pair-wise Comparisons of Pavement Current Condition Indicators for Rehabilitation Projects

Please assign a 1-9 relative degree of importance to the following pairs of indicators of pavement current condition according to their influence on prioritizing rehabilitation projects in your district.

1=Equal Importance | 3=Somewhat Greater Importance
5=Strong Importance | 7=Very Strong Importance
9=Absolute Importance | 2,4,6,8=Intermediate

If one factor or both factors in a pair are not considered by your district, do not click any buttons and proceed to the next pair.

	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Condition Score	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	*Rate of Deterioration
Condition Score	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Ride Score
Condition Score	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Skid Number
Condition Score	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	**Structural Evaluation (ie. FWD)
Condition Score	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	***District's Visual Assessment
Rate of Deterioration	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Ride Score
Rate of Deterioration	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Skid Number
Rate of Deterioration	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Structural Evaluation (ie. FWD)

To be continued in the next page

Notes:

*Rate of Deterioration: Annual drop in pavement condition indicators in past years. Generally, a high rate of deterioration is an early warning sign that the pavement is rapidly approaching unacceptable condition.

**Structural Evaluation: Assessment of the pavement structural condition based on falling weight deflectometer (FWD) testing. Past TxDOT research efforts suggested that this evaluation is needed for proper distinction between pavements that do and do not require structural improvements.

***District's Visual Assessment: District's own assessment of pavement condition through visual field inspection.

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Continuation:

1=Equal Importance	3=Somewhat Greater Importance
5=Strong Importance	7=Very Strong Importance
9=Absolute Importance	2,4,6,8=Intermediate

If one factor or both factors in a pair are not considered by your district, do not click any buttons and proceed to the next pair.

	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Rate of Deterioration	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	District's Visual Assessment
Ride Score	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Skid Number
Ride Score	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Structural Evaluation (ie. FWD)
Ride Score	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	District's Visual Assessment
Skid Number	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Structural Evaluation (ie. FWD)
Skid Number	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	District's Visual Assessment
Structural Evaluation (ie. FWD)	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	District's Visual Assessment

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Pair-wise Comparisons of Pavement Current Condition Indicators for <u>Routine and Preventive Maintenance Projects</u>

Please assign a 1-9 relative degree of importance to the following pairs of indicators of pavement current condition according to their influence on prioritizing routine and preventive maintenance projects in your district.

1=Equal Importance	3=Somewhat Greater Importance
5=Strong Importance	7=Very Strong Importance
9=Absolute Importance	2,4,6,8=Intermediate

If one factor or both factors in a pair are not considered by your district, do not click any buttons and proceed to the next pair.

	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Distress Score	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	*Rate of Deterioration
Distress Score	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Ride Score
Distress Score	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Skid Number
Distress Score	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	**District's Visual Assessment
Rate of Deterioration	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Ride Score
Rate of Deterioration	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Skid Number
Rate of Deterioration	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	District's Visual Assessment
Ride Score	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Skid Number
Ride Score	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	District's Visual Assessment

Skid Number	○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○	District's Visual Assessment

Notes:

*Rate of Deterioration: Annual drop in pavement condition indicators in past years. Generally, a high rate of deterioration is an early warning sign that the pavement is rapidly approaching unacceptable condition.

**District's Visual Assessment: District's own assessment of pavement condition through visual field inspection.

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Pair-wise Comparisons of Short-Term and Long-Term Indicators of Benefit and Cost

Please assign a 1-9 relative degree of importance to the following pairs of indicators of benefit and cost according to their influence on prioritizing M&R projects in your district.

1=Equal Importance
3=Somewhat Greater Importance
5=Strong Importance
7=Very Strong Importance
9=Absolute Importance
2,4,6,8=Intermediate

If one factor or both factors in a pair are not considered by your district, do not click any buttons and proceed to the next pair.

	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Pavement Current Condition	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Current Traffic Volume
Pavement Current Condition	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Initial Cost
Pavement Current Condition	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	*Long-Term Performance Benefits
Pavement Current Condition	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Life-Cycle Cost
Current Traffic Volume	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Initial Cost
Current Traffic Volume	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Long-Term Performance Benefits
Current Traffic Volume	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Life-Cycle Cost

Initial Cost	○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○	Long-Term Performance Benefits
Initial Cost	○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○	Life-Cycle Cost
Long-Term Performance Benefits	○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○	Life-Cycle Cost

Note:

*Long-term performance benefit of an M&R project represents the improvement in pavement performance throughout the analysis period, adjusted for forecasted AADT throughout the same analysis period and the project length

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Pair-wise Comparisons of Traffic Volume Indicators

Please assign a 1-9 relative degree of importance to Annual Average Daily Traffic (AADT) versus Truck AADT according to their influence on prioritizing M&R projects in your district.

1=Equal Importance	3=Somewhat Greater Importance
5=Strong Importance	7=Very Strong Importance
9=Absolute Importance	2,4,6,8=Intermediate

If one factor or both factors are not considered by your district, do not click any buttons.

	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
AADT	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Truck AADT

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Additional Factors

Q7. Do you consider other factors when developing the initial list of candidate projects for the 4-year PMP in your district (please check all that applies)?

- ☐ Section age (ie. years since original construction or last M&R action)
- ☐ Frequency of past maintenance actions applied to the section
- ☐ Condition of adjacent sections
- ☐ Pavement surface type (flexible/rigid); if yes, which type is given higher priority? [ ]
- ☐ Evacuation routes
- ☐ Population density
- ☐ Economic development
- ☐ Feedback from highway users (eg. complaints)
- ☐ Others - Please describe: [ ]

Closing and Follow-up

Q8. We anticipate conducting follow-up meetings or conference calls with interested districts. Do you want the research team to contact you (or other personnel in your district) for a follow-up meeting or conference call?

- ○ Yes
- ○ No

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Q9. Please provide any additional comments below:

End of Survey. Thank you for your time and valuable information.

(Please click the "next" button for your responses to be recorded)

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APPENDIX B: ASSESSING THE SUITABILITY OF SCI FOR PROJECT PRIORITIZATION DECISIONS

APPENDIX B: ASSESSING THE SUITABILITY OF SCI FOR PROJECT PRIORITIZATION DECISIONS

The structural condition index (SCI) was originally developed under TxDOT Project 0-4322 and was recently applied under Project 5-4322 (Peddibhotla et al. 2011) as a screening tool to identify pavements that need structural improvement. This appendix discusses the following:

- Verifying and improving the SCI computational procedure.
- Evaluating potential associations between SCI and pavement surface condition using 155 pavement sections from the Bryan and Fort Worth Districts.

Verifying and Improving the SCI Computational Procedure

Figure B1 illustrates the SCI calculation procedure. The researchers incorporated a procedure to normalize falling weight deflectometer (FWD) deflections taking into account the pavement temperature. Chen et al. (2000) reported that only the W_1 (closest to the loading plate) and W_2 FWD deflections are significantly influenced by pavement temperature. In this study, the researchers developed an equation to take into account the temperature effect on the FWD maximum deflection, as shown below.

$$W_{Tw}^{1} = W_{T_C}^{1}\left(\frac{1.0823^{-0.0098t}}{0.8631}\right)T_{w}^{0.8316}T_{c}^{-0.8419}$$

Equation B1

Where W_{TW}^{1} is W_1 deflection adjusted to temperature T_w (mm); t = thickness of the AC layer (mm); T_w is temperature to which the W_1 deflection is adjusted (°C); and T_c is mid-depth temperature at the time of FWD data collection (°C). In this technical memorandum, T_w was chosen 25°C, as a reference temperature. With regard to normalizing W_2 deflection, a simple interpolation was applied using normalized W_1 and un-normalized W_3 deflections.

The researchers replicated the SCI procedure in a spreadsheet. The researchers took the FWD normalized deflection basins for 10 FWD stations on FM 2199 and then used the spreadsheet to compute the SCI. The SCI values calculated using this spreadsheet were then compared to the corresponding values obtained from Project 5-4322. The roadway section used in this comparison (FM 2199) is composed of 2 inches of asphalt concrete surface and 7 inches of base that results in 9 inches of total pavement thickness. The 20-year equivalent single axle load (ESAL) is 1.4 million based on PMIS data. As shown in Figure B2, the SCI original calculation procedure was replicated successfully. Note that the FWD deflections in the original procedure are only normalized by the reference loading.

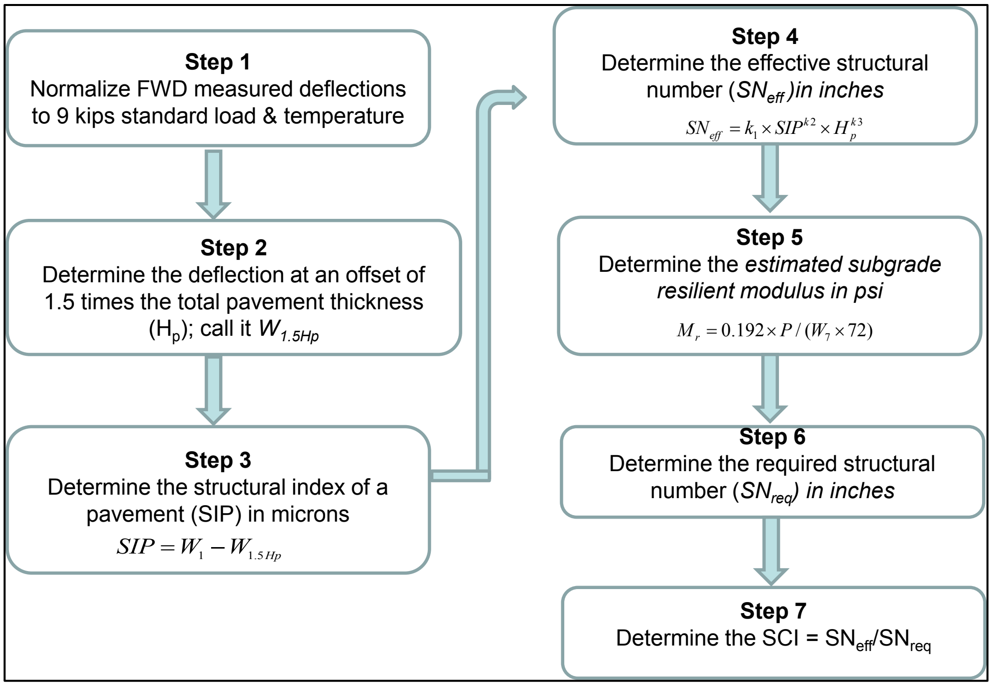

Figure B1. Illustration of SCI Computation Procedure.

where W_1 = normalized peak deflection; k_i are regression coefficients; P = applied load in pounds; and W_7 = FWD deflection at sensor 7 in mils.

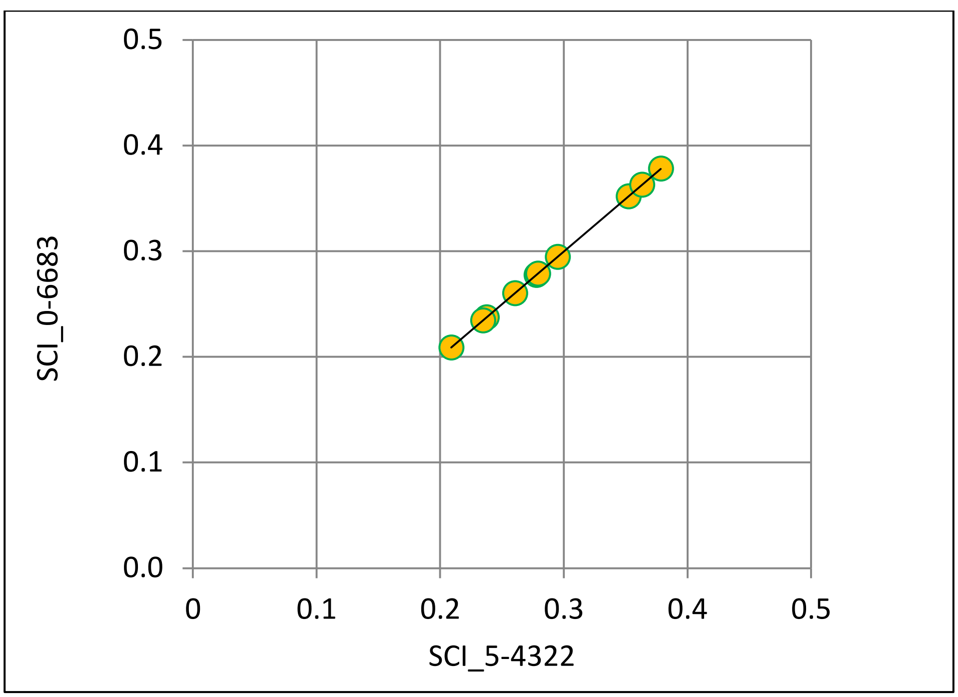

Figure B2. SCI values Computed Using Original Procedure (Developed under Project 5-4322) and Replicated Procedure (Replicated under This Study).

Pavement total thickness is an input to the SCI calculation procedure. However, currently TxDOT's pavement-related databases lack reliable information on layer thickness and thus the total pavement thickness is often estimated from construction plans, pavement forensic reports, etc. To assess the sensitivity of SCI to this input parameter, the researchers calculated SCI by varying the total pavement thickness from 6 to 22 inches for selected pavement sections that represent ACP and surface-treated pavement on FM roads, and ACP on SH roads.

Figure B3 to Figure B5 show the sensitivity of SCI to change in total pavement thickness. Each data point represents the average SCI of seven pavement sections. The red dot indicates the SCI computed with a reference thickness. The effect of total pavement thickness on SCI is more evident in surface-treated sections than in ACP sections. The results of this sensitivity analysis demonstrate the importance of using accurate total pavement thickness data in SCI calculations.

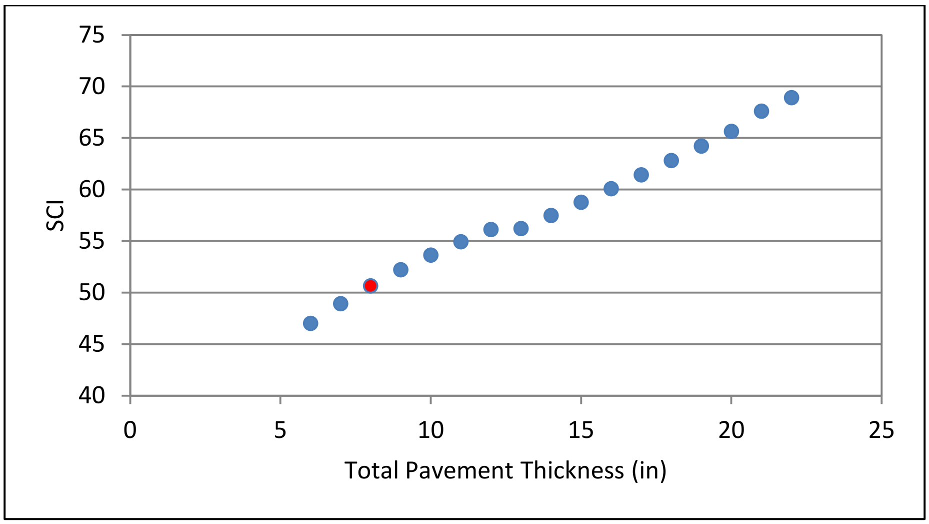

Figure B3. Effect of Total Pavement Thickness on SCI for ACP on FM Roads.

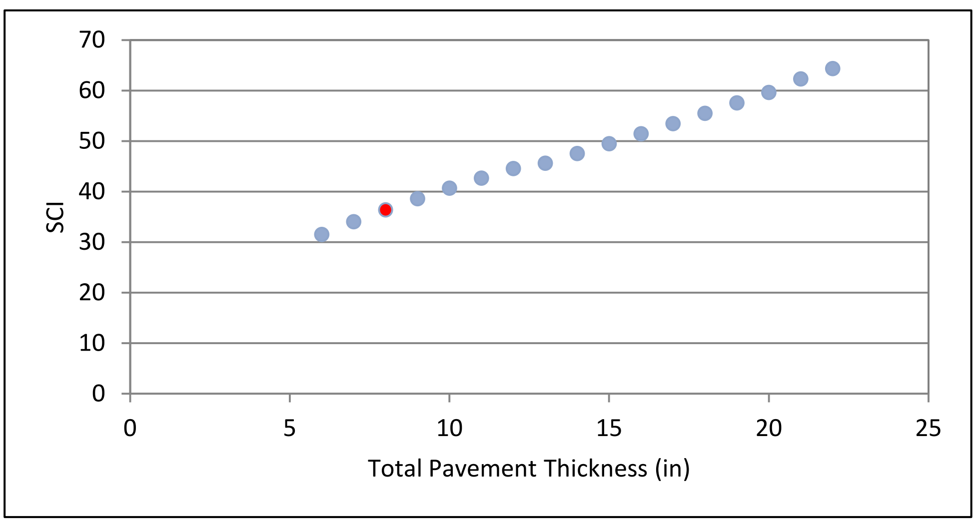

Figure B4. Effect of Total Pavement Thickness on SCI for Surface-Treated Pavement on FM Roads.

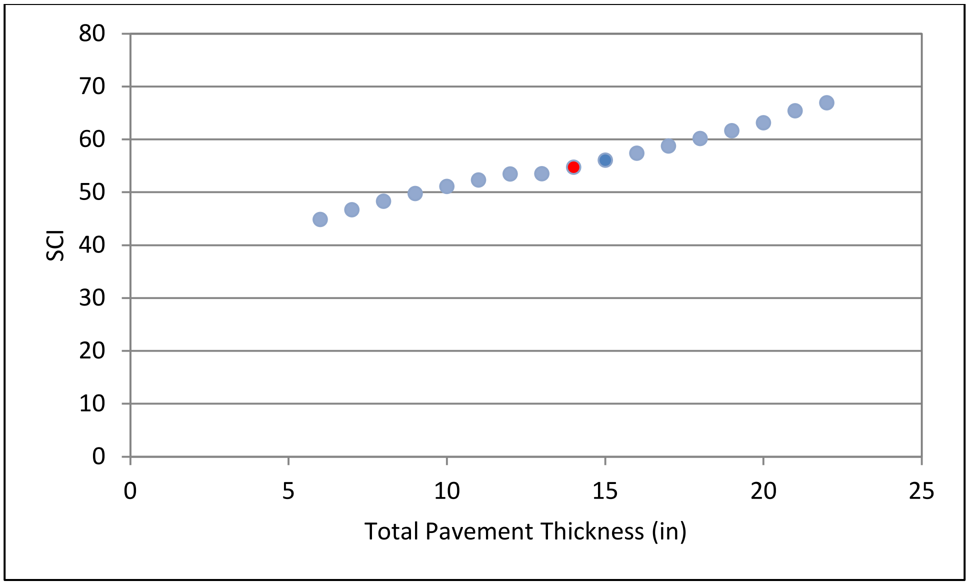

Figure B5. Effect of Total Pavement Thickness on SCI for ACP on SH Roads.

Association between SCI and Surface Condition

SCI was computed using available data for eight roadway corridors in the Fort Worth District and 25 corridors in the Bryan District (see Table B1). For the Fort Worth sections, the data on FWD deflections, surface type, and total pavement thickness were obtained from FWD measurements and ground penetrating radar (GPR) surveys that were conducted in summer 2010 as part of TxDOT project 0-6498. For the Bryan sections, the FWD deflection data were provided by the district, pavement surface type was obtained from PMIS, and the total pavement thickness was estimated based on typical cross sections (typically, 8 inch for FM roads, 14 inch for SH roads, and 18 inch for US roads).

For brevity, the detailed data for FM 52 and FM 2257 only are presented and discussed here. These corridors represent two different cases that provide insights into the patterns and possible associations between FWD data and PMIS scores. The first case (FM 51) shows high variability in deflection measurements along the tested segment, while the second case (FM 2257) shows fairly uniform deflection measurements.

Table B1. Roadway Corridors Used in SCI vs. Surface Condition Analysis.

Roadway	Section Limits	District	FWD Test Lane	Surface Type	ESALs, million
FM 52	RM 506-0.1 –RM512+1.75	FWT	K1	1.5"AC	0.29
FM 2257	RM 542 – RM 546	FWT	K1	1-course surface treatment (1-2")	3.7
FM 2331	RM 292-0.6 – RM 302+0.1	FWT	K6	2" AC	0.68
FM 2738	RM 290-1.7 – RM 294+0.2	FWT	K1	1-course surface treatment (1-2")	1.76
FM 3048	RM 556-2.1 – RM 558+0.1	FWT	K1	1-course surface treatment (1-2")	1.79
FM 3325	RM 264 – RM 270+1.1	FWT	K6/K1	5" AC	8.59
SH 171	RM 294 – RM 306	FWT	K1	2.5" AC	15.7
SH 174	RM 304 – RM 310	FWT	K1	2.0" AC	10.9
FM 158	RM616 – RM616+1	BRY	K1	2.0" AC	2.6
FM 1179	RM408 – RM410+0.5	BRY	K1	2.0" AC	2.3
FM 1687	RM606 – RM614+1.5	BRY	K6	2.0" AC	0.3
FM 111	RM424 – RM426+1.5	BRY	K6	2.0" AC	0.12
FM 166	RM600 – RM604+1.5	BRY	K6	2.0" AC	0.7
FM 80	RM370+1 – RM374	BRY	K6	2.0" AC	0.9
FM 1124	RM324 – RM324+1.5	BRY	K1	2.0" AC	0.1
SH 105	RM650– RM658	BRY	K1	4.0" AC	4.5
SH 150	RM670– RM678	BRY	K1	4.0" AC	1.7
SH 21	RM610– RM618	BRY	L, R	6.0" AC	2.6
SH 30	RM640+0.5– RM648	BRY	K1	4.0" AC	4.1
SH 47	RM416+0.5– RM418	BRY	L, R	4.0" AC	1.1
SH 6	RM610– RM616	BRY	L, R	6.0" AC	9.1
SH 7	RM620– RM622+1.5	BRY	K1	4.0" AC	3.2
SH 75	RM390– RM390+1	BRY	K1	4.0" AC	0.8
SH 90	RM416+1– RM430+0.5	BRY	K1	4.0" AC	2.7
US 190	RM628-1– RM634+1	BRY	K6	6.0" AC	7.1
US 290	RM676+0.5– RM686	BRY	K1	6.0" AC	8.5
US 77	RM442+1.5– RM444+0.5	BRY	K1	4.0" AC	4.4
US 79	RM508+1.5– RM444+0.5	BRY	K1	4.0" AC	6.3
US 84	RM742+0.3– RM742+0.8	BRY	K1	4.0" AC	10.4
FM 2038	RM624– RM628+1	BRY	K1	1-course surface treatment (1-2")	0.38
FM 27	RM620+0– RM626+1.5	BRY	K6	2.0" AC	2.8
FM 1365	RM616+0– RM620+1.5	BRY	K6	2.0" AC	2.8
FM 1451	RM342+0.5– RM6\348	BRY	K6	2.0" AC	0.3

FM 2257

This 4-mile segment (RM 542 – RM 546) of FM 2257 is located in Parker County. The GPR survey and FWD tests were conducted in August 2010. As illustrated in Figure B6, several patched areas existed near RM 544. This is consistent with the 2011 condition and distress scores (obtained from PMIS). According to the GPR data, the total pavement thickness of this roadway segment ranged from 7 to 11 inches, as shown in Figure B7.

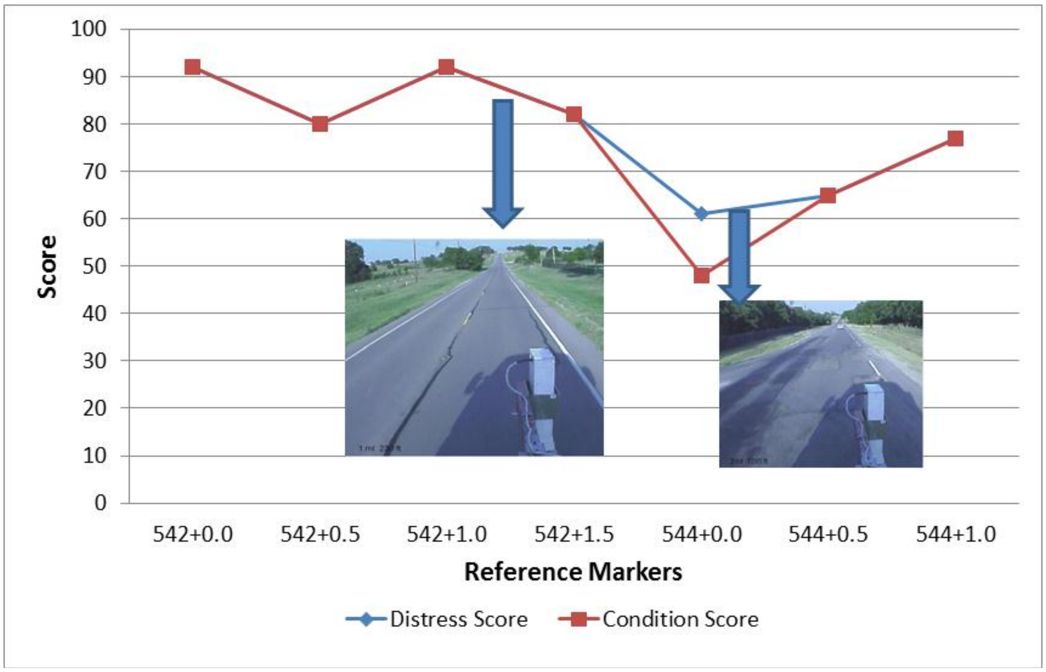

Figure B6. FM 2257 2011 PMIS Scores along with Snapshot Surface Images Obtained from GPR Survey.

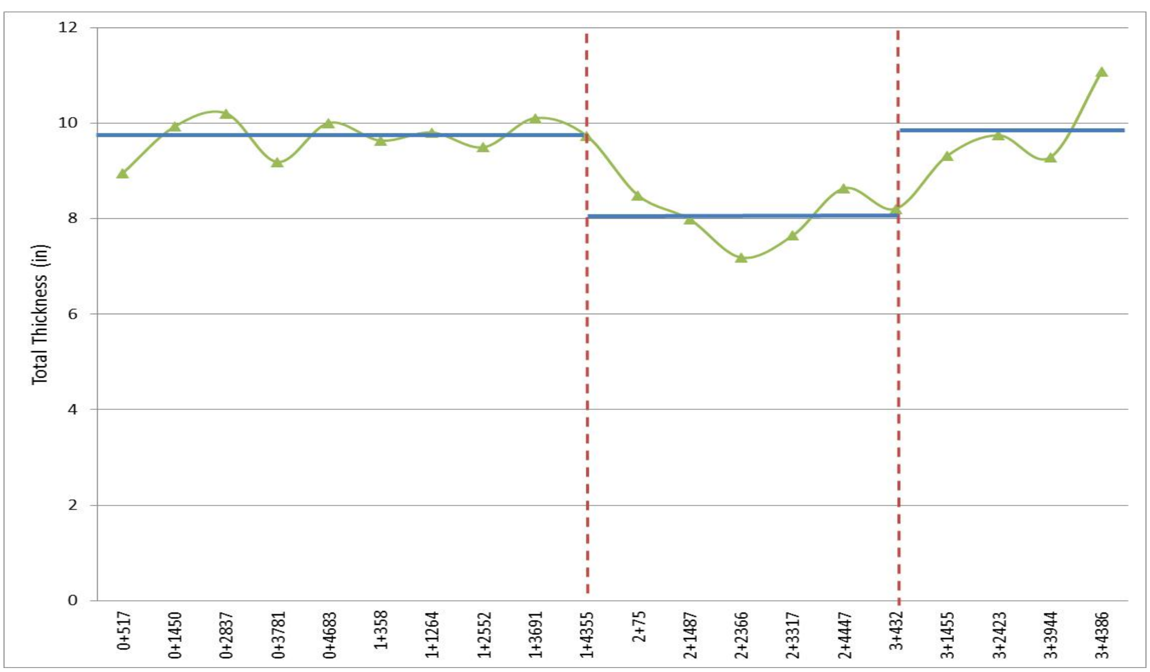

Figure B7. Segmentation of Total Pavement Thickness of FM-2257 Based on GPR Data.

The deflection measurements for this roadway segment are shown in Figure B8. Normalizing FWD deflections with respect to load and temperature generally yields higher SCI values than those normalized by 9 kips of standard load only. The measured pavement temperature was approximately 105.5°F during FWD data collection. As shown in Figure B9, the PMIS scores and SCI follow a similar pattern. This roadway segment is an example of cases where deflection measurements are uniform, and consequently SCI and PMIS scores are consistent (i.e., follow a similar pattern). In these cases, it appears reasonable to use SCI in the M&R project prioritization process.

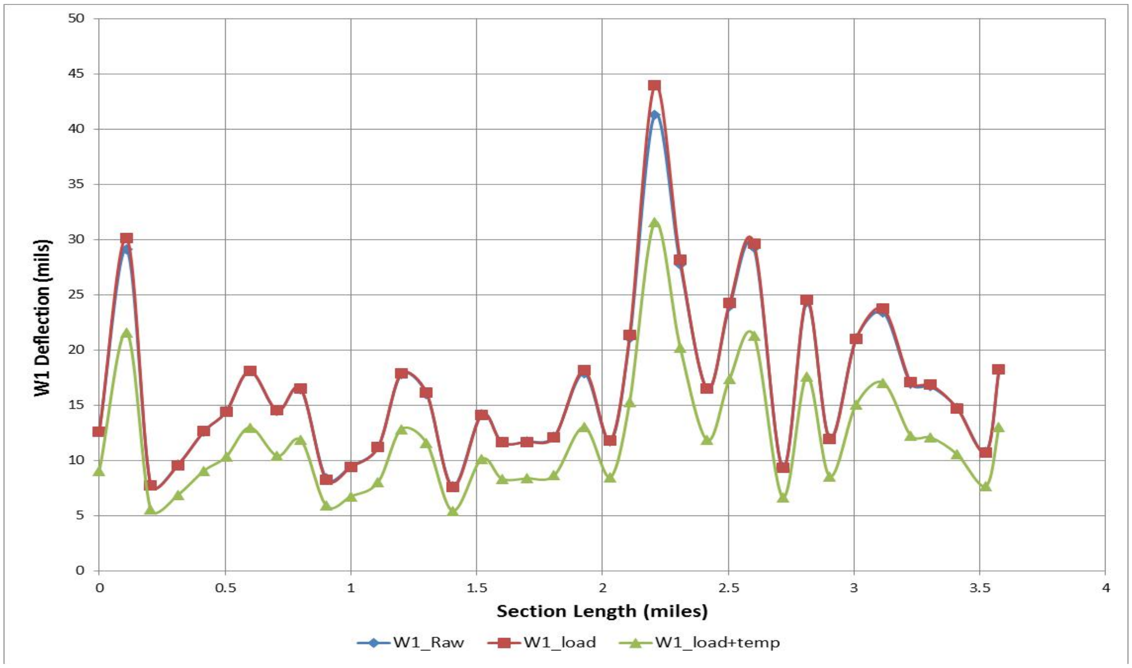

Figure B8. Deflection Measurements along FM 2257 Segment.

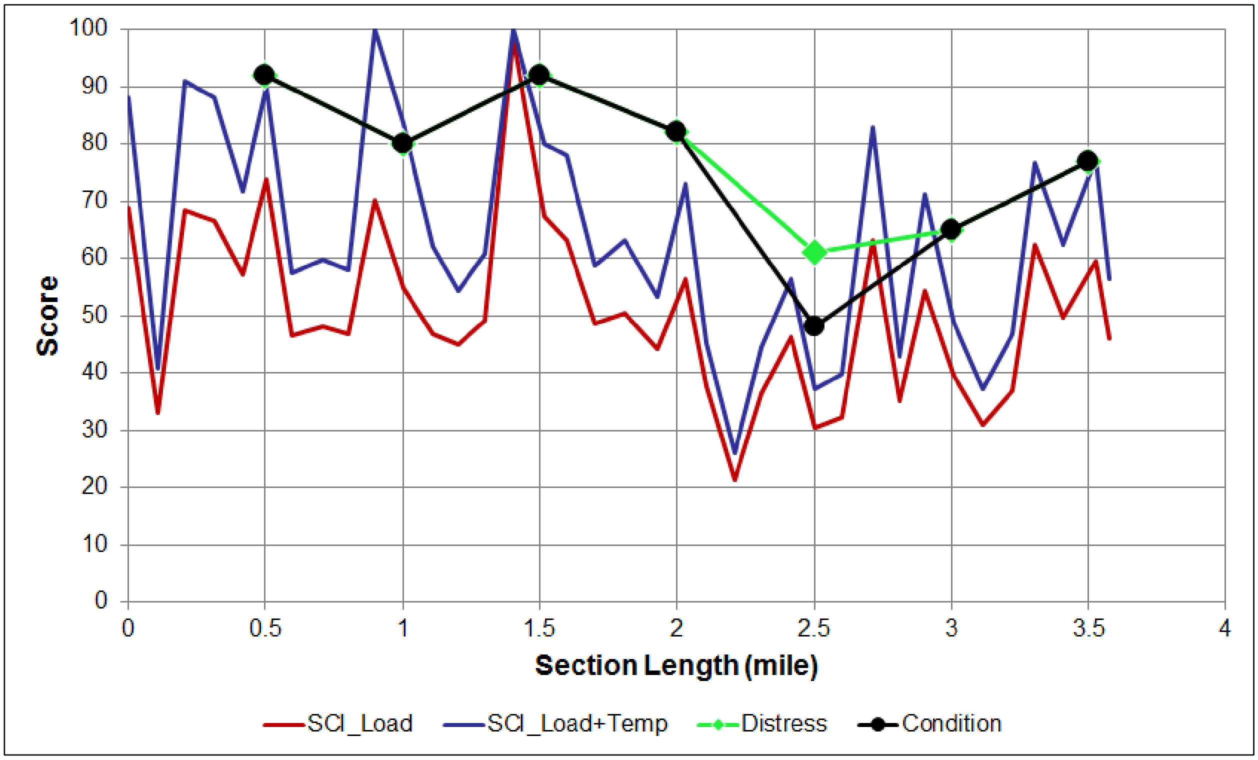

Figure B9. Comparison of SCI and PMIS Scores for FM 2257.

FM 52

This segment of FM 52 (RM 506-0.1 – 512+1.75) is located in Palo Pinto County. The GPR survey and FWD tests were conducted in August 2010. As illustrated in Figure B10, the section exhibited no surface distress, which is consistent with 2011 PMIS scores. The section was treated by full depth reclamation (FDR) in early 2010. According to the GPR data, the total pavement thickness of this roadway segment ranged from 8.2 to 17 inches, as shown in Figure B11.

Figure B10. Snapshot Surface Images of FM 52 Obtained from GPR Survey.

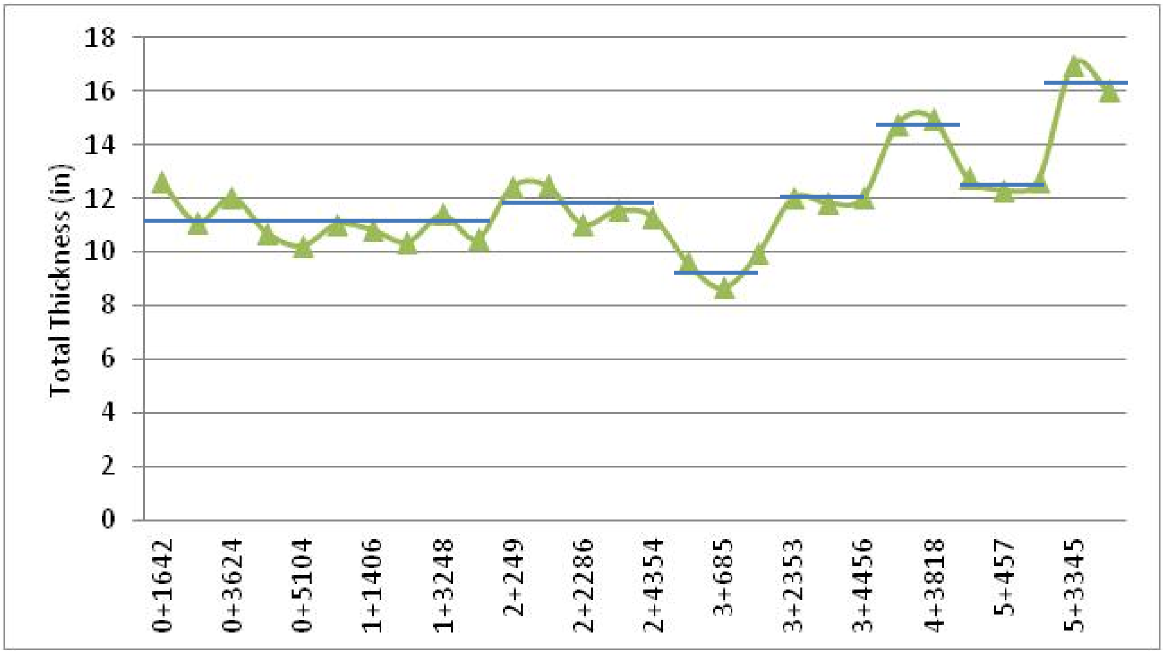

Figure B11. Total Pavement Thickness of FM-52 Based on GPR Data.

While normalizing deflections based on temperature and load reduced measurement variability, extreme SCI values remain present (see Figure B12). In this case, SCI computed for individual FWD tests (e.g., taken every 0.1 mile) may not agree with PMIS distress and condition scores (which typically represent the pavement condition over 0.5-mile long sections). These discrepancies between SCI and condition and distress scores are visible in Figure B13.

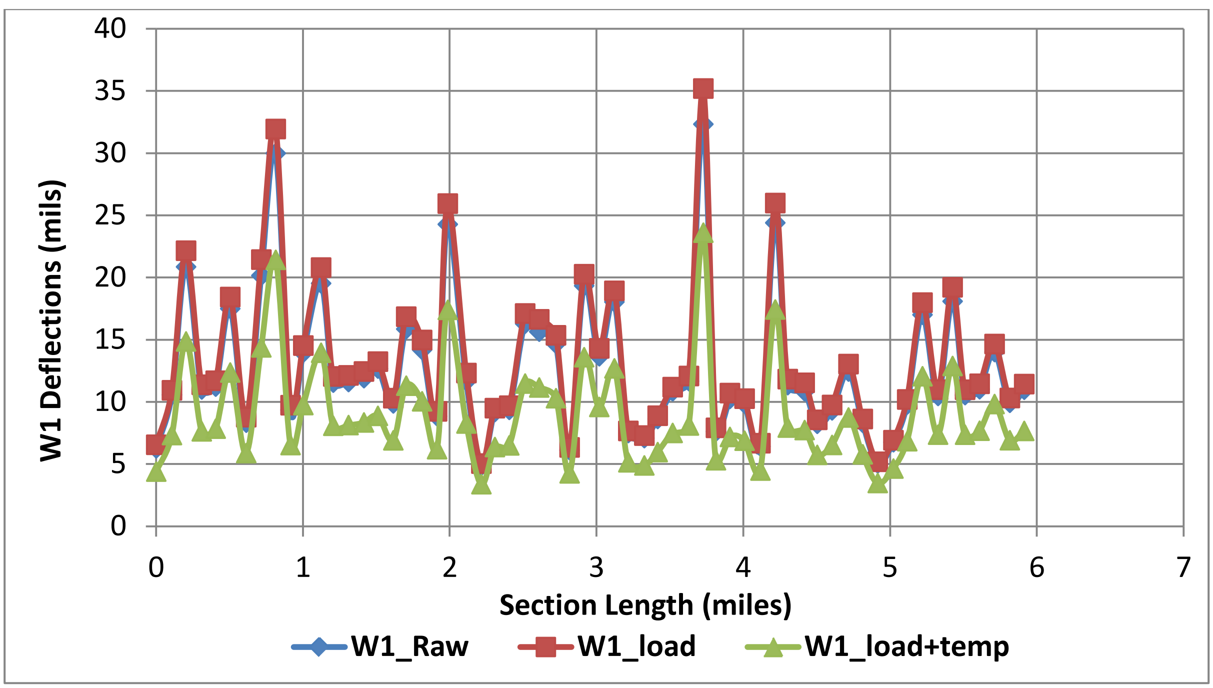

Figure B12. Deflection Measurements along FM 52 Segment.

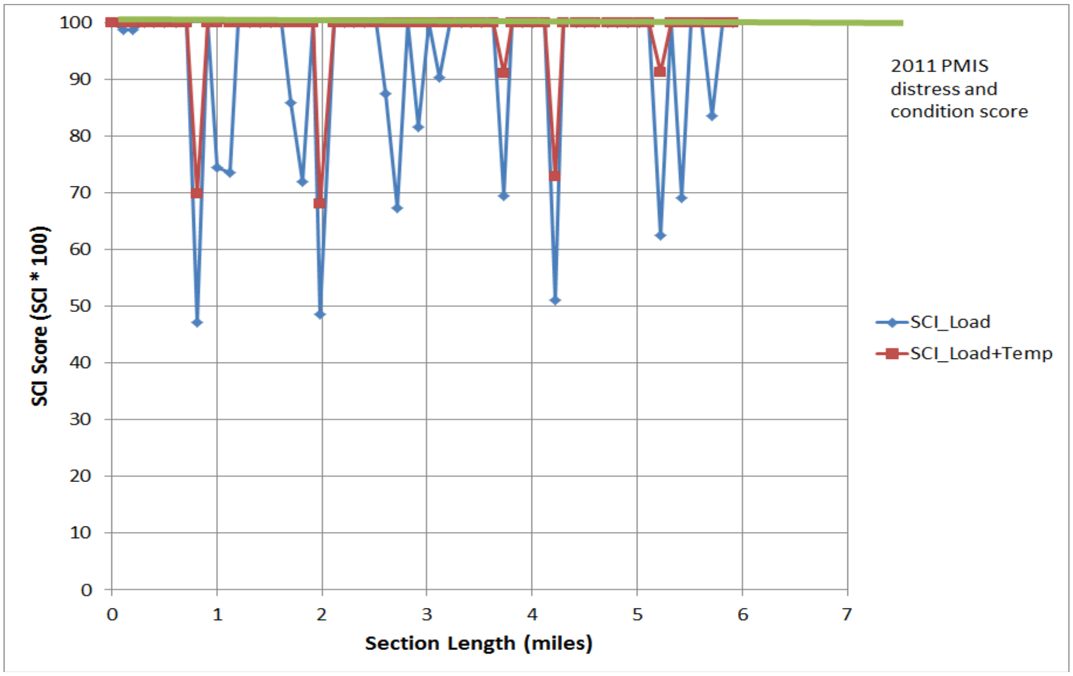

Figure B13. Comparison of SCI and PMIS Scores for FM 52.

Prediction of SCI Based on Changes in Distress Score

SCI can potentially be considered by the districts when developing their PMPs, as a measure of the pavement's structural condition. However, in many cases the FWD data needed to compute SCI is not available. The models developed in this study and discussed here provided the districts with a tool to predict SCI as a function of distress score value and annual drop. The rational of these models is that a significant drop in distress score can be associated with inadequate structural adequacy, which is estimated in terms of SCI. This concept is illustrated in Figure B14. If DS_0 is the value of DS in the year prior to year of the FWD deflection testing (i.e., the SCI year) and DS_1 is the value of DS in the same year of FWD testing; the drop in DS (ΔDS) is the difference between DS_0 and DS_1 (DS_0-DS_1).

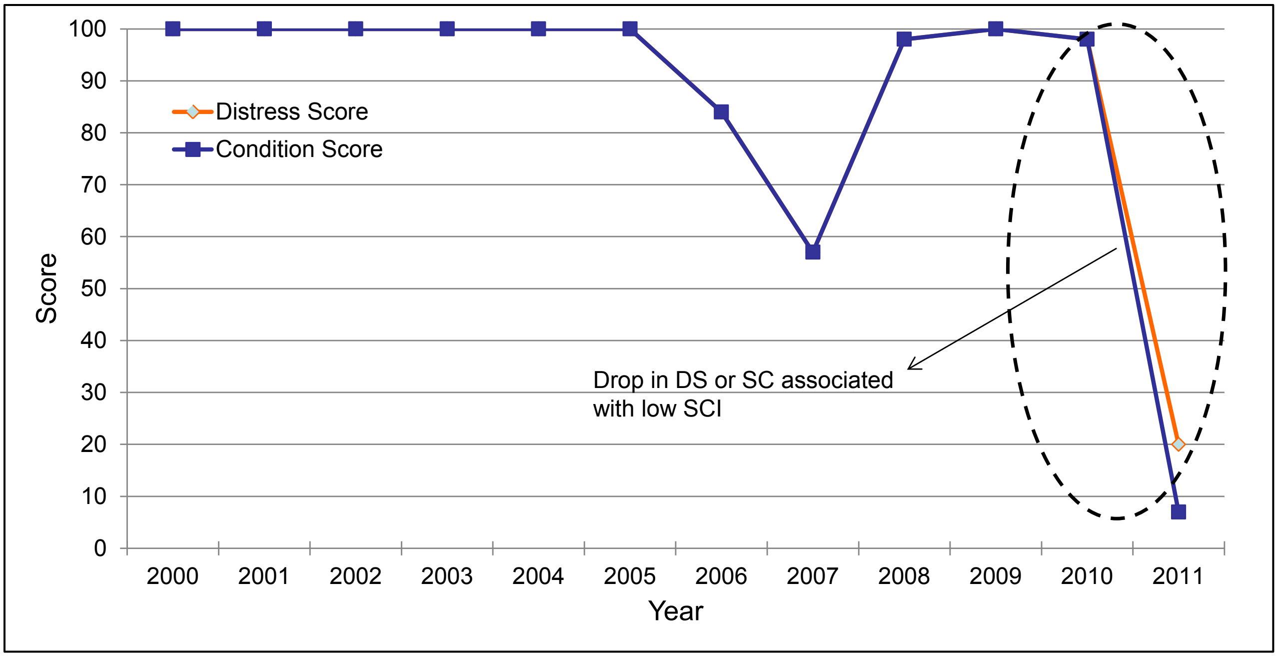

Figure B14. SCI versus Drop in PMIS Scores for an Example Pavement Section.

The FWD tests were delineated for each PMIS section. To ensure adequate representation of the entire PMIS section (typically 0.5-mi long), only PMIS sections that have at least five FWD tests per section are used in this analysis. Initial comparisons between SCI and PMIS scores (both score value and annual drop) showed that sections with SCI < 50 have the least agreement between the PMIS scores and SCI. There were 29 sections in this category, which were excluded from any further analysis. Ultimately, 123 PMIS sections (out of the initial 152 sections) were used in developing deterministic and probabilistic models for predicting SCI as a function of distress score value and annual drop. Note that the SCI plotted are based on temperature and load normalization of FWD deflection data.

Deterministic Model for Predicting SCI

Based on the limited data available in this study, a reasonable trend exists between the calculated SCI and drop in DS when the current DS is ≥ 70 (see Figure B15); however, no such trend could be found when the current DS is < 70 (see Figure B16). For the purpose of identifying pavement sections that need M&R work, the second case is irrelevant since the low DS is likely to identify these sections for possible M&R work, regardless of the SCI value.

The following best fit model represents the relationship between SCI and drop in DS when current DS is ≥ 70:

$$SCI_{AVE} = \frac{100}{1+\alpha(\Delta DS)^{\beta}} \qquad \textbf{Equation B2}$$

Where, α and β are regression coefficients. The fitted coefficients are 0.0189 and 0.9333 with standard errors of the estimate (SEE) of 10.8.

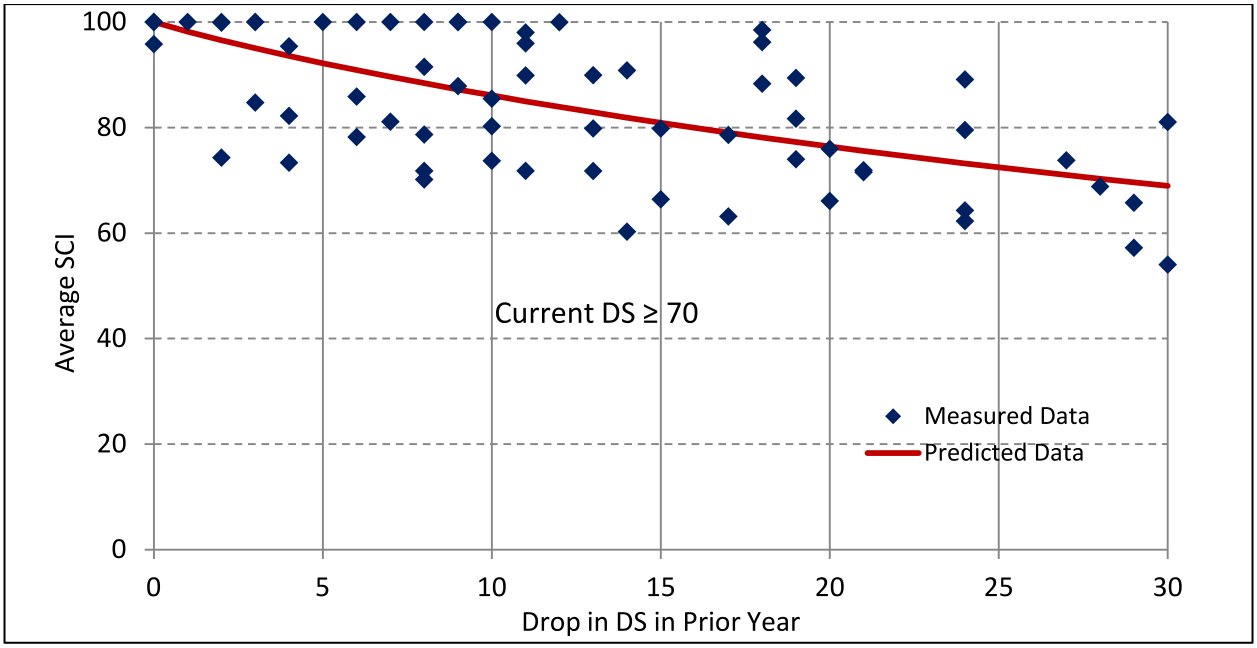

Figure B15. Potential Relationship between SCI and Drop in DS when Current DS ≥70.

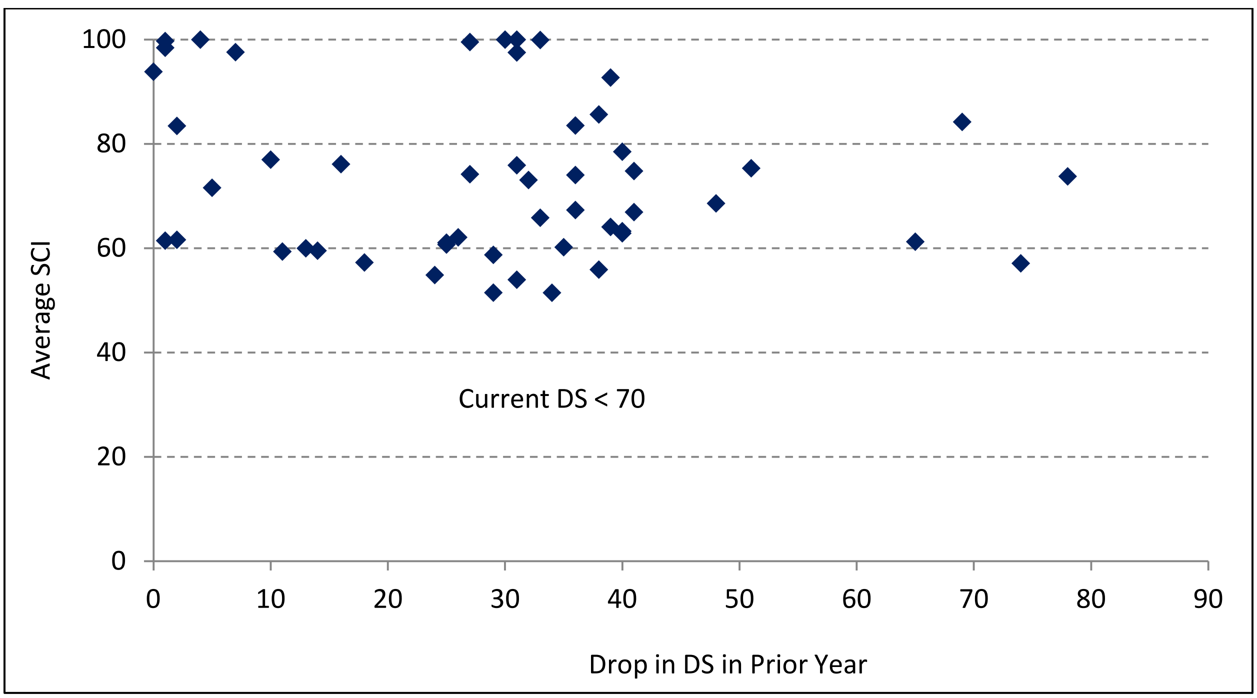

Figure B16. No Clear Relationship between SCI and Drop in DS when Current DS <70.

Probabilistic Model for Predicting SCI

To provide TxDOT with an additional tool for estimating SCI when FWD data are not available, the researchers employed a probabilistic approach to detect structurally-weak pavements based on current DS and ΔDS. TxDOT Project 5-4322 suggested that an SCI greater than 80 indicates that the pavement does not need any type of rehabilitation (which indicates that the pavement is structurally adequate). The researchers developed a probabilistic model that allows for predicting the probability that SCI is less than 80 based on current DS (i.e., DS_1) and ΔDS. This model is based on the conditional probability mass function, which is defined as follows:

$$P_{X|Y,Z}(x \mid y, z) = \frac{P_{X,Y,Z}(x, y, z)}{\sum_{x} P_{X,Y,Z}(x, y, z)} = \frac{P_{X,Y,Z}(x, y, z)}{P_{Y,Z}(y, z)}$$

Equation B3

where x, y, and z are three discrete random variables; $P_{X|Y,Z}(x|y,z)$ is the conditional probability of x, given y and z; and x, y and z represent SCI, ΔDS, and DS_1 conditions, respectively (e.g., SCI <90, ΔDS >10 and DS≥70).

The above model was employed to compute the probability of having SCI less than 80 for various ranges of DS_1 and ΔDS (see Table B2). This probability can be used as an indicator of structural inadequacy when FDW measurements are not available (and consequently SCI cannot be computed directly). For example, if the current DS is ≥ 70 and the drop in DS since last year was greater than 10 points, there would be a 76 percent chance that the pavement is having structural problems (i.e., its SCI is less than 80). While this approach appears promising, it is limited to the data that were available in this study and thus requires further validation.

Table B2. Conditional Probability of SCI<80 Based on DS1 and ΔDS.

	DS_1<70	DS_1≥70
ΔDS <5	55%	32%
5≤ ΔDS ≤10	67%	40%
ΔDS >10	82%	68%