# INCORPORATING RISK AND UNCERTAINTY INTO PAVEMENT NETWORK MAINTENANCE AND REHABILITATION BUDGET ALLOCATION DECISIONS

A Dissertation

by

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# ABSTRACT

According to the American Society of Civil Engineers, 33% of the United States' major roads are in poor or mediocre condition with a projected funding shortfall of $549.5 billion for 2010–2015. Environmental factors, increased traffic, and lack of adequate maintenance are causing many of these roads to deteriorate faster. The imbalance between maintenance needs and available funds tends to become more critical over time, demanding more reliable and advanced tools for allocating funds and prioritizing projects.

In 2012, the U.S. Congress passed the Moving Ahead for Progress in the 21st Century Act (MAP-21) to fund surface transportation programs for 2013–2014 and beyond. MAP-21 establishes a framework for federal transportation investments with the goals of preserving the highway system while improving its condition and performance. This law requires states to develop risk-based asset management plans that include risk management analysis. In order to fulfill MAP-21 requirements, pavement management systems must be upgraded to incorporate risk management, permitting pavement management systems to serve as a more realistic decision support tool for planning and budget allocation in pavement maintenance and rehabilitation.

This dissertation aims to incorporate risk assessment into maintenance and rehabilitation budget decisions at the planning stage. For risk assessment, uncertainty was incorporated into the analysis process, and factors influencing decisions are modeled as probability distributions. The factors included are pavement conditions, available funds, maintenance and rehabilitation costs, and performance prediction. The risk for each scenario is defined as the probability of failing to achieve pre-defined performance goals.

The results of this research show that the benefit-cost budget allocation method has the lowest risk to fail to achieve the performance goals. The maintenance-first method has slightly higher risk but averages scores are better compared with benefit-cost. The method with highest risk is the rehabilitation-first, which have a significant difference with all the other allocation methods.

This research demonstrates that incorporating uncertainty and risk assessment into pavement management can lead to better-informed decision and ultimately improved M&R budget allocation policies. This work provides DOTs with analytical tools and methods for meeting the requirements of MAP-21.

# DEDICATION

In memory of my father Juan Julio J., who was a professor and example for many generations of civil engineers in Cusco. Dedicated to my dear wife, Rocío; to my daughter, Marisol; and to my mother, Libertad.

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# NOMENCLATURE

| | |
|---|---|
| AADT | Annual average daily traffic |
| AASHTO | American Association of State Highway and Transportation Officials |
| ACP | Asphalt concrete pavement |
| AHP | Analytic hierarchy process |
| AUPC | Area under the performance curve |
| B-C | Benefit cost allocation method |
| BRM | Beginning reference marker |
| CDA | Cumulative difference algorithm |
| CDF | Cumulative distribution function |
| CS | Condition score |
| DISCOS | District and county statistics of TxDOT |
| DOT | Department of transportation |
| DS | Distress score |
| EffecLife | Effective life |
| ERM | Ending reference marker |
| HR | Heavy rehabilitation |
| IBC | Incremental benefit-cost |
| ID | Highway identification |
| ISTEA | Intermodal Surface Transportation Efficiency Act |
| LCC | Life-cycle cost |
| LCCA | Life-cycle cost analysis |

| | |
|---|---|
| LM | Project length |
| LR | Light rehabilitation |
| LTPB | Long-term performance benefit |
| LTPP | Long-term pavement performance |
| MAP-21 | The Moving Ahead for Progress in the 21st Century Act |
| MCA | Multi-criteria analysis method |
| MCS | Monte Carlo simulation |
| M-F | Maintenance first allocation method |
| M&R | Maintenance and rehabilitation |
| MR | Medium rehabilitation |
| N | Number of lanes |
| NCHRP | National cooperative highway research program |
| NHS | U.S. national highway system |
| OECD | Organisation for Economic Co-operation and Development |
| PDA | Proximity to deficient areas |
| PDF | Probability density function |
| PM | Preventive maintenance |
| PMIS | Pavement management information system |
| PMS | Pavement management system |
| PMP | Pavement management plan |
| R-F | Rehabilitation first allocation method |
| RF | Reference marker |

| | |
|---|---|
| RS | Ride score |
| SPS | Specific pavement study |
| TPM | Transition probability matrix |
| TxDOT | Texas Department of Transportation |
| UACost | Uniform annual cost |
| VMT | Vehicle-miles traveled |
| W-F | Worst first allocation method |

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# 1. INTRODUCTION

## 1.1 Problem statement

According to the American Society of Civil Engineers, 33% of the United States' major roads are in poor or mediocre condition with a projected funding shortfall of $549.5 billion for 2010–2015(ASCE 2013). Many of these roads are deteriorating faster due to environmental factors, increased traffic, and deferred maintenance (Galehouse et al. 2003). The imbalance between maintenance needs and available funds tends to become more critical over time, since the overall cost of maintenance increases significantly as more expensive interventions are needed to bring back the roads to adequate condition levels.

Allocating the scarce funds available demands more reliable and advanced analysis tools and models for prioritizing maintenance and rehabilitation (M&R) projects. This decision-making process needs to incorporate the uncertainty in relevant influencing factors and the risk of failing to achieve target performance levels. Consequently, roads network can be managed in more cost-effective, efficient, and reliable manner.

The Moving Ahead for Progress in the 21st Century Act (MAP-21) was signed in 2012 to fund surface transportation programs for 2013–2014 and beyond (Congress of the United States of America 2012). MAP-21 is performance oriented and establishes a framework for federal transportation investments, with the goal of preserving the U.S. national highway system (NHS) and improving its condition and performance. Under this law, state departments of transportation (DOTs) are required to develop risk-based asset management plans that include lifecycle cost and risk management analysis.

In order to fulfill MAP-21 goals, pavement management systems (PMSs) need to be upgraded to incorporate risk management, which will permit PMSs to serve as a more realistic decision support tool for pavement maintenance and rehabilitation planning and budget allocation.

This dissertation focuses on incorporating risk assessment into maintenance and rehabilitation budget allocation decisions at the planning stage. Relevant factors that affect decisions will are modeled as probability distributions in order to incorporate uncertainty into the analysis process. These factors are pavement conditions, available funds, maintenance and rehabilitation (M&R) costs, and performance prediction models. The risk level for each budget allocation scenario is expressed as the probability of failing to achieve pre-defined performance goals.

This research demonstrates that incorporating uncertainty and risk assessment into pavement management can lead to better-informed decisions and ultimately improved M&R budget allocation policies. This work provides DOTs with analytical tools and methods for meeting the requirements of MAP-21.

## 1.2 Research objectives

The purpose of this research is to develop a framework that incorporates risk and uncertainty into pavement M&R budget allocation decisions at the network level. The specific objectives of this research are to:

- define the uncertainties in key pavement management input data (i.e. condition, budget, and M&R unit costs) and in the pavement performance predictions.
- develop a computational model for prioritizing M&R projects, considering uncertainties in key input parameters and in performance predictions.
- assess how useful the model is through an application in a selected roads network.
- assess the risk of failing to achieve pavement network performance goals (measured in terms of pavement condition indicators such as percent lane-miles in adequate condition and average network condition).

### 1.3 Dissertation organization

The dissertation is organized in five sections. The first section covers the motivation for the research and specific objectives of the project. A literature review is presented in section two with emphasis on issues relevant to the research. Section three explains the budget allocation framework and computational tool. Section four contains the model application to a roadway network. In section five, the risk assessment results of the analysis conducted using the model are presented. The last section is comprised of the conclusions from this research and recommendations for future research.

# 2. LITERATURE REVIEW

In order to understand how decisions regarding pavement maintenance, management, and related budgeting are currently made and how the research in this dissertation is relevant, a review of the literature is imperative. To begin with, existing asset management systems are described to know the context and to give readers an overview of the maintenance actions usually taken. Then, possible ways to segment pavement network are discussed, and available performance prediction models are reviewed. Next, the decision-making process itself is reviewed to determine which optimization algorithms and techniques are available. To conclude, the history and current state of incorporating risk assessment and uncertainty into pavement maintenance decisions are summarized. This literature review helps put the budget allocation framework presented here into perspective in terms of how it fills a gap in the current theory as well as practice of budget allocation in pavement maintenance.

## 2.1 Pavement and asset management

As defined by the American Association of State Highway and Transportation Officials (AASHTO) Standing Committee on Highways, Planning Subcommittee on Asset Management:

> “Transportation Asset Management is a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their lifecycle. It focuses on business and engineering practices for

> resource allocation and utilization, with the objective of better decision making based upon quality information and well defined objectives" (FHWA 2007).

AASHTO clearly defines the objective of asset management as building and operating infrastructure facilities in the most reliable, cost effective, and sustainable way possible.

The development of PMS began approximately 40 years ago. Initially, such systems were oriented toward keeping pavement condition data organized. Later, decision trees and simple benefit-cost analyses were incorporated into the systems. In 1982, the Arizona PMS applied a true network multilayer optimization system with Markov deterioration forecasting models for the first time (Wang et al. 1993). More recently, PMSs are web-based with multilayer programming optimization by road segment and enhanced GIS capabilities (Mikhail 2012).

In 1990, the Intermodal Surface Transportation Efficiency Act (ISTEA) set a new trend in PMS contents and capabilities (U.S. Department of Transportation 2005). Under ISTEA, PMSs included capabilities for pavement condition data collection, data management, and pavement analysis. As a consequence, PMSs began to incorporate more sophisticated tools for statistical processing, optimization, multi-objective analysis, knowledge-based decision making, and expert system techniques (Markow 1995).

Figure 1, adapted from Walsh (Walsh 2011), shows the pavement management process. Clearly, risk assessment is a key component in the decision-making process. In order to run a proper assessment, risk identification needs to be done. Same than the analysis of data variability, uncertainty incorporation into performance prediction, and incorporation of variability in unit cost, are among the factors that can affect the DOT risk of not delivering an expected level of service to the road network users.

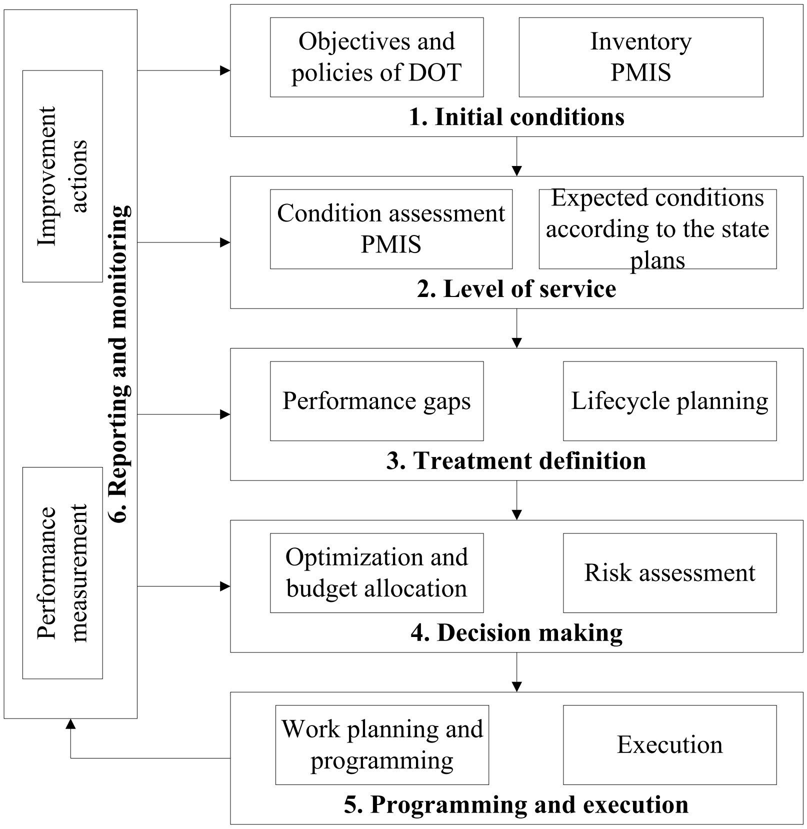

**Figure 1.** Overview of asset management process, adapted from Walsh (2011)

The 2012 U.S.federal transportation bill, MAP-21, requires state DOTs to develop risk and performance-based asset management plans for preserving and improving the condition of the national highway system (NHS). The plans must include, among others components, a description of the condition of the assets; asset management objectives and measures; performance gap identification; lifecycle cost and risk management analysis; a financial plan; and investment strategies. If a DOT fails to develop, implement, and state an asset management plan, that DOT federal funding is reduced by 35% (Congress of the United States of America 2012; Perkins-Smith 2013).

## 2.2 Pavement maintenance and rehabilitation

Keeping pavement in good condition requires a combination of activities that can be broadly grouped into M&R treatments. Pavement maintenance is comprised of activities oriented toward correcting minor defects, restoring uniform surface texture, and providing adequate skid resistance. In contrast, the purpose of pavement rehabilitation is to recover the structural integrity, improve ride quality, and correct surface irregularities. Preventive maintenance is recognized as being able to reduce the need for major rehabilitation and to extend pavement life.

Maintenance is divided into three categories preventive maintenance, corrective maintenance, and emergency maintenance. Preventive maintenance includes light treatments such as crack sealing, slurry sealing, chip sealing, fog sealing, rut filling, pothole patching, thin cold-mix sealing, and thin hot-mix overlaying. Such light treatments are intended to preserve the pavement life and are usually regularly scheduled. However, corrective maintenance is reactive and oriented toward correcting a specific distress. Finally, emergency maintenance is performed when an unexpected situation happens requiring immediate repair of the road in a short period of time (Foundation of Pavement Preservation 2001; Zaniewski and Mamlouk 1996).

Rehabilitation is divided according to its intensity and ranges from light to heavy. Light rehabilitation consists of a thin overlay applied directly to the surface. Medium rehabilitation includes patching and a thick overlay, which in some cases requires surface milling beforehand. Heavy rehabilitation involves the total renovation of the pavement surface; it can be extended to the base and even into subgrade.

The effectiveness of M&R treatments is an important factor in defining the best solution. Effectiveness is a function of multiple factors such as pavement type, type and extent of distress, roadway use, level of traffic, climate, environmental factors, cost of treatment, expected life of treatment, availability of materials and contractors, pavement noise, and surface friction (Johnson 2000). Short-term M&R effectiveness can be measured in terms of the reduction of deterioration, and performance improvement jump (Labi and Sinha 2003). For a long-term analysis, the cost-effectiveness approach based on the equivalent annual cost and the pavement performance can be used (Hicks et al. 1997; Peng and Ouyang 2010).

The Texas DOT (TxDOT), applies a decision tree at the programming stage to define the most appropriate option (Dessouky et al. 2011). According to the Pavement Management Information System (PMIS) Technical Manual maintenance treatments are selected based on average daily traffic (ADT), ride score (RS), deep rutting, shallow rutting, alligator cracking, failures, block cracking, longitudinal cracking, transverse cracking, and age of last treatment (TxDOT 2011).

The TxDOT PMIS Technical Manual divides M&R treatments into four groups: preventive maintenance (PM), light rehabilitation (LR), medium rehabilitation (MR), and heavy rehabilitation (HR). According to TxDOT, PM tasks are crack and surface sealing. LR corresponds to thin asphalt overlay. MR corresponds to mill and thick asphalt overlay. HR includes removing and replacing asphalt surface and reworking the base (TxDOT 2011). Table 1 presents TxDOT maintenance and rehabilitation activities for each treatment category and pavement type.

**Table 1.** TxDOT treatment categories by pavement type

| **Pavement Type** | **Treatment Category** | | | |
|---|---|---|---|---|
| | **PM** | **LR** | **MR** | **HR** |
| Continuous reinforced concrete pavement | crack (or joint) seal | concrete pavement restoration (CPR) | patch and asphalt overlay | concrete overlay |
| Joined concrete pavement (Reinforced) | joint seal | CPR | patch and asphalt overlay | concrete overlay |
| Joined concrete pavement (Unreinforced) | joint seal | CPR | patch and asphalt overlay | concrete overlay |
| Thick hot-mix | crack seal or surface seal | thin asphalt overlay | thick asphalt overlay | remove asphalt, surface, replace and rework base |
| Intermediate hot-mix | crack seal or surface seal | thin asphalt overlay | thick asphalt overlay | remove asphalt, surface, replace and rework base |
| Thin hot-mix | crack seal or surface seal | thin asphalt overlay | thick asphalt overlay | reconstruction |
| Composite pavement, unwidened | crack seal or surface seal | thin asphalt overlay | mill and asphalt overlay | remove asphalt surface, replace and repair concrete base |
| Composite pavement, widened | crack seal or surface seal | thin asphalt overlay | mill and asphalt overlay | remove asphalt, surface, replace and repair concrete base |
| Asphalt concrete pavement, overlaid and widened | crack seal or surface seal | thin asphalt overlay | thick asphalt overlay | remove asphalt, surface, replace and rework base |
| Seal coat | crack seal, no patching | surface seal, light/medium patching | surface seal, heavy patching | rework base and surface seal |

## 2.3 Pavement condition and segmentation

Pavement condition is generally expressed through condition indices. These indices are numerical indicators of a certain functional condition and structural integrity of a pavement. In some cases the indices are an aggregation of several distress types and in others a direct measurement of a physical condition (Gharaibeh et al. 2010).

For TxDOT-maintained roads, pavement condition is expressed as a distress score (DS), a condition score (CS), and a RS. The DS is a function of the utility values of distress types which are visually evaluated every year and illustrate the amount of visible surface wear due to traffic and environmental factors. The CS is function of ride utility and the DS, where RS is obtained from a road roughness measurement (TxDOT 2010). Distress and CSs are computed as follows:

$$DS = 100 \prod_{i=1}^{n} U_i \tag{2.1}$$

$$CS = U_{ride}\ DS \tag{2.2}$$

where *DS* = distress score; $U_i$ = utility values of each individual distress (i.e. shallow rutting, deep rutting, parching, localized failures, block cracking, alligator cracking, longitudinal cracking and transverse cracking); *CS* = condition score; $U_{ride}$ = ride utility.

The DS values range from 0 (very poor) to 100 (very good). A pavement with DS value between 90 and 100 is classified as very good; 80 to 89 is classified as good; and a score less than 70 is considered poor. In the same way CSs values range also from 0 (very poor) to 100 (very good). A pavement with CS value between 90 and 100 is classified as very good; a range of 70 to 89 is classified as good; and a score less than 50 is consider poor.

In August 2001, the Texas Transportation Commission set a statewide goal to have 90% of Texas pavements in “good” or better condition by the year 2011. “Good or better condition’ is represented by CS of 70 or above, as is explained in the previous paragraph and according to PMIS (TxDOT 2011).

TxDOT applies a system of utility factors to combine different distress and ride quality data. According to Stampley et al. (Stampley et al. 1995), utility is the value of service provided by pavement with a particular damage level. Utility values vary from 0.0001 to 1 corresponding respectively from poor condition to perfect. The general utility value can be expressed by the following equation:

$$U_i = 1 - \alpha_i e^{-\left(\frac{\rho_i}{L_i}\right)^{\beta_i}} \tag{2.3}$$

where $U_i$ = utility value from 0.0001 to 1.000; $i$= distress type; $\alpha$ = horizontal asymptotic factor that controls the maximum amount of utility that can be lost; $\beta$ = factor that controls how steeply utility is lost in the middle of the curve; $\rho$ = prolongation factor that controls how long the utility curve will last above a certain value; and $L$ = level of distress (for distress type) or ride quality lost (for ride quality), as illustrated in Figure 2.

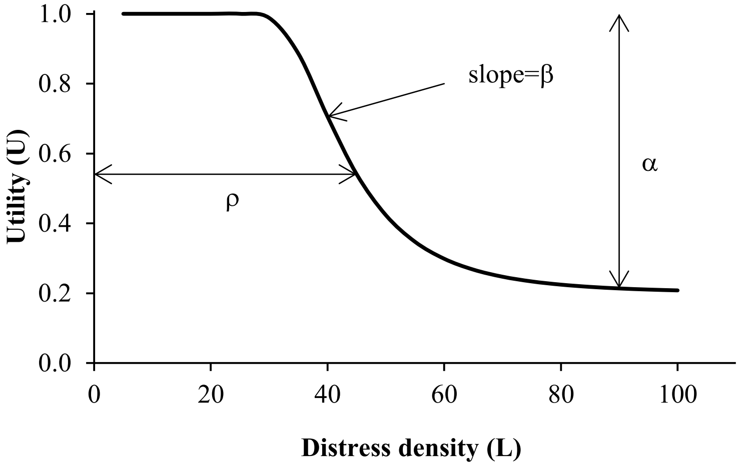

**Figure 2.** General shape of utility curves

Pavement condition data are usually available for fixed distance. In Texas the standard PMIS collection sections are 0.5 miles in length; however, some are longer and some are shorter, designed to coincide with the road begin or/and end (TxDOT 2010). For practical purposes potential M&R projects (i.e., segments) are comprised of a group of sections. The length of each segment is limited by agency contract limits and uniform pavement conditions.

Segmentation can be approached in three primary ways: fixed length segments, dynamic segments, and static segments. Fixed length segmentation keeps the segments constant over time; they are created to match fixed features like mile posts or city blocks. Dynamic segmentation divides the network based on the homogeneity of their attributes and can change every time the attribute is measured. Static segmentation creates segments based on their attributes but the boundaries are maintained for many years. From the planning point of view, static segmentation is more useful since it allows trends in conditions to be monitored over time and can be updated after four or more years (Bennett 2004).

Segmentation has two main objectives: to identify change points and to calculate the representative parameters between change points (Vargas et al. 2008). Segmentation methods are classified as elemental, cumulative sum, autoregressive, decision trees, and Bayesians. The common objective, of then all is to minimize the difference between the “true” distribution of data and the model distribution (Kullback and Leibler 1951).

A relatively straightforward method for segmentation is the cumulative difference algorithm (CDA). The differences between the actual values of certain pavement attributes and an established threshold for each are computed and added together. Points where the cumulative difference graph changes slope mark changes in the measured attribute and hence, in the uniformity of the pavement (AASHTO 1993; Jordaan and deBruin 2002).

CDA can also be applied when the segmentation is based on a combination of attributes. When more attributes are included, the segments become shorter. Thus, a minimum length criterion needs to be applied to prevent impractically short segments.

The identification of homogeneous segments is not a straightforward process. Grouping data into segments is a combination of engineering judgment and applying a grouping algorithm to minimize the effects of localized factors. Accurate identification of homogeneous segments influences in the posterior analysis of the cost -effectiveness and optimality of a project (Thomas 2003) . To assess the soundness of the segments, agencies should verify them in the field as a part of their quality assurance process (Bennett 2004).

Proper segmentation helps define an adequate M&R treatment. As seen in the simple case in Figure 3, if pavement attribute change is not detected, the maintenance would be applied to the entire section whether needed or not. However, after applying a segmentation process, two segments were identified and only one of them required maintenance (Cafiso and Di Graziano 2012).

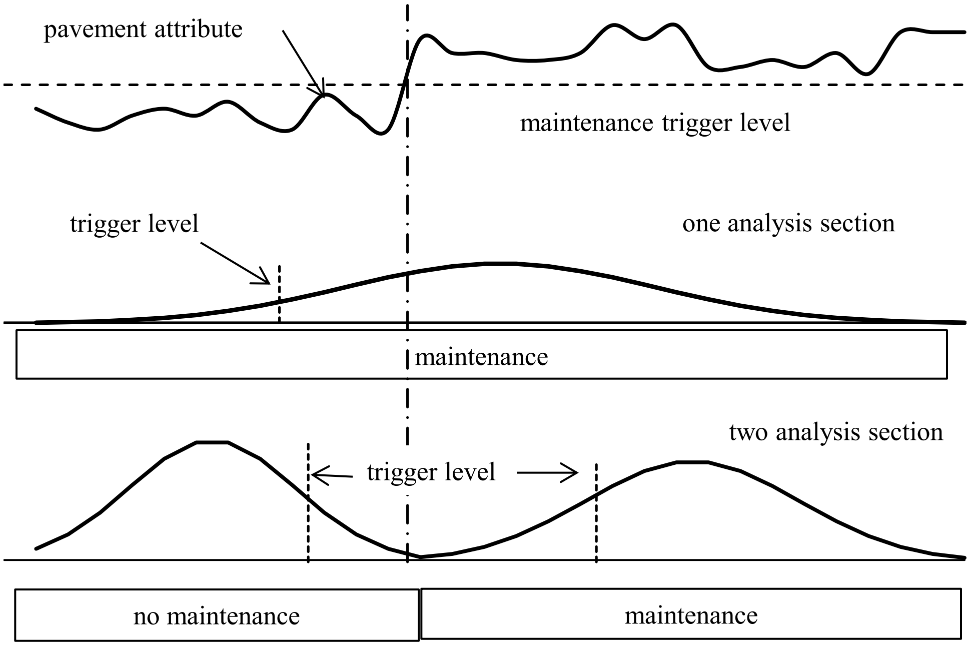

**Figure 3.** Consequences of segmentation, adapted from Cafiso and Graziano (2012**)**

## 2.4 Performance prediction models

Performance models, also called deterioration prediction models, are mathematical expressions that represent the pavement deterioration process as a function of one or more relevant variables. These models depend on traffic, type of pavement, weather conditions, construction quality, type of materials, and maintenance characteristics. Performance models are developed to have a close representation of the future behavior of a certain pavement under a specific set of conditions (Stampley et al. 1995; Gharaibeh et al. 2012).

A limitation of most performance models is that they are not able to predict deterioration with maintenance (Paterson 1987; Shahin 2005). The need to incorporate the effects of maintenance into performance models is clear, but doing is a technical challenge (Lytton 1987; Chu 2007). Some attempts have been made to build an integrated model, such as dynamic models. However, dynamic models to date have had limited success due to computational capacity limitations and by the analytical framework employed in the model's design. (Chu and Durango-Cohen 2007; Chu and Durango-Cohen 2008b).

In general, performance models can be classified into two types: deterministic and probabilistic (Lytton 1987). From the operational point of view performance models are considered to fit into the following four categories: purely mechanistic, mechanistic-empirical, regressions based on observed behavior, or subjective based on experience (Haas et al. 1994; Chu and Durango-Cohen 2008a).  Performance models are selected according to three criteria, specifically application level (network or project level), available data, and complexity of the analysis.

### *2.4.1. Deterministic models*

In deterministic models, pavement future condition is predicted based on past performance condition. One of the most well-known deterministic models was developed by the American Association of State Highway Officials (Highway Research Board 1962), where the pavement condition is expressed in terms of a serviceability index visually evaluated. An important limitation of this type of model is that it does not consider the stochastic nature of infrastructure deterioration.

Deterministic models are usually expressed as a linear relation between the condition observed and a set of explanatory variables. Additionally, a deterioration function must to be defined along with an initial condition, and a random error. A general expression of the deterioration can be seen below:

$$y_i = x_o + h(x_i, \alpha) + \varepsilon_i \tag{2.4}$$

where $y_i$ = condition observed; $x_i$ = explanatory variable; $x_o$= initial condition of the explanatory variable; $\alpha$ = vector of model parameters;and $\varepsilon_i$ = random error term.

In addition to the linear model, non-linear deterministic models have also been developed. The most common of these are exponential, logistic, polynomial, and power (Pasupathy et al. 2007).

### *2.4.2. Probabilistic models*

Probabilistic models differ from deterministic models in that the future condition is expressed as the probability of changing from an initial stage to the next stage under a random process. Below, the three primary types of probabilistic models the Markov chain model, the reliability model, and the discrete choice model are described.

#### *2.4.2.1. Markov chain model*

The stochastic nature of M&R can be modeled as a Markovian process (Abaza et al. 2004; Kobayashi et al. 2012; Thomas 2011). Golabi et al (Golabi et al. 1982) presented the first application of a Markovian process to a pavement management problem. A Markovian process is discrete in time; it has a countable state space; and the future state or condition depends only on the current state (Ross 2010). Homogeneous and non-homogenous are the two categories of methods to solve the problem. In the first category, the transition probability matrix (TPM) does not change with time, and in the latter, the probability of changing from one state or condition to another depends on the length of the time step (Feldman and Valdez-Flores 2010). The probability that a certain process in initial condition will be in different stage is expressed as

$$P_{ij} = P\{X_{n+1} = j | X_n = i, X_{n-1} = i_{n-1}, \dots., X_1 = i_1, X_0 = i_0\} \qquad (2.5)$$

where $P_{ij} \geq 0; i, j \geq 0 ; \sum_{j=0}^{\infty} P_{ij} = 1; i = 0,1, \dots.$

In the transition probability matrix$[P]$, the elements $P_{ij}$ are replaced by 0 for $i > j$ because a pavement condition cannot improve by itself.

$$|P| = \begin{vmatrix} P_{00} & P_{01} & P_{02} & \dots & \dots \\ 0 & P_{11} & P_{12} & \dots & \dots \\ \vdots & \vdots & \vdots & \dots & \dots \\ 0 & P_{i1} & P_{i2} & \dots & \dots \\ \vdots & \vdots & \vdots & \dots & \dots \\ 0 & 0 & 0 & \dots & 1 \end{vmatrix} \quad (2.6)$$

The core of the Markov chain is the TPM. Three ways to develop a TPM exist, data based, experience based, and the method of moments. In all of them, the TPM requires a certain amount of deterioration data. Collecting and processing the data require significant resources, and if the matrix is combined with the maintenance action matrix, inevitably, some information will be lost (Abaza et al. 2004; Gao et al. 2007; Tabatabaee and Ziyadi 2013).

#### *2.4.2.2. Reliability model*

The reliability model models the probability of an element surviving past a certain time. Reliability of pavement is the probability that can behave according to a predefined function. Chou and Le (Chou and Le 2011) stated that reliability models are only effective for forecasting pavement performance if the failure and non-failure modes are well defined.

Since a pavement structure has a complex interaction between components, Chou and Le proposed a reliability model at system level, which comprises the reliability of the components into a limit-state function. This function express the difference between allowable and the demand load application of a given pavement section. Same approach was taken by Deshpande et al.(Deshpande et al. 2010) modeling pavement reliability and rehabilitation treatments as parametric fragility curves based on simulated pavement responses (i.e. pavement strain).

#### *2.4.2.3. Bayesian approach*

A Bayesian approach can be used to estimate the *a posteriori* distribution of the prediction model parameters based on the likelihood and the prior distribution before seeing any data (Hoff 2009; Koch 2007). The Bayesian approach is applied to improve pavement distress prediction equations by developing a data analysis tool that cans periodically update the expected pavement performance equations (Liu and Gharaibeh 2013; Mrawira and Amador 2011; Park et al. 2008). In the same way, Bayesian approach can be applied to develop an expert TPM when existing data are insufficient (Tabatabaee and Ziyadi 2013; Mrawira and Amador 2011).

## **2.5 M&R costs and life-cycle cost analysis**

M&R costs depends on many factors such as pavement condition; labor and machinery cost; weather; availability of materials; and expected level of service. Since transportation agencies have no widely accepted process for determining M&R costs, often they are calculated based on historical data (Sobanjo et al. 2002). National cooperative highway research program (NCHRP) report 688 (Cambridge Systematic et al. 2011) presents a practical process for determining an agency's highway maintenance costs. The process classifies and allocates the expenditures between maintenance programs and line activities to later combine both cost categories to derive the full cost.

In addition to estimates based on previous data, costs can be estimated using engineering judgments, standard unit costs, or even correlations with pavement condition and characteristics (Juni et al. 2008; Sinha et al. 2005). Perrone et al. (Perrone et al. 1998) point out that no matter which approach is taken to obtain the estimate; it can represent a specific value for each treatment or a random distribution.

In the Long-Term Pavement Performance (LTPP) sections of the Specific Pavement Study (SPS) in Texas, Chen et al. (2003) found that preventive maintenance costs ranged from $500 per mile for crack sealing to $35,000 per mile for 50 mm of overlay (Chen et al. 2003). This study demonstrated that the cost ratio between the most expensive preventive maintenance and the cheapest is between 20 and 50 times. One of the observations that they made is that in low traffic areas, the differences of DSs for various preventive maintenance treatments are non-relevant. However, in high traffic areas the best choice is the chip seal, followed by thin overlay and crack seal (Chen et al. 2003). Similar results were obtained by Chang et al. (Chang et al. 2005) , who clarified that those costs may not be representative of typical projects since the lengths of the test sections were rather short, less than five miles.

Treatment costs need to be analyzed in conjunction with treatment effectiveness to make an informed decision regarding which is the most appropriate.  Cuelho et al. (Cuelho et al. 2006)  conducted an extensive study on preventive maintenance treatments of flexible pavements and found very little quantitative evidence to support the cost effectiveness of certain pavement maintenance, recommending addition al research to quantify the short and long-term effects that treatment alternatives have on roads performance.

The life-cycle cost analysis (LCCA) is an evaluation technique considered necessary for appraising long-term public projects. For a specific segment of pavement, LCCA considers all the anticipated future costs necessary to maintain a specific level of service (Figure 4). To calculate this, data on pavement performance, treatment cost, project characteristics, user added cost, and expected level of service are required (Perrone et al. 1998; Hall et al. 2003; Ozbay et al. 2004; Walls III and Smith 1998).

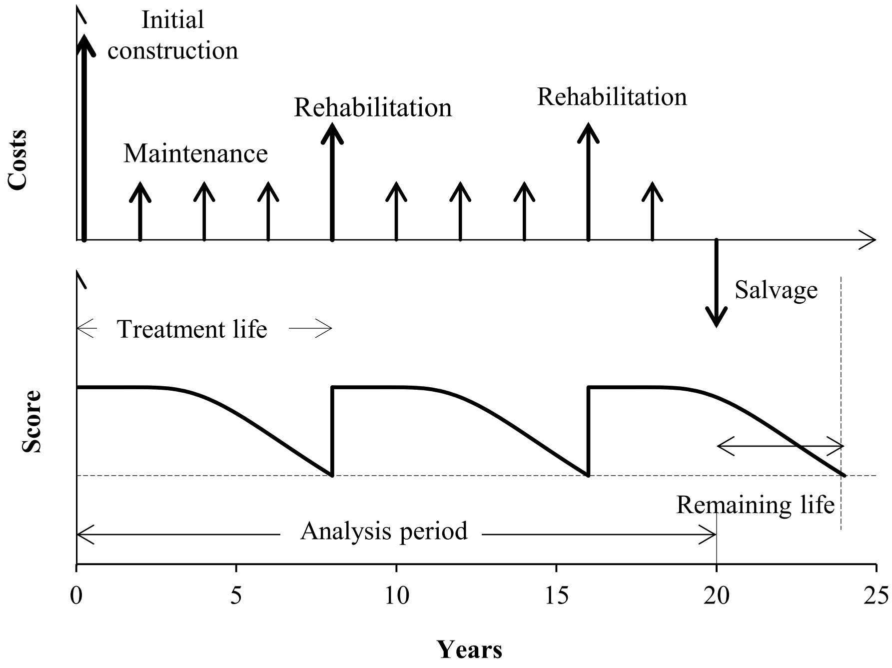

**Figure 4.** Life cycle costs in relation to road score condition

The benefits of using a particular M&R treatment can be computed using the area between the CS curve and an agency-defined threshold value called the area under the performance curve (AUPC). By considering the condition improvement caused by the treatment, the area below the curve is a quantification of the performance benefit of applying a certain M&R treatment. Then the annual benefit is calculated as:

$$Annual\ Benefit = \frac{AUPC}{n}\ (AADT)\ (365)\ (N)(L) \qquad (2.7)$$

where $AADT$ = average annual daily traffic; $n$ = number of years; $N$ = number of lanes; and $L$= section length in miles, as illustrated in Figure 5.

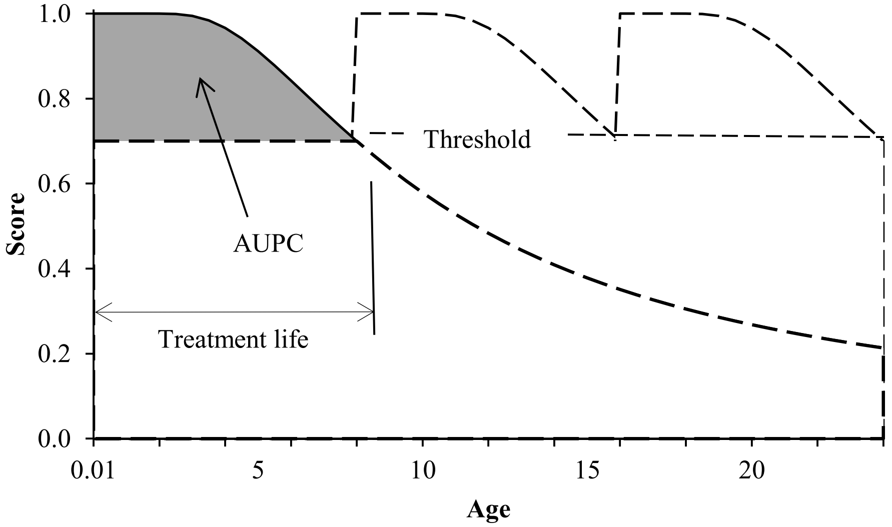

**Figure 5.** Illustration of AUPC concept

Life cycle cost (LCC) can be analyzed using a probabilistic-based risk approach. Walls and Smith (Walls III and Smith 1998) introduce a risk analysis approach, in which input variables and therefore analysis results are expressed in the form of probability distributions. More recently, their approach was improved with the development of input probability distributions based on the LTPP database (Tighe 2001) and by taking the uncertainty involved in determining the service life of pavement into consideration (Salem et al. 2003).

## 2.6 Funding and allocation strategies

Resource allocation is an important part of infrastructure asset management. For example, the funds required to satisfy maintenance needs are often more than the available funds. Because of that, the strategic goals of the DOT, network management objectives, road conditions, and budget and administrative constraints (Augeri et al. 2011) must be assessed to allocate available funds in a way to maximize the outcomes.

According to the Organisation for Economic Co-operation and Development (OECD)(OECD Scientific Expert Group 1994), allocation approaches can be classified into three categories: need based, zero maintenance, and engineering-economic.

- In the need-based approach, the decisions are made according to technical requirements, acceptable service levels for users, and affordable budget level.
- In the zero-maintenance approach, the pavement is used until service is obstructed, and reconstruction work is necessary.

- In the engineering-economic approach, decisions are made to minimize agency expenses, reduce the life-cycle cost, and reduce the users' cost in order to maintain certain technical characteristics and standards.

Fund distribution among M&R activities requires a rational assessment of the advantages and disadvantages of choices (Boamah 2010). Rational assessment can be made through various approaches depending on the complexity of the system and the DOT preference. Some approaches use optimization algorithms that can help the decision makers analyze different scenarios and consequently choose the most efficient budget allocation option (Colombrita et al. 2004; Mild and Salo 2009).

### 2.7 M&R project selection

Project selection is critical because agencies generally have a limited maintenance budget. The selection process is comprised of selecting an adequate treatment, and defining the right time to apply it. Both decisions are made under budget constraints while pursuing the goal of sustaining a well-functioning system at a reasonable cost. In this context, project prioritization and/or optimization are complex processes that involve a balance among decision tools, engineering judgment, and maintenance policies. Table 2 presents a comparison of different approaches to project selection (Mohseni 1991).

**Table 2.** Approaches to project selection

| **Type of approach** | **Subjective** | **Prioritization** | **Optimization** |
|---|---|---|---|
| Condition Rating | Subjective | Subjective or condition index | Condition index |
| Condition prediction | None | None of judgment | Models |
| Project level selection | Judgment | Judgment of LCCA | Generate all feasible alternatives |
| Network level selection | Ad-hoc | Ranking | Objective functions |

One way to prioritize M&R projects is to rank them using a formal procedure. Ranking techniques are better than subjective procedures such as engineering judgment, which has been proved inefficient and often infeasible, especially for managing large pavement networks (Reddy and Veeraragavan 2001). The main feature of a ranking procedure is that each pavement section in the network is rated on one or more criteria with a set rating scheme (Frangopol and Liu 2007; Liu and Frangopol 2006; Sinha et al. 2009).

Some of the most common criteria used to rank M&R projects are current pavement condition, initial cost, cost and timing, LCC, index value; and benefit-cost ratio (Bemanian et al. 2005; Tavakoli et al. 1992; Zimmerman 1995). However, ranking techniques have some limitations. Among the most important limitations are that future conditions are not considered or are only estimated subjectively; trade-offs between alternatives cannot be considered; multi-year analysis cannot normally be performed; and inclusion of too many factors can result in an excessively complex ranking index.

Another alternative for prioritization is the multi-criterion analysis method (MCA). In this method, the possibilities are compared and ranked according to pre-established preferences for achieving defined objectives (Cafiso et al. 2002). Consequently, with the inclusion of multiple criteria, M&R decisions become more balanced, cost-effective, rational, and justifiable (Sinha et al. 2009; Li and Sinha 2009).

In the MCA method, a key aspect is the relative importance of weights assigned to each criterion. Sinha et al. (2009) summarize the weighting methods as direct, observed-derived, gamble, swing, indifference trade-off, and pairwise comparison. The most widely-used method is pairwise comparison which is a feature of the analytical hierarchy process (Li and Sinha 2009; Palcic and Lalic 2009).

The pavement management problem involves a large number of variables, which makes it complex. A single approach for finding the best M&R plan does not exist. The optimization formulation falls into the category of the non-deterministic polynomial-time hard zero/one integer knapsack problem, where the computational time to reach an optimal solution grows exponentially with the problem size (Martello and Toth 1990).

Solving algorithms for the optimization problem are classified as exact and heuristic. Exact algorithms are based on branch-and-bound (Martello and Toth 1990; Sinha and Zoltners 1979), dynamic programming, or a hybrid of these two techniques. In contrast, though heuristic algorithms do not guarantee optimality, but they are optimal in a reasonable computational time (Abaza and Ashur 2009; Di Mino and Nigrelli 2007; Ferreira et al. 2002a; Pilson et al. 1999). The optimization problem can be simplified at the network level by grouping the pavement sections into projects or even into classes with similar characteristics. However, at the project level, each section is analyzed using a substantial number of variables that restrict the available optimization techniques.

When the objective functions and the constraints are formulated as linear functions of the variables, a linear programming technique is the most common optimization method used in PMS. In this optimization method, both the objective functions and the variables are continuous. Linear programming is applied to homogeneous system problems, mainly at project level. Nevertheless, it cannot handle large number of variables. Linear programming can be applied in conjunction with other techniques, such as the weighted objective linear programming model (Chassiakos et al. 2005), expert opinions (Harper and Majidzadeh 1991) or even a multi-objective problem (Wang et al. 2003).

Golabi et al (Golabi et al. 1982) created a pioneering work in linear programming for the Arizona PMS. This management system had a network optimization algorithm for a short-term analysis to minimize the total expected discounted costs, and a long-term analysis, which minimizes the expected long-term average cost.

The objective function and some of the constraints in linear programming may be formulated as non-linear equations, and in such cases a non-linear programming method should be applied. Abaza ( 2006) pointed out that solving a non-linear model with a large number of variables is a very complex task. To simplify, the non-linear model can be formulated as a series of linear problems where the optimal solution of one becomes the input for the next one.  Several algorithms are available to solve non-linear models such as branch and bound, generalized benders decomposition, and outer approximation (Ouyang and Madanat 2004).

Integer programming is considered when the variables are no longer continuous, but rather, when they can only take the values of zero or one. A value of zero is an indication that the decision is not to do something, and a value of one indicates the decision to do it (Lytton 1985). The most common application is in cost-effectiveness based integer programming on an annual basis, where the prediction of individual pavement segment deterioration is modeled as a Markov chain (Li et al. 1998; Mahoney et al. 1978). More recently, Abaza (2009) developed an application of integer programming to optimize decision making at the segment level, which he called the microscopic pavement management model.

Another optimization technique is dynamic programming; it solves an optimization problem in sequence, breaking a complicated problem down into a number of simpler, more easily solvable problems (Feighan et al. 1988). Using this technique, earlier decision conditions determine what subsequent decision will be, thus saving computational time and finding provable, near-optimal solutions in a reasonable time (Dahl and Minken 2008). This technique can be combined with others to create hybrid dynamic programming thereby increasing computational efficiency (Yoo and Garcia-Diaz 2008)

Optimization problems can also be solved using heuristic methods, which are more efficient but do not guarantee optimality (Li et al. 2010). The most common techniques to solve optimization problems by heuristic algorithms are the Lagrange relaxation (Li et al. 2010; Magazine and Oguz 1984), artificial neural networks (Bosurgi and Trifiro 2005), the genetic algorithm (Di Mino and Nigrelli 2007; Bosurgi et al. 2005; Bai et al. 2012; Ferreira et al. 2002b; Tack and J. Chou 2002), pattern search heuristics, evolutionary algorithms (Yeo et al. 2013), and robust neural dynamic models (Senouci and Adeli 2001).

## 2.8 Risk assessment

According to the International Organization for Standardization (ISO), the term "standard risk" is the effect of uncertainty on objectives (Leitch 2010). Haimes (Haimes 2004) defines it as a measure of the probability and severity of adverse effects. The risk can be represented as the probability that a hazard will generate consequences, due to the vulnerability of the element being analyzed.

$$Risk = Hazard\ x\ Vulnerability\ x\ Consequences \qquad (2.8)$$

Risk analysis is conducted to support decision making in the design and operation of roadways. Risk analysis includes identification of hazards, consequence analysis, and risk description (ISO 2009). Similarly, risk assessment is the evaluation of results of the risk analysis and risk evaluation. Risk management is used to refer to the systematic application of management policies to establish the context, assessment, treatment, monitoring, review, and communication of risks, as shown in Figure 6 (ISO 2009; Aven 2008).

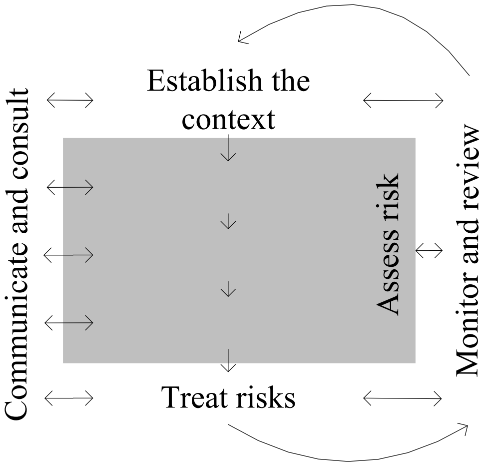

**Figure 6.** Risk management process

According to NCHRP study, risk assessment is a tool needed to analyze the impact of alternative policies (Cambridge Systematic et al. 2005). AASHTO *Transportation Asset Management Guide* (AASHTO 2011) explains the sources and types of risk, how to apply risk management, and how to identify risks. The risk assessment process is extracted from the general risk management framework proposed by AASHTO and presented in Figure 7.

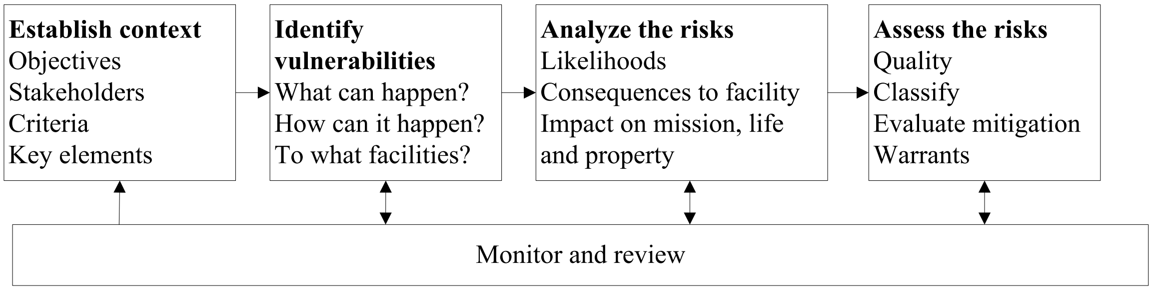

**Figure 7.** Risk assessment, adapted from AASHTO (2011).

Risk assessment consists of three components. The first component is the identification of different types of potential risks and their causes. The second component is the evaluation of the effects of such risks and their consequences for the road network expressed in a quantitative or qualitative manner. The last component is the evaluation of identified risks to define the risk treatment options and their prioritization.

Seyedshohadaie et al. (Seyedshohadaie et al. 2010) presented an approach to determine optimal M&R policies that satisfy a certain level of risk for the long and short term. The advantage of this approach is that M&R treatments are selected to reach the pre-defined level of risk. However, a limitation of this approach is the complexity of the mathematical formulation for probability distribution at the end of the planning horizon.

## 2.9 Key findings from the literature review

PMSs have evolved over time. In the beginning they were oriented to data storage and management, and then gradually these systems have become complex tools to support decision making. Present PMS goal is to have the capacity to deal with all road system assets.

A critical aspect for making budget decisions is to have reliable deterioration models. These models vary in complexity according to the level of analysis and can be deterministic or probabilistic. Probabilistic models are more suitable in pavement management since they can include M&R effectiveness and have an update mechanism.

According to the literature review of pavement management, the most studied analyzed and developed topics are optimization algorithms and deterioration prediction models. Due to increased computer processing capacity and the consequent ability to incorporate a larger number of optimization objectives and constraints into the analysis, both topics have produced important insights.

However, the development of comprehensive probabilistic models for decision making is not seen in the literature. This is due in part to the complexity of the issue and in part to the fact that each institution has a different approach to making decisions. Despite advances in the processing power of computers, programs, and optimization algorithms require simplifications to be applied at the network level.

The dissertation addresses one of the requirements of MAP-21 to quantify the risk of failure to achieve or exceed the performance goals of the road system. A comprehensive model for M&R budget allocation that applies the concepts of reliability and variability as risk assessment is developed.

# 3. BUDGET ALLOCATION DECISION ANALYSIS FRAMEWORK

Agencies use a variety of budget allocation approaches. Among the alternatives are historical allocation ratios, formula-based allocation, need-based allocation, and performance-based allocation (OECD Scientific Expert Group 1994; Javed 2010). The performance-based is more logical than other allocation methods since it ties funding allocation to the desired level of performance. Additionally, if risk assessment is incorporated into the analysis, decision makers will have a way to compare levels of confidence of the proposed fund distribution to achieving agency goals.

Quantifying uncertainty is a fundamental component of the decision-making process. Total uncertainty is consequence of the interaction and propagation of uncertainty in factors that have influence in performance prediction and cost quantification. Uncertainty results from errors introduced by mathematical performance models, inherent randomness of the input data, inaccurate quantification of cost variation, and unforeseen issues that can affect pavement performance.

The models developed in this work analyze the random uncertainty of condition data, construction cost, performance models and budget availability. Those factors are represented as probability distributions, and then these distributions are sampled for risk assessment using Monte Carlo simulation (MCS).

### 3.1 Overview of the budget allocation framework

The budget allocation analysis framework in this PMS is composed of six modules. The first module collects CS and DS data from PMIS from which it then creates segments and fits distributions for the CS and DS. The second module fits equations to the performance family of curves for uniform mathematical expression. The third module incorporates reliability into the performance prediction equations. The fourth module develops the probability density function (PDF) for unit cost and budget availability. The fifth module runs the optimization algorithm for the random data generated by MCS for each possible allocation policy. The sixth model collects the results produced in previous modules and builds the risk cumulative distribution function (CDF) for CS and DS over the planning horizon.

### 3.2 Data processing module (Module 1)

Pavement condition data is stored in the PMIS annually for each section, each typically 0.5 miles long. In order to run the analysis these sections need to be grouped in segments, having a total length ranging from 2 to 10 miles. Deciding where the segment begins or ends is supported by statistical analysis and physical constraints such as bridges or intersections. Pavement condition along the segments is represented by a unique value that can be the average, a lower or upper bound, or a percentile. However, the variability in the segment data will become a source of uncertainty, and it should be incorporated into the model.

The data processing model was comprised of the procedure to create the segments and the corresponding frequency distributions for CS and DS. A flowchart of the model is presented in Figure 8. The data used are from the TxDOT PMIS, and consistency was checked to adjust any questionable data. Then segments were formed based on CDA, which was code to take all defined constraints for segment formation into consideration. Based on the segment formed, the statistics were calculated. Then, frequency distributions were fitted to each segment as well as to the CS and DS. Lastly, the distribution parameters and statistics are stored, and applied to sampling during the analysis.

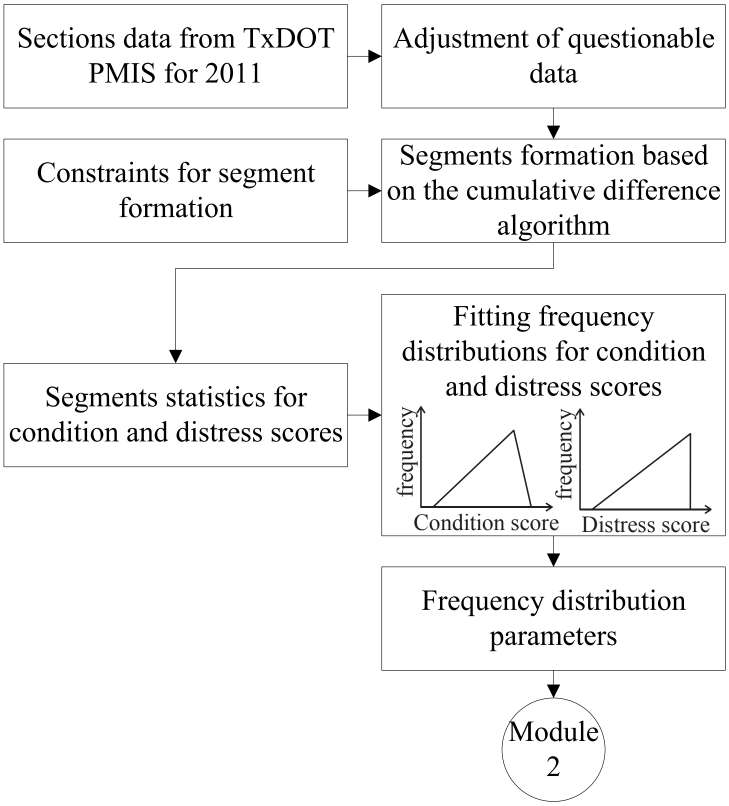

**Figure 8.** Data processing module

### *3.2.1. Section identification and data verification*

Pavement data was gathered from TxDOT PMIS. This system assigns a unique identification (ID) to each highway, and a reference marker (RF) for section location. The ID contains the route type, highway number, and roadbed where data were collected, for example IH0030R (TxDOT 2011).

Following the highway ID are four RFs that specify the exact location of the section along the highway from which data were collected. The first number corresponds to the beginning RF (BRM); second number is the BRM displacement; third number is the ending RF (ERM); and the last number is the ERM displacement, ex. IH0030R 128 00 128 0.5.

The consistency of all data values was checked before running the segmentation algorithm. Inconsistencies were detected when the information was out of range or missing. Both situations were corrected to avoid unrealistic cases and additional uncertainties not related with the inherent randomness of the data.

The CS of each section was verified to be within expected range. Values below twenty are questionable since that is so far below any maintenance standard. Values equal to zero are due to ongoing M&R work during the data collection process or lack of condition data. In both cases the questionable values were replaced with an average of the data from adjacent sections.

### *3.2.2. Segment formation*

Maintenance is performed in projects that are formed by a certain number of sections. Project lengths are set based on budget limits and homogenous characteristics of sections. No two sections segments have the exact same characteristics, so having a certain level of variance inside a "homogenous" project is acceptable and even expected.

Potential projects were formed by applying the CDA for DS, CS, and truck traffic (AASHTO 1993). This statistical methodology helps to create M&R projects that are homogeneous in terms of a specific score or a group of scores. CDA assumes that the response value ($r_i$) is constant in a certain interval along the project length ($L_p$), and the cumulative difference ($Z_x$) is the difference between the cumulative area ($A_x$) and the cumulative area media ($\bar{A}_x$) along the portion of measurement at a given location. Figure 9 represents an example where a road is divided in three segments applying the CDA methodology.

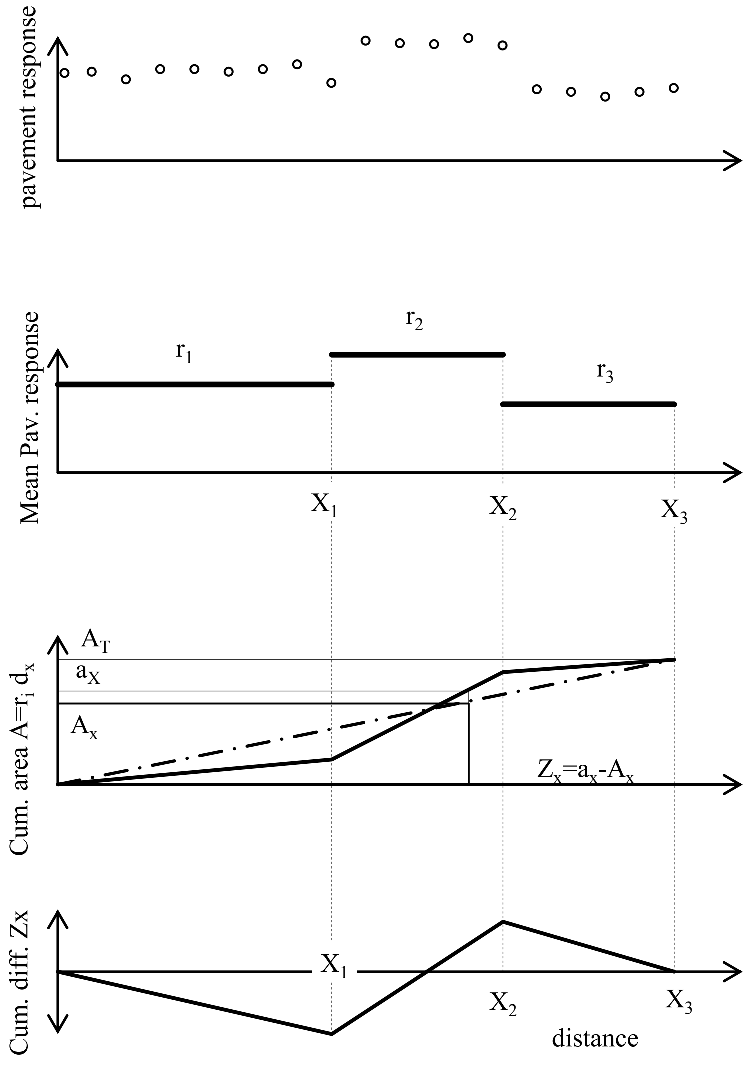

**Figure 9.** Graphic representation of CDA

A segment is defined every time that cumulative difference value ($Z_x$) tendency change of direction. However, in order to define a segment that can be considered a potential project, the following conditions must be met: The sections must belong to the same highway; sections must be on the same type of roadbed; sections must be contiguous; sections must be of the same pavement family, and project length must be between the pre-defined minimum and maximum lengths of 2 miles and 10 miles, respectively. The mathematical expression to calculate the cumulative difference value is the following:

$$Z_x = \sum_{i=1}^{n} a_i \left(1 - \frac{1}{L_p} \sum_{i=1}^{n} x_i\right) \tag{3.1}$$

where: $a_i = \frac{(r_{i-1}+r_i)x_i}{2}$; $Z_x$ = the cumulative difference; $r_i$ = pavement score used to create the segments; $x_i$ = section length; $L_p$ = the total length included in the analysis $L_p = \sum_{i=1}^{n} x_i$

The procedure described was repeated for DS and truck traffic. Because the boundaries of each criterion did not necessarily coincide, an additional calculation step was taken. After all the separate segments for CS, DS, and truck traffic were defined, the final segment boundaries were defined by the border of each attribute segment in the following order: CS, DS and truck traffic. After applying this procedure, a last check is performed to assure that the maximum length of 10 miles was not exceeded.

### *3.2.3. Fitting frequency distributions*

After segments were defined, the variability in segment data needs to be represented by a frequency distribution. Then for each segment a fitting process was done to find the best frequency distribution. The batch fitting function of the software @RISK® version 6.01, 2012 (Palisade Corporation 2012) was applied to obtain the PDF and the corresponding distribution parameters.

Since segments length varies from 2 to 10 miles the number of data points was in the range of 5 to 20. With this small amount of data, fitting a well-defined distribution is not possible; therefore, only two types of distributions were adopted, triangular and uniform. Triangular distribution is applied when a set of outliers is present in the data; uniform distributions are applied when data are scattered but within a certain range.

For the following analysis steps, information at the segment level is no longer applied; rather information is grouped by segments. With this approach, changing project segments after first year is not possible. This is a limitation since changes in the segment formation can be expected.

## 3.3 Performance prediction functions module (Module 2)

This module generates simplified performance functions that will later take variability in the performance prediction into account. According to TxDOT PMIS (TxDOT 2011), the DS is calculated based on the distress utility value and the CS is the product of the DS and ride quality utility. However, incorporating variability into each distress type and ride score is a complex task. Hence, a simplification was introduced to create a model that relates CS and DS directly to time, pavement type, M&R treatment type, and traffic class.

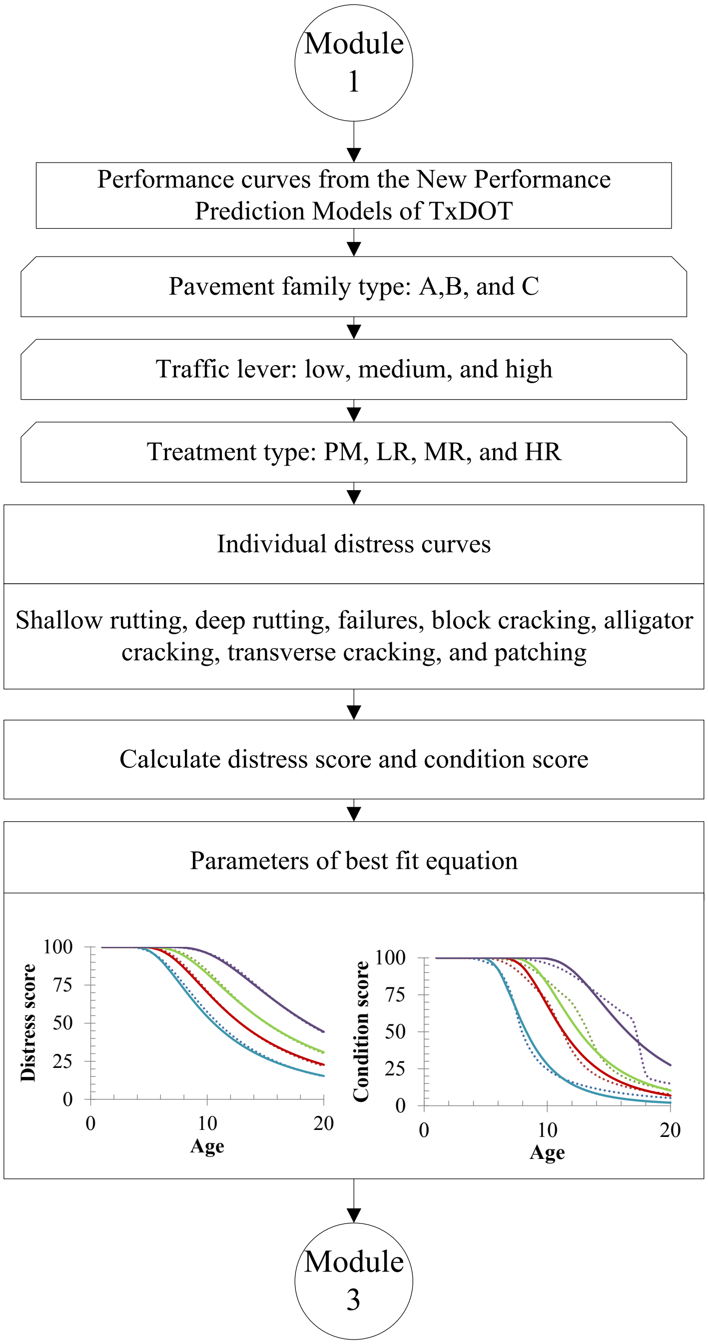

**Figure 10.** Flowchart of fitting equations to performance prediction functions

This model generates simplified sigmoidal expressions. These expressions are obtained after fitting curves to the output values from PMIS performance prediction expressions. Figure 10 presents a flowchart of the module in which simplified expressions were developed for each combination of pavement type, traffic class, and M&R treatment type. The family of curves generated represents a condition with 50% reliability; in the following module the reliability level will be incorporated into those expressions.

### *3.3.1. Performance curves from TxDOT PMIS*

Performance functions are mathematical expressions that describe deterioration. As analyzed in the literature review, depending on the confidence level, algorithm complexity, and the amount of available information, more complex functions can be built. TxDOT performance functions were adopted for the present research. Those expressions were initially developed by Stampley et al. (1995) and later updated by Gharaibeh et al. (2012).

TxDOT PMIS applies the utility theory (Stampley et al. 1995) to combine different distress and ride quality data. Utility value represents the subjective value of the value at different levels of condition; in other words, it is the value of the service provided by the pavement in use with a particular damage level. Utility value can vary from a minimum value of zero to a maximum value of one. The basic shape of a pavement utility curve is sigmoidal, represented by the following equation:

$$U_i = \begin{cases} 1, & when\ L_i = 0 \\ 1 - \alpha e^{-\left[\left(\frac{\rho}{L_i}\right)^{\beta}\right]}, & when\ L_i > 0 \end{cases} \tag{3.2}$$

where $L_i$ = density of individual distress types or ride quality; $i$= type of distress; $L_i = 0$ when $Age = 0$, and $L_i = \alpha_i\, e^{-(A_i/Age)^{\beta_i}}$ when $Age > 0$; $U_i$ = utility value (ranging between zero and 1.0); $\alpha$ and $\alpha_i$ = maximum loss factor; $\beta$ and $\beta_i$ = slope factor which controls how steeply $L_i$ increases in the middle of the curve; $\rho$ and $A_i$ = prolongation factor that controls the location of the $L_i$ curve's inflection point.

Utility equation factors are a function of pavement type. According to TxDOT PMIS, pavements are divided into 10 different types of pavements. The classification is based on type of surface layer, thickness of surface layer, and existence of an overlay or widening. The surface layer is divided into asphalt concrete pavements (ACP), concrete pavements with continuous reinforcement (CRCP), and joint concrete pavement (JCP). A chart with the utility value for each type of distress is presented in Appendix A. In Table 3, the TxDOT pavement types are described.

| **Pavement type** | **Code** | **Description** |
|---|---|---|
| CRCP | 1 | Continuously-reinforced concrete pavement |
| JCP | 2 | Jointed concrete pavement, reinforced |
| JCP | 3 | Jointed concrete pavement, unreinforced ("plain") |

**Table 3.** Continued

| **Pavement type** | **Code** | **Description** |
|---|---|---|
| ACP | 4 | Thick asphalt concrete pavement (greater than 5.5 in. or14.0 cm thick) |
| ACP | 5 | Intermediate asphalt concrete pavement (2.5–5.5 in., 6.4–14.0 cm, thick) |
| ACP | 6 | Thin asphalt concrete pavement (less than 2.5 in., 6.4 cm, thick) |
| ACP | 7 | Composite pavement (heavily-stabilized asphalt-surfaced pavement) |
| ACP | 8 | Overlaid or widened old concrete pavement |
| ACP | 9 | Overlaid or widened old flexible pavement |
| ACP | 10 | Thin-surfaced flexible base pavement (surface treatment or seal coat) |

Utility is defined in terms of the PMIS distress rating. Ratings expressed as percentages can be used directly in the utility factor equation. Distress types given as a number of occurrences need to be divided by section length before they can be used in the utility factor equation (Eq. 3.2). Table 4 explains how to compute the density of individual distress type $L_i$ values for pavement types 4, 5, and 6 (Table 3).

| **Asphalt concrete pavement** | **Rating method** | **Computing $L_i$** |
|---|---|---|
| Shallow (1/4–1/2 in.) rutting | Percent of wheelpath length | $L_i$ =PMIS rating |
| Deep (1/2–1 in.) rutting | Percent of wheelpath length | $L_i$ =PMIS rating |
| Severe (1–1.99 in.) rutting | Percent of wheelpath length | $L_i$ =PMIS rating |
| Failure (>2 in.) rutting | Percent of wheelpath length | $L_i$ =number of failures per mile $L_i = \frac{rating}{length}$ |
| Patching | Percent of lane area | $L_i$ =PMIS rating |

**Table 4.** Continued

| **Asphalt concrete pavement** | **Rating method** | **Computing $L_i$** |
|---|---|---|
| Failures | Total number (0 to 99) | $L_i$ =PMIS rating |
| Block cracking | Percent of lane area | $L_i$ =PMIS rating |
| Alligator cracking | Percent of wheelpath length | $L_i$ =PMIS rating |
| Longitudinal cracking | Length per 100 ft. station (0 to 999) | $L_i$ =PMIS rating |
| Transverse cracking | Number per 100 ft. station (0 to 99) | $L_i$ =PMIS rating |

After utility values are obtained, the DS is calculated. It is a measure of the visible surface deterioration (pavement distress) and is the product of the utility values of each type of failure according to the following expression.

$$DS = 100 \prod_{i=1}^{n} U_i \qquad (3.3)$$

where *DS* = DS with a 1–100 scale (100 represents no or minimal distress); $U_i$ = utility value (ranging between zero and 1.0); $n$ = total number of distresses.

After calculating the DS, the utility value for ride quality was calculated. It depends on traffic volume and speed limit. PMIS uses three classes of traffic based on the product of (ADT) and speed limit. The traffic classes are low, medium, and high and are important because they affect the CS. The following chart presents the traffic classes for computing ride quality utility.

**Table 5.** PMIS traffic classes for computing ride quality utility

| Traffic class | ADT x speed limit | ADT range in number of vehicles for speed limits of | | | | | |
|---|---|---|---|---|---|---|---|
| | | **55 mph** | **60 mph** | **65 mph** | **70 mph** | **75 mph** | **80 mph** |
| Low | 1~27500 | 1~500 | 1~458 | 1~423 | 1~367 | 1~367 | 1~324 |
| Medium | 27501~165000 | 501~3000 | 459~2750 | 424~2538 | 367~2357 | 368~2200 | 324~1941 |
| High | >165000 | >3000 | >2750 | >2538 | >2357 | >2200 | >1941 |

For ride quality, the $L_i$ values are computed based on traffic class. Ride quality values are calculated based on a serviceability index value (TxDOT 2011); ride quality values decrease as the road gets smoother in order to keep the same calculation logic as distress utility curve. The following equations are applied to calculate the ride quality.

Low traffic

$$L_i = 100x\left(\frac{2.5 - SI}{2.5}\right) \tag{3.4}$$

Medium traffic

$$L_i = 100x\left(\frac{3.0 - SI}{3.0}\right) \tag{3.5}$$

High traffic

$$L_i = 100x\left(\frac{3.5 - SI}{3.5}\right) \tag{3.6}$$

where $SI$= serviceability index value (from profiler).

CS is a measure of overall condition in terms of distress and ride quality. It is the product of DS and ride quality utility ($U_{ride}$). CS can vary from 1 to 100, where 100 represents no or minimal distress and roughness. CS is calculated with the following expression:

$$CS = DS \; x \; U_{ride} \tag{3.7}$$

### *3.3.2. Simplified expressions*

In order to fit the simplified equations, a set of values were calculated from the previously explained equations (from equation 3.2 to 3.7), and then an optimization process was applied to find the best parameters. The objective was to minimize the error between the output from TxDOT PMIS equations and a sigmoidal curve.

To derive a performance model for the DS as a function of age, the $L_i$ vs. age models were converted to $U_i$ vs. age models with the $L_i$ vs. $U_i$ equation for distress type which 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, a DS vs. age relation can be established. The resulting relationship is a sigmoidal curve derived from the individual utility curves as shown in Figure 11.

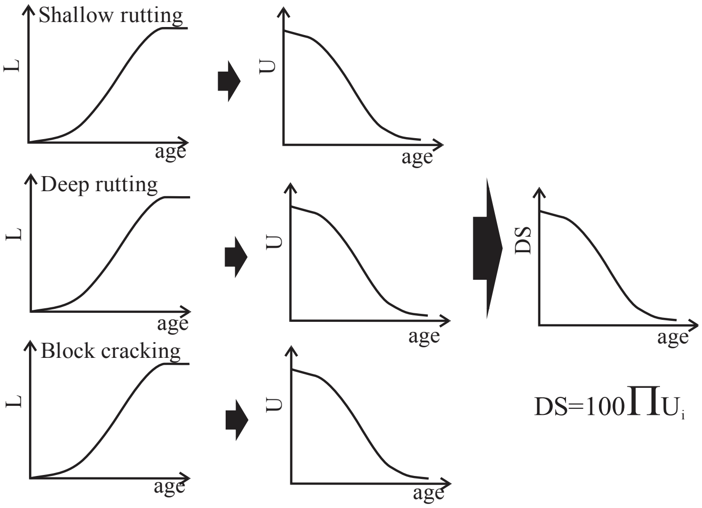

**Figure 11.** Derivation of DS prediction models.

Similarly to the DS, the CS can be expressed as a function of age. The CS vs. age curve was derived by combining the DS curve with the utility curve for ride quality as shown in Figure 12.

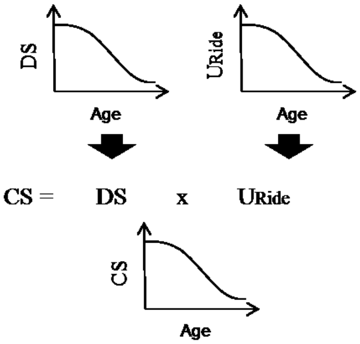

**Figure 12.** Derivation of CS prediction models.

Simplified function parameters for both the DS and the CS were calculated by solving an optimization problem, which was an objective function to minimize the error between the model and PMIS performance prediction functions. The mathematical expressions for the optimization problem are

DS objective function:

$$Min \sum_{j=1}^{4} \sum_{age=1}^{T} \sum_{i=1}^{n} \left[ DS_0 \left( 1 - e^{-\left(\frac{A_{DS}}{Age}\right)^{\beta_{DS}}} \right) - DS_{(j,age,i)} \right]^2 \tag{3.8}$$

CS objective function:

$$Min \sum_{j=1}^{4} \sum_{age=1}^{T} \sum_{i=1}^{n} \left[ CS_0 \left( 1 - e^{-\left(\frac{A_{CS}}{Age}\right)^{\beta_{CS}}} \right) - CS_{(j,age,i)} \right]^2 \tag{3.9}$$

Subject to the following constraints:

$A_{PM} < A_{LR} < A_{MR} < A_{HR}$

$\beta_{PM} < \beta_{LR} < \beta_{MR} < \beta_{HR}$

$e^{\left(\frac{A_{PM}}{age}\right)^{\beta_{PM}}} > e^{\left(\frac{A_{LR}}{age}\right)^{\beta_{LR}}} > e^{\left(\frac{A_{MR}}{age}\right)^{\beta_{MR}}} > e^{\left(\frac{A_{HR}}{age}\right)^{\beta_{HR}}}$

where $A_{DS,CS}$ and $\beta_{DS,CS}$ =coefficients obtained after the optimization problem is solved; $DS_{(j,age,i)}$ = DS for a specific type of pavement and M&R treatment, $DS = 100 \prod_{i=1}^{n} U_i$; $U_i$ = utility value of each distress type, $U_i = 1 - \alpha e^{-\left[\left(\frac{\rho}{L_i}\right)^{\beta}\right]}$; $\alpha, \rho, and\ \beta$= coefficients from the performance prediction equation (see Appendix A); $CS_{(j,age,i)}$= CS for a specific type of pavement and M&R treatment, $CS = DS\ x\ U_{ride}$; $age$ = treatment age; $n$ = total number of output values; $T$ = type of M&R treatment; and $j$ = type of treatment.

### 3.4 Probabilistic performance prediction module (Module 3)

This module generates the probability distribution of the simplified performance function coefficients. The previous module generated the simplified performance functions for a reliability level of 50%, thus it is necessary to extend the performance models to others reliability levels. Figure 13 presents a flowchart of the calculation process. The results from this module are the probability distribution for the coefficients of performance function for different pavement types, traffic classes, and M&R treatments.

Model reliability was incorporated into the performance prediction equations by changing the objective function proposed by Gharaibeh et al. (2011) to include a term that consider the reliability level. The optimization function is formulated to obtain the sigmoidal curve coefficients that minimize the difference between the proposed model and the real data for a certain reliability level. The optimization procedure is repeated for a different set of reliability values to obtain a series of coefficients $A, \beta$ for each combination of pavement type, traffic class, and M&R treatment.

Objective function:

$$Min \sum_{j=1}^{4} \sum_{age=1}^{T} \sum_{i=1}^{n} \left\{ R \left| 100e^{\left(\frac{A_j}{age}\right)^{\beta_j}} - RV(j, age, i) \right| + min \left[ 0, \left( 100e^{\left(\frac{A_j}{age}\right)^{\beta_j}} - RV(j, age, i) \right) \right] \right\} \qquad (3.10)$$

Subject to the following constraints:

$A_{PM} < A_{LR} < A_{MR} < A_{HR}$

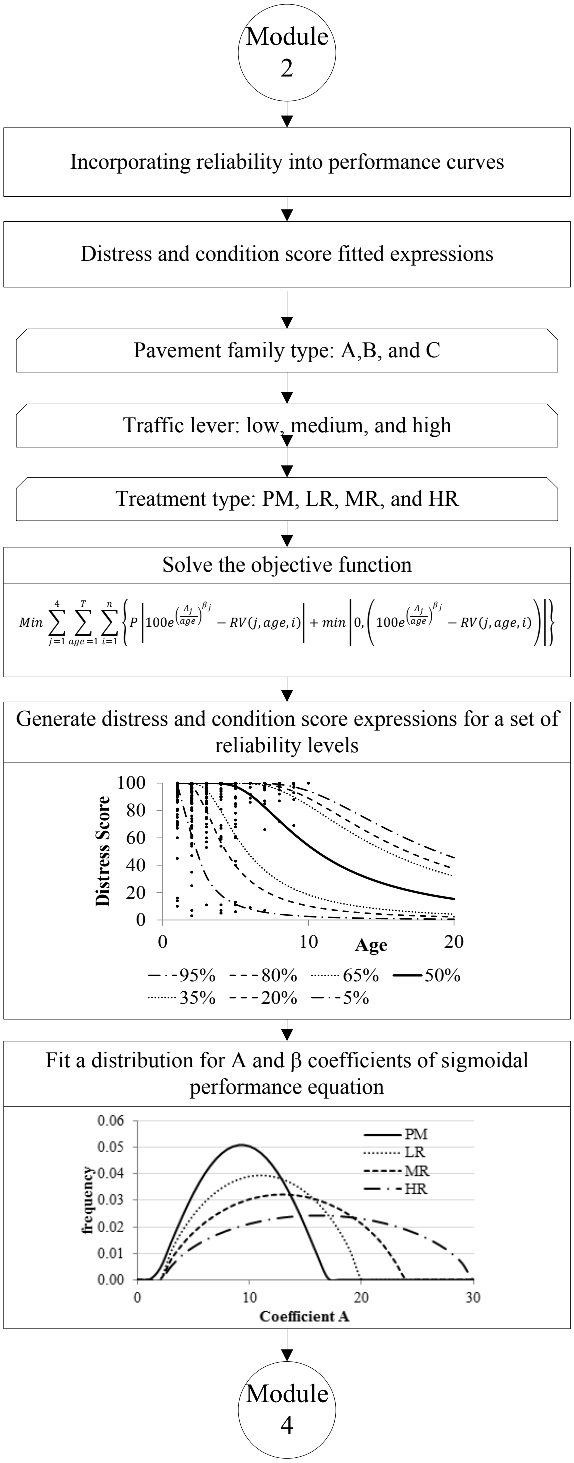

**Figure 13.** Flowchart for incorporating reliability into performance equations

$$\beta_{PM} < \beta_{LR} < \beta_{MR} < \beta_{HR}$$

$$e^{\left(\frac{A_{PM}}{age}\right)^{\beta_{PM}}} > e^{\left(\frac{A_{LR}}{age}\right)^{\beta_{LR}}} > e^{\left(\frac{A_{MR}}{age}\right)^{\beta_{MR}}} > e^{\left(\frac{A_{HR}}{age}\right)^{\beta_{HR}}}$$

where: $R$ = reliability level; $A$ and $\beta$ = calibration factors that depend on type of pavement, traffic class and M&R treatment type; RV = real value extracted from PMIS; T = number of years in the analysis; $age$ = treatment age; and $n$ = total number cases in the database.

Finally, probability distributions are fitted to the individual points obtained after running the optimization procedure in @RISK. Those distributions will be used to generate the values of $A, \beta$ in the MCS process.

### 3.5 Unit cost and budget availability module (Module 4)

This module generates the unit cost and available budget probability distributions. Unit cost distribution is obtained from construction cost data collected in Texas (Narciso 2013). These data were separated by type of treatment, and the corresponding unit cost was calculated. For budget availability, the TxDOT district and county statistics (DISCOS) information was collected. Figure 14 presents the module process used to obtain unit cost and budget availability probability distributions.

Unit costs were calculated from construction data for maintenance projects in Texas for the last five years. The values present variability since a variety of alternatives are possible in the M&R treatment groups. For budget availability, the data from previous years were converted to current dollars applying the Texas highway construction index (TxDOT 2013).

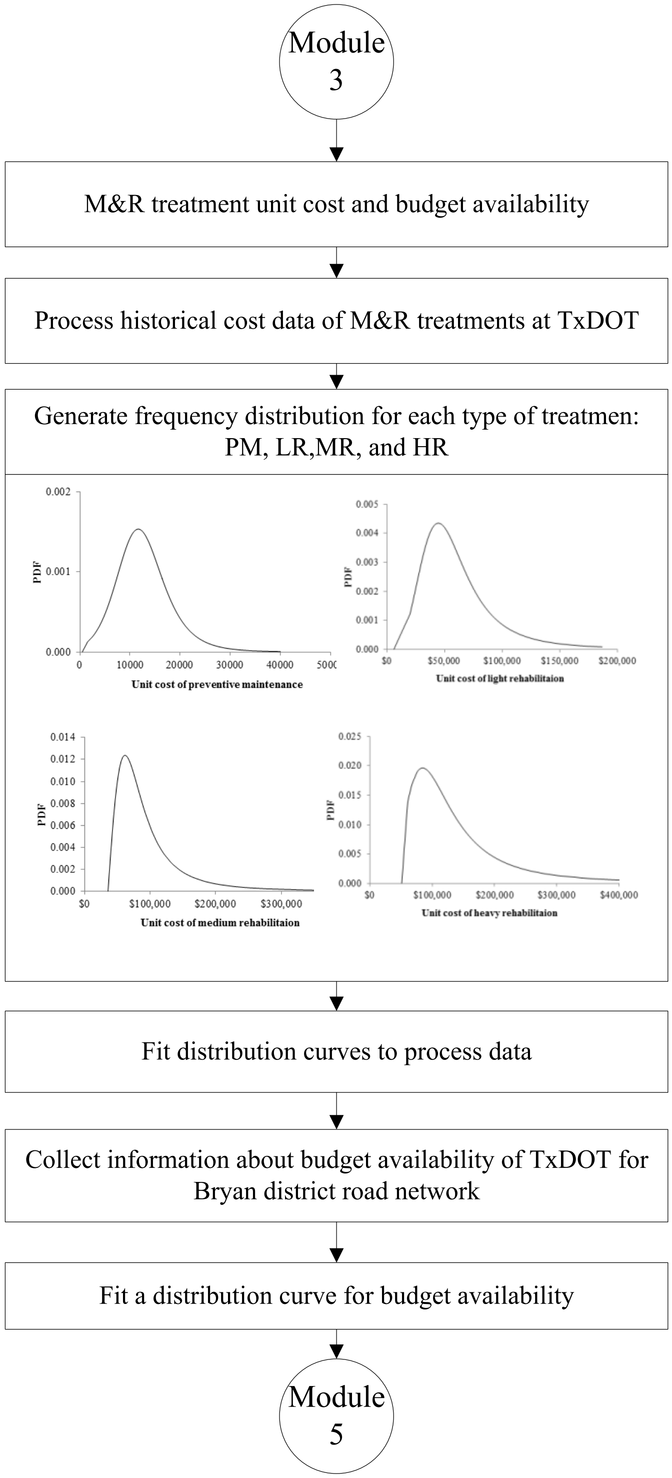

**Figure 14.** Flowchart for fitting distribution curves to unit cost and budget availability

### 3.6 Project ranking and optimization module (Module 5)

The ranking and optimization module is the core module of the entire model since it is comprised of the random data generation, benefit-cost calculation, and the optimization algorithm. The random data were generated with MCS using the @RISK software. Benefit-cost calculation was made following the TxDOT PMIS procedure, and the optimization was solved with integer programming coded in MATLAB® V. R2013a, 2013 (MathWorks 2013). Figure 15 presents a flowchart of the ranking and optimization module, in which the calculation process was repeated for each budget allocation policy.

The process begins with the random generation of CSs and DSs for each section. Then, for each one of the four M&R treatments, random unit cost and random performance coefficients are calculated. With the data generated, the benefit-ratio is calculated. The process is repeated again for each year; when the last year result is processed, the information is exported from @RISK to MATLAB to run the integer programming optimization. Finally, the projects are selected, and risk is calculated along with the backlog and the proposed investment amount per year.

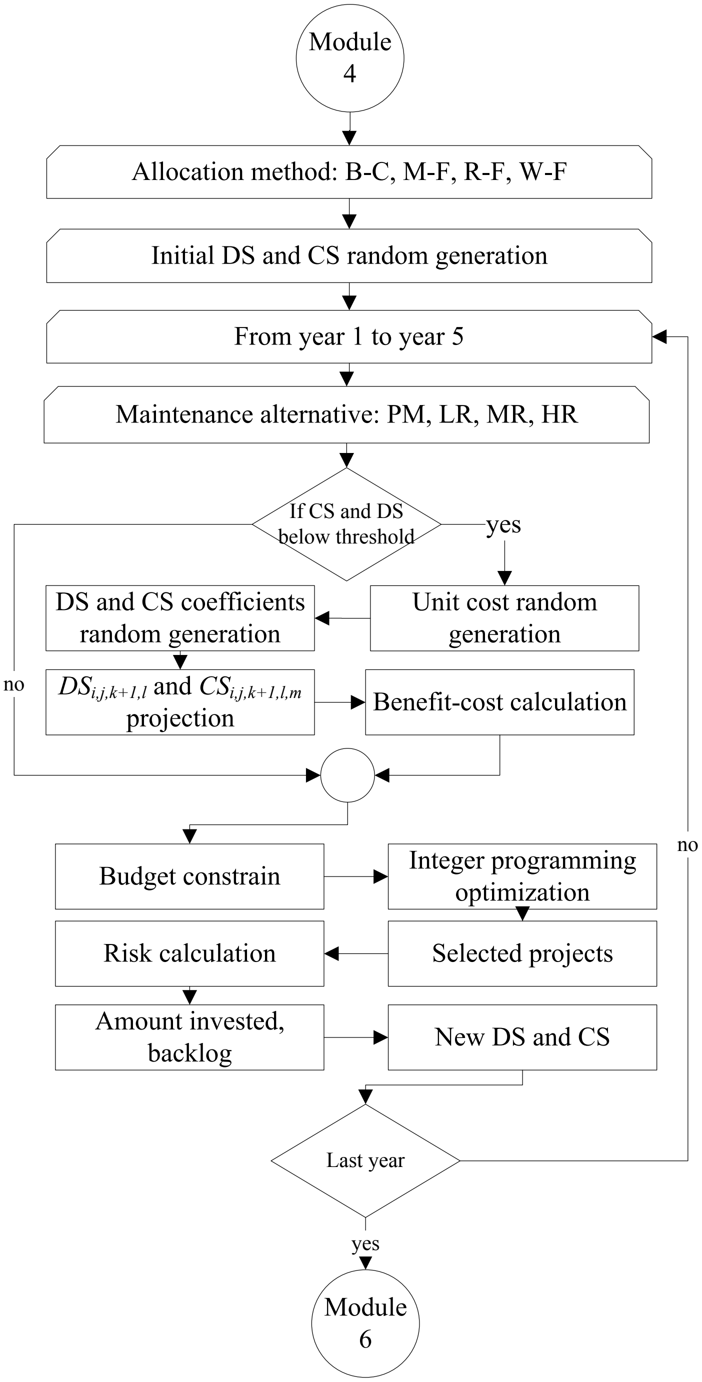

**Figure 15.** Flow chart of ranking and optimization process

### *3.6.1. Random variable generation*

The model is formulated to generate random variables according to the probability distribution of each variable. The risk cannot be calculated directly because the process is too complex to solve analytically. Instead, an MCS is implemented to generate key input data that follow the distributions obtained in the previous steps.

### *3.6.2. M&R treatment selection*

TxDOT PMIS selects the M&R treatments following a decision tree. The limitation of this approach is that the selected solution is not necessary the best from the benefit-cost point of view. In order to avoid this limitation, the model makes a comparative analysis of M&R treatment candidates, according to the segment average CS value (Table 6). This procedure prevents the selection bias that can be introduced by the decision tree procedure, the gain in the rating values after M&R treatment is presented in Table 6.

**Table 6.** Treatment selection criteria and gain of rating values

| **Treatment type** | **Treatment selection based on CS** | **Gain in distress utility** | **Gain in ride quality utility** |
|---|---|---|---|
| Need nothing | >90 | No change in distress ratings | No change in RS |
| PM | 90-70 | Reset DS to zero | Increase RS by 0.5 |
| LR | 80-60 | Reset DS to zero | Increase RS by 1.5 |
| MR | 70-50 | Reset DS to zero | Increase RS by 4.8 |
| HR | <50 | Reset DS to zero | Increase RS by 4.8 |

An additional check is done to avoid multiple applications of the same treatment in certain segment along the analysis period. This problem is presented specially with preventive maintenance treatment s, which tends to be selected multiple times due to the high benefit –cost ratio. Although, is not realistic that a pavement can be keep in good condition solely applying preventive maintenance, knowing that this treatment tends to lost its effectiveness after several applications (Labi and Sinha 2003).

### *3.6.3. Benefit calculation*

The benefit of applying certain M&R treatments is a fundamental factor. Benefit can be quantified in terms of user benefits, condition improvement, or a combination of benefits (e.g., user cost, reduction of travel time, increased safety, environmental benefits) (Peshkin et al. 2004). In the model, the benefits are calculated as the product of AUPC times ADT. AUPC is calculated before and after the M&R treatment for DS and CS curves before and after the suggested treatment is applied to both CS to DS.

$$B = 2\left[\frac{W_D}{100}A_D + \frac{W_R}{100}A_R\right] \tag{3.11}$$

Where $B$ = benefit of the proposed M&R treatment; $A_D$ = area between the "before" and "after" DS performance curves; and $A_R$ = area between the "before" and "after" dide quality performance curves.

Four possible scenarios for "before" and "after" utility curves are analyzed in order to calculate the area between curves: (1) that curves intersect before 20 years, (2) that the curves become parallel, (3) that the distance between the curves approaches a minimum value, or (4) that the curves reach a failure criterion.

The first case is when curves intersect before the age of 20 years (Figure 16). This is a typical case when the proposed M&R treatment has a shorter life than the previously applied treatment. It means that the improvement, or "jump," of the condition is lost at a greater rate than the previous deterioration rate.

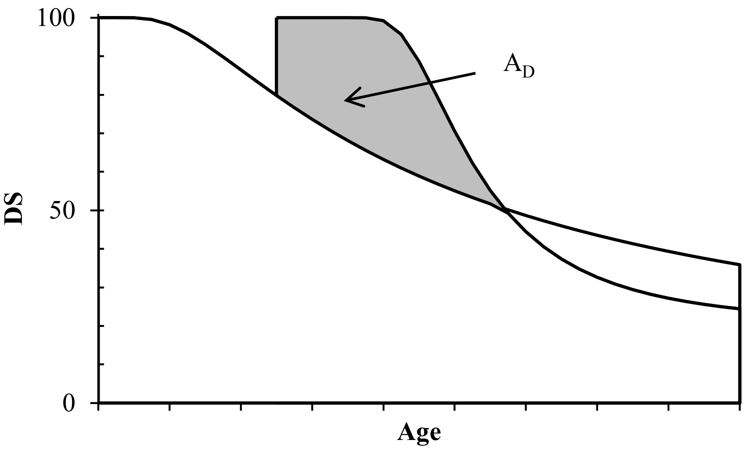

**Figure 16.** Boundary condition for curves intersecting

The age or time where "before" and "after" curves intersect needs to be calculated before the area. Since both curves are expressed as sigmoidal curves, the age at which curves intersect can be obtained by applying the following expressions:

DS curve intersection:

$$t_{id} = \left[\frac{A_{da}{}^{\beta_{da}}}{A_{db}{}^{\beta_{db}}}\right]^{1/(\beta_{da}-\beta_{db})} \tag{3.12}$$

RS curve intersection:

$$t_{ir} = \left[\frac{A_{ra}{}^{\beta_{ra}}}{A_{rb}{}^{\beta_{rb}}}\right]^{1/(\beta_{ra}-\beta_{rb})} \tag{3.13}$$

where $t_{id,ir}$= age when distress or ride “after” and “before” curves intersects; $A_{da,ra}$ ,$\beta_{da,ra}$= coefficient of “after” curve for distress and ride; $A_{db,rb}$ ,$\beta_{db,rb}$= coefficient of “before” curve for distress and ride.

Another case is when curves become parallel (Figure 17). This happens when the previous treatment and proposed treatment are similar and the segment still belongs to the same traffic class. The area between curves is calculated for a period of 20 years.

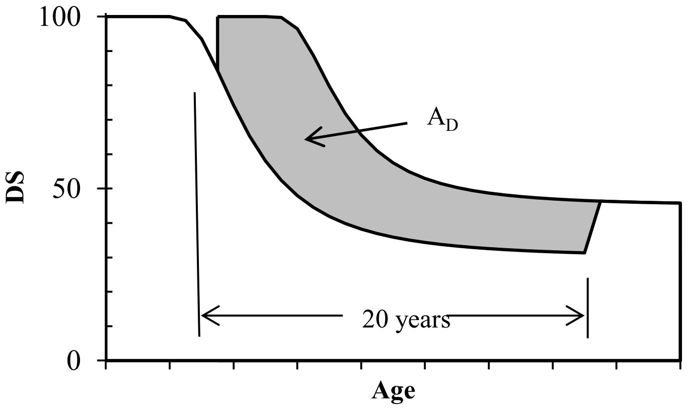

**Figure 17.** Boundary condition for 20 year treatment life

The third case is when curves approach each other very closely, a difference equal to or less than 0.0001 utility units (Figure 18), but do not intersect. As in the previous case, the area between curves is calculated for a period of 20 years.

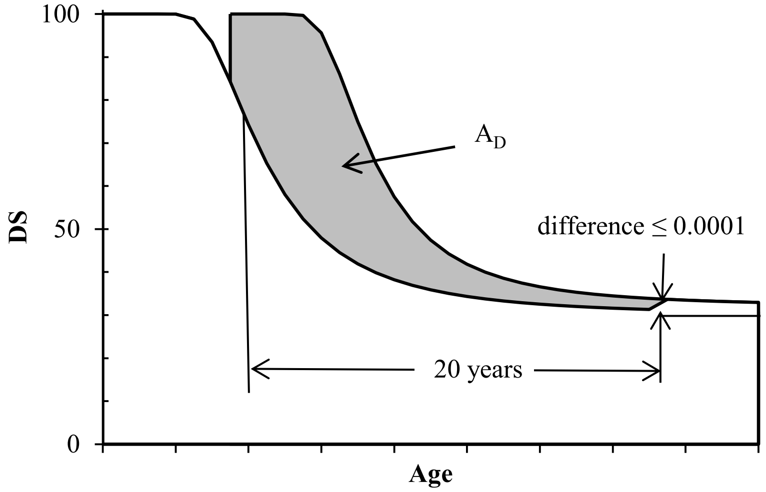

**Figure 18.** Boundary condition for minimum difference between curves

The last case is when curves reach the failure criterion. In this case, the benefit is the difference between the areas below the curves. For DS and CS, the failure criterion is 60% (or below) as can be seen in Figure 19.

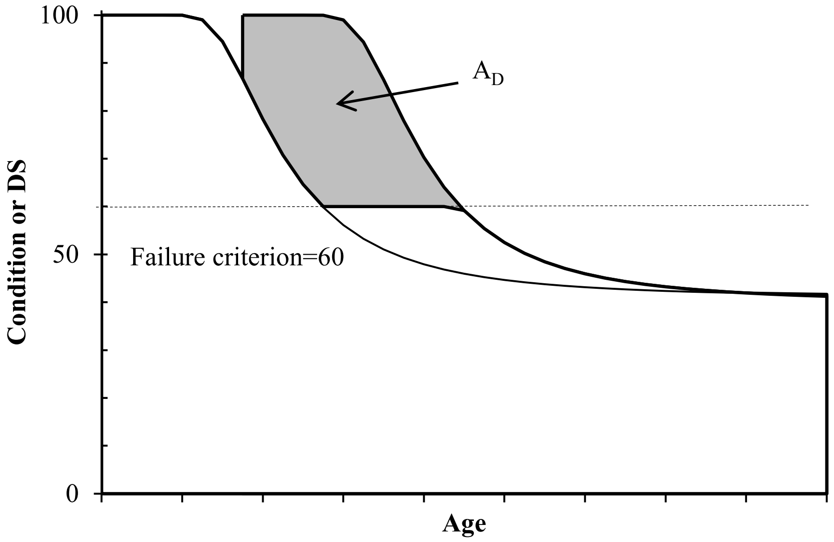

**Figure 19.** Boundary condition for failure criterion of DS or CS reached

For ride quality, the failure criterion is 30%, as is presented in Figure 20. In this case, the area between curves is the difference between the areas below the curves minus the area below the failure criterion.

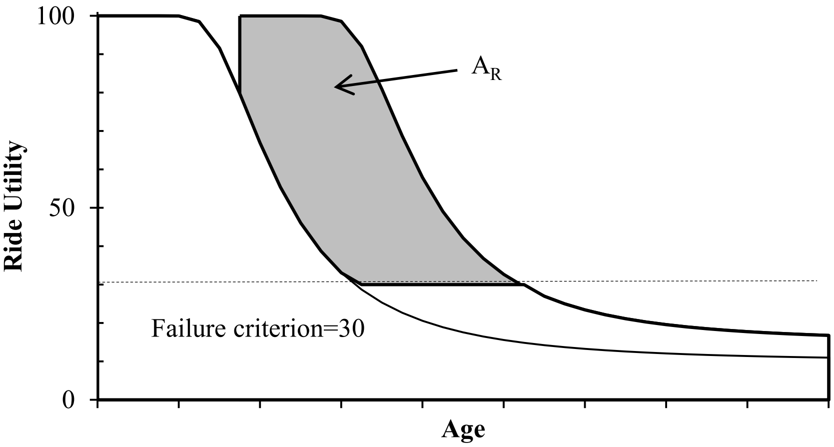

**Figure 20.** Boundary condition for ride utility failure criterion reached

The age at which the distress and ride failure criteria are reached needs to be calculated before the area calculation. As can be seen in the following expression, the age to reach failure depends only on the sigmoidal curve coefficients.

DS:

$$t_{fd} = Age_{distress\ failure} = \frac{A_d}{[-\ln(1-0.6)]^{1/\beta_d}} \tag{3.14}$$

Ride utility:

$$t_{fr} = Age_{ride\ failure} = \frac{A_r}{[-\ln(1-0.3)]^{1/\beta_r}} \tag{3.15}$$

where $t_{fd,fr}$= age when DS or RS “after” and “before” curves intersect the failure criterion; $A_{da,ra}$ , $\beta_{da,ra}$= coefficient of “after” curve for distress and ride; $A_{db,rb}$ , $\beta_{db,rb}$= coefficient of “before” curve for distress and ride.

In general terms, the area after the treatment can be mathematically expressed as the difference between areas ($Benefit = Area_{after} - Area_{\ before}$). Because a sigmoidal equation cannot have an exact solution for a defined integral, Simpon’s rule was applied (Kreyszig 2011). The resulting approximate expressions for calculating the area between performance curves were

DS:

$$A_D = \left(\frac{t_1 - t_2}{6}\right)\left\{-e^{-\frac{A_{db}}{t_1}^{\beta_{db}}} + e^{-\frac{A_{da}}{t_1}^{\beta_{da}}} - e^{-\frac{A_{db}}{t_2}^{\beta_{db}}} + e^{-\frac{A_{da}}{t_2}^{\beta_{da}}} - 4e^{-\frac{A_{da}}{t_1+t_2}^{\beta_{da}}} + 4e^{-\frac{A_{db}}{t_1+t_2}^{\beta_{db}}}\right\} \qquad (3.16)$$

Ride quality:

$$A_R = \left(\frac{t_1 - t_2}{6}\right)\left\{-e^{-\frac{A_{rb}}{t_1}^{\beta_{rb}}} + e^{-\frac{A_{ra}}{t_1}^{\beta_{ra}}} - e^{-\frac{A_{rb}}{t_2}^{\beta_{rb}}} + e^{-\frac{A_{ra}}{t_2}^{\beta_{ra}}} - 4e^{-\frac{A_{ra}}{t_1+t_2}^{\beta_{ra}}} + 4e^{-\frac{A_{rb}}{t_1+t_2}^{\beta_{rb}}}\right\} \qquad (3.17)$$

where $t_1$= initial year of the analysis; $t_2$= end year of the analysis; $t_{d,r}$= age defined according to the previously explained cases $t_{d,r} = t_2 - t_1$; $A_{da,ra}$ ,$\beta_{da,ra}$= coefficient of “after” curve for DS and ride utility; $A_{db,rb}$ ,$\beta_{db,rb}$= coefficient of “before” curve for DS and RS.

The effective life of the proposed M&R treatment is estimated as the minimum value between time to curves intersection, time to reach failure or twenty years. Those time periods are calculated according to the previous expression.

$$EffLife = \min(t_{id,ir}, t_{fd,fr}, 20) \qquad (3.18)$$

Where $EffLife$= effective life in years; $t_{id,ir}$= age when DS or RS "after" and "before" curves intersect; $t_{fd,fr}$= age when DS or RS "after" and "before" curves intersect the failure criterion.

The following graph (Figure 21) shows the effective life concept for the four cases already described. The model checks all possible cases before calculating the effective life. The maximum effective life is set at twenty years because most pavement requires at least one M&R treatment in this period of time.

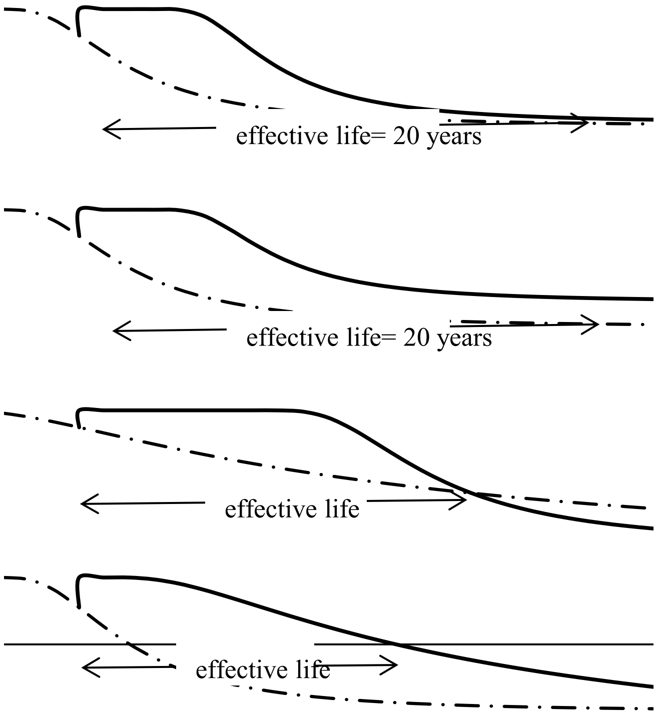

**Figure 21.** Effective life for each boundary condition (solid line indicates projected deterioration after M&R; dashed line shows deterioration without M&R)

### 3.6.4. *Uniform unit cost calculation*

The unit cost sampling from the probabilistic distribution needs to be annualized to properly calculate the benefit-cost ratio. Equivalent annual cost converts a onetime expense or investment in annual quotes in a period equivalent to the effective life (Bunn 1982). So the unit cost is discounted at a rate of 6.5% per year, similar to the assumption made in PMIS. The expression to calculate uniform annual cost is

$$UACost = UCost\ x \left[\frac{DRate(1 + DRate)^{EffLife}}{(1 + DRate)^{Efflife} - 1}\right] \tag{3.19}$$

Where $UACost$ = uniform annual cost of the M&R in US dollars; $DRate$ = discount rate in percent per year, estimated at 6.5%; $UCost$ = unit cost of the needs estimate treatment in US dollars.

### 3.6.5. *Benefit-cost ratio*

The benefit-cost ratio is the product of the division of benefit with uniform annual cost times vehicle-miles traveled (VMT), and it is normalized with the effective life. This model applies the following expression, which is similar to the cost-effectiveness ratio presented in PMIS:

$$B/C = 10{,}000x \left[\frac{LMxB}{EffLife\ x\ UACost}\right] x\ log_{10}VMT \tag{3.20}$$

Where B/C = benefit-cost ratio; $LM$= lane miles; $B$= benefit (DS and RS); $EffLife$ = effective life of the needs estimate treatment, in years; $UACost$ = uniform annual cost of the needs estimate treatment in US dollars; $VMT$ = vehicle miles traveled. The benefit-cost ratio is multiplied by 10,000 to convert a small decimal value in an integer of four digits.

### ***3.6.6. Project selection***

The last step in the ranking and optimization module is generating the list of segments selected to receive an M&R treatment. This process has four different components, each corresponding to an allocation policy. The budget allocation scenarios are benefit-cost (B-C), preventive maintenance first and then rehabilitation (M-F), rehabilitation first and then preventive maintenance (R-F), and worst-first (W-F). A detailed explanation of each is presented in 3.7.1.

For the first three scenarios, the optimization algorithm is similar. B-C alternative selects projects based on maximizing the benefit-cost ratio. The M-F scenario runs the optimization in the same way as B-C does, but rehabilitation projects are selected only when all preventive maintenance projects have already been funded. R-F is similar to M-F, but in this scenario preventive maintenance projects are selected only if all rehabilitation projects have already been funded. The W-F scenario does not require an optimization process. Projects are sorted according to their CSs and prioritized form the worst to best and funding is allocated to projects in that order until the budget is depleted.

The optimization is proposed as an integer programming problem. The decision to fund a project can be zero (not selected) or one (selected). The constraints are (a) available annual budget and (b) a maximum of two applications of the same treatment during the analysis period. Then the optimization problem is solved year by year and expressed as

The objective function:

$$Max.\sum_{i=1}^{n}\sum_{r=1}^{s}\left[\frac{(LM_i)\left(B_{i,r}\right)}{\left(EffLife_{i,r}\right)\left(UACost_{i,r}\right)}\right]\left(log_{10}VMT_i\right)\left(x_{i,r}\right) \qquad (3.21)$$

Subject to the following constraints:

$$x_{i,r} \geq 0, x_{i,r}\ is\ binary$$

$$\sum_{i=1}^{n}\left(Ucost_{r,i}\right)(LM_i) \leq Annual\ budget$$

$$\sum_{j=1}^{y} x_{i,r} \leq 2$$

where $LM$ = project length; $B$ = benefit expressed as the area under the performance curve; $EffLife$ = effective life; $VMT$ = vehicles miles traveled; and $UACost$ = uniform annual cost; $s$ = number of possible M&R alternatives for a specific segment; $n$ = number of network segments; $y$ = number of years.

In order to solve the optimization problem, data are generated by @RISK and exported to MATLAB. Optimization was solved using the MATLAB optimization tool box (the code is in Appendix B). Results were exported to Excel to complete the analysis process.

## 3.7 Risk assessment module (Module 6)

The last component of the framework is the risk assessment module. This component summarizes the results of the previous components and calculates the risk for each allocation policy. Figure 22 summarizes the entire model with the risk results at the end. Risk calculations are saved during the process since samples are generated with MCS. In the final stage, risk results are processed to obtain the risk distributions and compare the budget allocation methods at equal expected levels of service.

### *3.7.1. M&R budget allocation methods*

Four scenarios among numerous allocation possibilities were selected to be included in this study. As previously described, the budget allocation scenarios analyzed were benefit-cost; preventive maintenance first and then rehabilitation; rehabilitation first and then preventive maintenance; and worst-first.

### *3.7.2. Risk calculation*

Conceptually, risk is the probability that a certain hazard or hazards can cause some negative consequences depending on the system's vulnerability (Aven 2003). In this module, risk is calculated as the product of the budget availability and network projected performance. The result represents the probability of not achieving the state's goal of a certain percentage of roads in good condition.

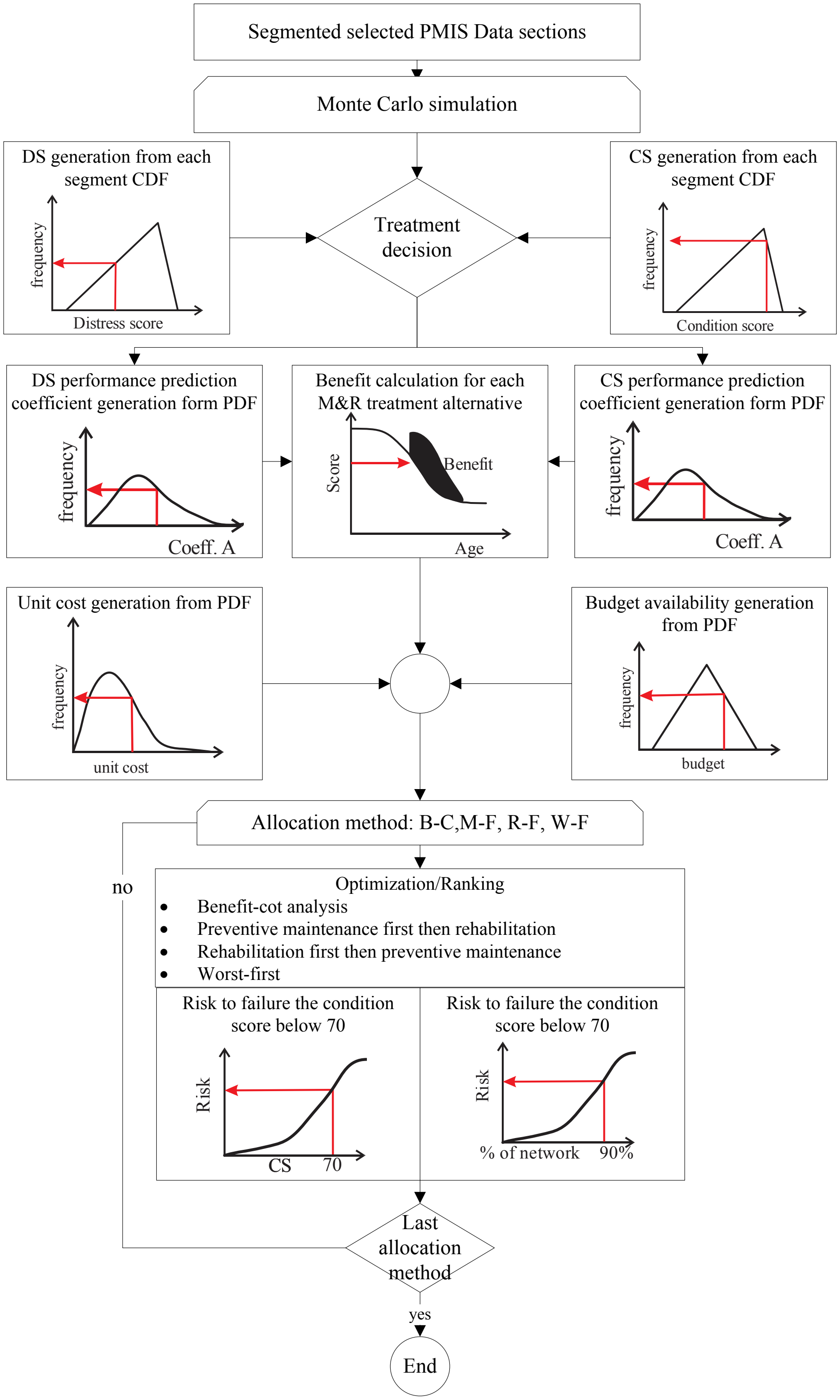

**Figure 22.** Flowchart of entire budget allocation decision framework

At the end of each year for which the model is run, the DS distribution and the percent of the network in “good” condition, (i.e., CS of 70 or higher), are obtained. Risk is presented in two forms: as the probability of reaching the expected value of 70 for CS and as the probability of reaching the Texas goal of 90% of the network in “good” condition.

# 4. MODEL APPLICATION TO SELECTED NETWORK

The pavement network in the Bryan district of Texas was chosen for analysis using the framework described in Section 3. The analysis was done for a period of five years, and a part of the Bryan district network was selected to quantify the risk under four different budget scenarios.

## 4.1 Road network

2011 pavement condition data were gathered from TxDOT PMIS for Bryan district. The Bryan district road network consists of 3,397.1 centerline-miles (PMIS 2011). Table 7 presents a summary of Bryan district road network.

**Table 7.** Summary of the Bryan district road network according to TxDOT PMIS (2011)

| Type of road | Total centerline-miles | % of entire networks | Average AADT |
|---|---|---|---|
| Interstate highways | 356.5 | 10.5% | 7,874 |
| U.S. highways | 387 | 11.4% | 7,608 |
| State highways | 750 | 22.1% | 4,847 |
| Farm to market roads | 1,855.8 | 54.5% | 2,100 |
| Business routes | 32.3 | 1.0% | 7,277 |
| Park and recreational roads | 15.5 | 0.5% | 476 |
| **Total** | **3,397.1** | **100%** | **n/a** |

Figure 27 shows a group of maps of the Bryan district road network by type of road. Farm to market roads make up the majority of the roads, 54.5% of the total district network. At the other end of the scale are the park and recreational roads, which are only 0.5% of the entire district. However, interstate highways, U.S. highways, and business routes have disproportionally high AADTs, though they represent only 22.9% of the total network.

Only a portion of the network was selected to perform the model. The area selected covers all the possibilities in terms of type of pavement, conditions, and traffic that can be solved efficiently by the model. Selected roads are the part of the Bryan district comprised by the entire network of state highways, business routes, and park and recreational roads. Table 8 shows a summary of selected roads, which represent 23.6% of the entire network of Bryan district and have a length of 797.8 centerline-miles equivalent to 1718.6 lane-miles.

**Table 8.** Analyzed Bryan district network

| Type of road | Total length (center-line miles) | % of entire network |
|---|---:|---:|
| State highways | 750 | 22.1% |
| Business routes | 32.3 | 1.0% |
| Park and recreational roads | 15.5 | 0.5% |
| **Total** | **797.8** | **23.6%** |

**Figure 23.** Maps of the Bryan district road network, (A) total network, (B) interstate highways, (C) U.S. highways, (D) state highways, (E) farm to market roads, (F) business routes.

## 4.2 Network segmentation

The network that was selected for the analysis is composed of 1,695 sections of approximately 0.5 miles each. The segmentation process, described in section 3.2.2, was applied after the information from PMIS was retrieved. It results in a total number of 237 segments or potential projects which will be used in the analysis. The list of segments and the characteristics of each are in Appendix C.

The segmentation process takes not only the CDA results but also existing constraints such as bridges, type of pavement, and number of lanes into consideration. For that reason, the number of sections in each segment is not constant; the segments vary from 1 to 25 sections. The average length of each segment in miles is 3.37, with a maximum length of 10 miles. Figure 24 shows the frequency distributions for the number of sections forming a segment and the length of segments in miles.

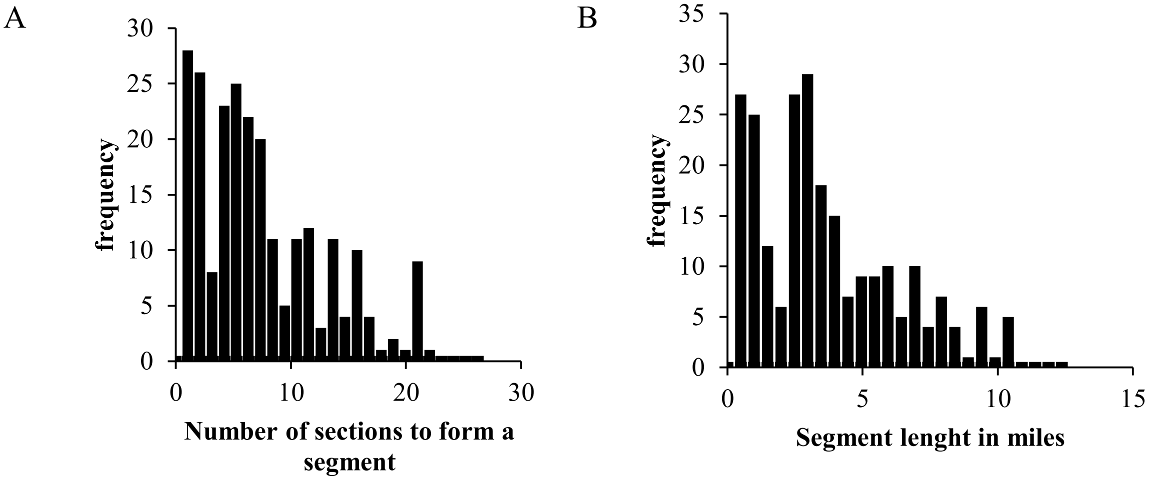

**Figure 24.** Network segmentation frequencies: (A) number of section that forms a segment, (B) segment length in miles.

In Table 9 the total length of network by type of road in center-line miles and the number of segments for each type of road are shown. As expected, the highest number of segments is from the state highway network. The smallest number of segments and the shortest average segment length were in the park and recreational roads.

**Table 9.** Network included in the analysis with the number of projects

| Type of road | Total length (in center-line miles) | Nº of segments |
|---|---|---|
| State highways | 750.0 | 206 |
| Business routes | 32.3 | 23 |
| Park and recreational roads | 15.5 | 8 |
| **Total** | **797.8** | **237** |

Figure 25 shows the locations of the potential projects. These segments were obtained after applying the CDA approach to the PMIS 2011 data. Since the state highway network was the longest network, most of the segments were connected, working together as a network. In contrast, most of the business and recreational road segments were not connected, and consequently, CDA segmentation was less effective.

The model can be applied to a broad variety of score frequency distributions. Segments of state highway tended to have more uniform distribution of DSs and CSs because the segmentation was mainly based on CDA. Due to the limitations of CDA by physical restrictions, business and park road segments had a more complex distribution of DSs and CSs.

**Figure 25.** Network roads included in the analysis: (A) total network, (B) state highways, (C) business routes, (D) park and recreational roads

### 4.3 Initial condition of roads

According to the proposed model, initial condition of DS and CS are represented as probability density functions. Best fit distribution parameters are saved in the model to generate random samples. These distributions are applied only in the first year; for the following years, the score is calculated from the performance predictions.

Figure 26 presents a comparison of DS and CS distributions for all sections included in the analysis. DS results are more concentrated and have a minimum value of 38. CS results are more spread and have a minimum of 22. Although both sets of scores have a high frequency of values of 100—the frequency scale is logarithmic—implying that the overall initial condition of the network is good.

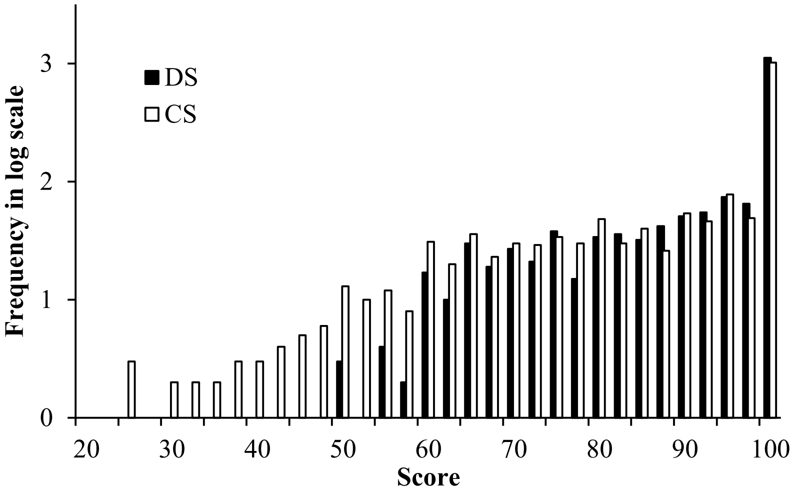

**Figure 26.** Frequency distributions for DS and CS

In 2011 selected network had an average DS of 94 considered very good (i.e. DS between 90 and 100) according to TxDOT (TxDOT 2011) and an average CS of 89 considered a good condition (i.e. CS between 70 and 89). It is recognized that a pavement in very good initial condition is less sensible to the budget allocation methods, since most of the needs are preventive maintenance. Therefore, it was generated two additional initial conditions.

Those additional conditions were fair average initial condition (i.e. CS between 50 and 69), and poor average initial condition (i.e. CS between 35 and 49). The shape of probability distribution was maintained, but the minimum, mode and maximum scores were reduced proportionally to reach the new initial average condition. So, three different initial conditions were included into the analysis.

Parametric probability distributions of DS and CS were fitted in each segment using @RISK® software. The most common probability distributions were uniform and triangular. Uniform distributions are frequent in segments defined with CDA, because the borders were defined based on the change in CD or DS. Triangular distribution was the most frequent for other segments, since they have outlier values that need to be included into the distribution. In 2011 selected network had an average DS of 94, which was considered very good, i.e., a DS between 90 and 100, according to TxDOT (TxDOT 2011) and an average CS of 89, defined as good condition by TxDOT, i.e., a CS between 70 and 89. Pavement in very good initial condition is less sensitive to budget allocation methods, because most of their needs are preventive maintenance. To deal with this situation, two additional initial conditions were created.

The additional conditions were (1) fair average initial condition which meant a CS between 50 and 69) and (2) poor average initial condition with a CS between 35 and 49. The shape of the probability distribution was maintained, but the minimum, mode, and maximum scores were reduced proportionally to reach the new initial average condition. So, two different initial conditions were included in the analysis.

Parametric probability distributions of DS and CS were fitted in each segment using @RISK software. The most common probability distributions were uniform and triangular. Uniform distributions were frequent in segments defined by CDA because the borders were defined based on the change in CD or DS. Triangular distribution was the most frequent for other segments, since they have outlier values that needed to be included in the distribution. Figure 27 presents examples of DS probability distributions and the corresponding segment locations.

Figure 27 presents examples of DS probability distribution and the corresponding segment location. In most of the cases a triangular distribution has the best fitting unless results were regularly distributed along the range.  Graphs G and H represent a special case where outliers force to have a distribution that can cover a great range of results.

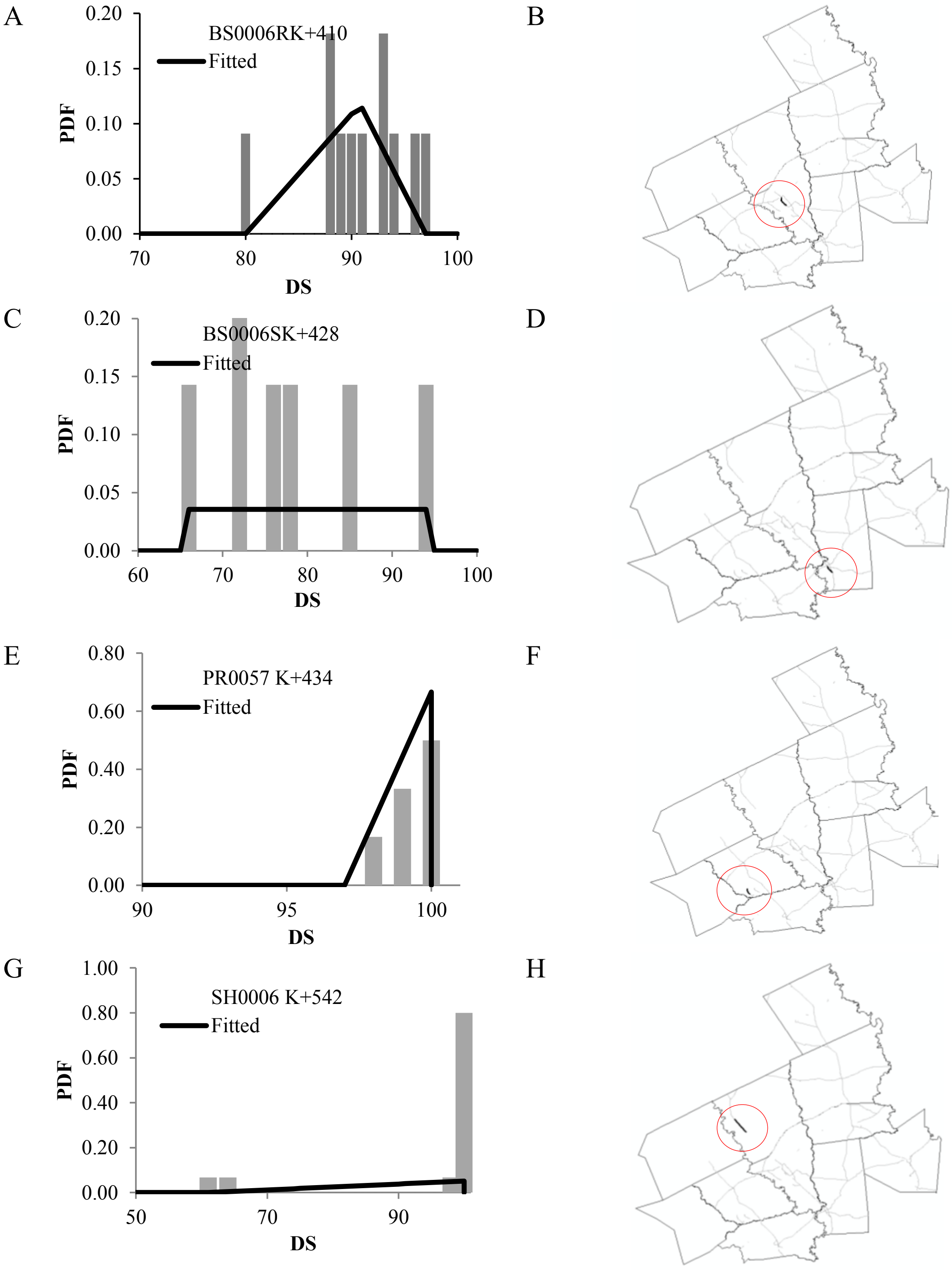

**Figure 27.** Examples of DS probability distribution and location of segments, (A) and (B) BS0006RK: 406.4 to 410.0; (C) and (D) BS 0006SK: 428.1 to 432.2; (E) and (F) PR0057K: 434.1 to 437.9; (G) and (H) SH0006K: 554.1 to 561.5

## 4.4 M&R unit costs

TxDOT for PMIS applies a unit cost for each treatment type, as can be seen in Table 10. Although a unique value of unit cost for each treatment is not a good representation of unit cost, since one treatment type is comprised of a number of different activities. However, sufficient detail is not usually available at the planning level to better estimate cost. Thus, using a probability distribution of unit cost instead of a unique unit cost value in the model is a better approach.

**Table 10.** State-wide unit cost for maintenance and rehabilitation treatments in Texas (Narciso 2013)

| **Treatment type** | **Unit cost (USD/lane-mile)** |
|---|---:|
| Preventive maintenance | 14,728 |
| Light rehabilitation | 76,086 |
| Medium rehabilitation | 78,429 |
| Heavy rehabilitation | 133,776 |

To obtain unit cost distributions for each M&R treatment, Texas construction data from 2009 to 2013 were compiled to obtain the unit cost of each type of treatment. After unit costs were calculated, data were separated into each M&R treatment. Table 11 summarizes the statistics of the data set used, which was composed of 1845 projects. The range of PM values is significantly lower than for other treatments. Rehabilitation treatment costs overlapped, but average unit cost increased as treatment complexity increased.

**Table 11.** Unit cost by type of treatment from 2009–2013

| Treatment type | Number of cases in the analysis | Minimum unit cost (USD) | Maximum unit cost (USD) | Average unit cost (USD) |
|---|---|---|---|---|
| PM | 967 | 1,540.24 | 94,973.00 | 14,150.90 |
| LR | 458 | 10,020.04 | 528,916.89 | 69,735.43 |
| MR | 292 | 10,000.00 | 676,454.40 | 75,612.57 |
| HR | 128 | 20,000.00 | 430,167.65 | 93,727.40 |

Of the 1845 cases analyzed, 52% correspond to PM, 25% to LR, 16% to MR, and 7% to HR. Figure 28 is a graphical representation of the range of unit costs and the number of data cases for each type of M&R. PM data were more concentrated and had a significant number of cases. LR data were more dispersed and had a set of results that coincides with PM. Finally, MR and HR data were dispersed and overlapped.

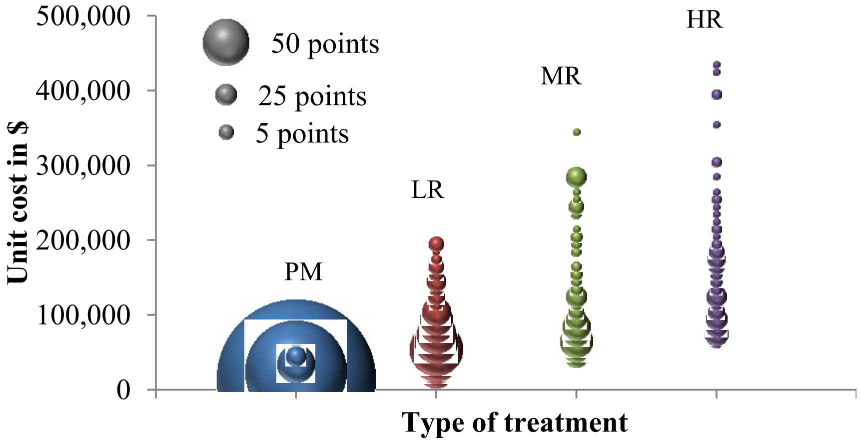

**Figure 28.** Number of data points and unit cost per each treatment type

After the results were divided into each M&R treatment, probability distributions were fitted for each treatment group. These distributions were integrated into a model to forecast the cost of each project using the MCS. In all cases, the best fitted expression was the log logistic, which is defined by three parameters. Additionally, a maximum unit cost restriction was placed into the model, since log logistic expressions can have an infinite maximum value, which is not realistic or useful in this case.

### *4.4.1. PM unit cost*

PM unit cost PDF was obtained using 967 cases. Almost all the cases corresponded to seal coats, and only two of them included patching. Although the performed work was uniform, the range of cost is broad, from 1,500 USD to 94,973 USD with an average of 14,150 USD, but there is a good agreement with values presented in Table 10. The equation that represents the best fitting PDF is the following.

$$f(x) = \frac{10.303\left(\frac{x + 19357.8}{31609.6}\right)^{10.303-1}}{31609.6\left[1 + \left(\frac{x + 19357.8}{31609.6}\right)^{10.303}\right]^{2}} \tag{4.1}$$

Figure 29 presents a comparison between the data distribution and the fitted generated distribution. Both had similar tendencies with the main difference that the fitted PDF was skewed to the left. The PM budget was calculated from a randomly generated unit cost and multiplied by the number of lanes and the length of the segment.

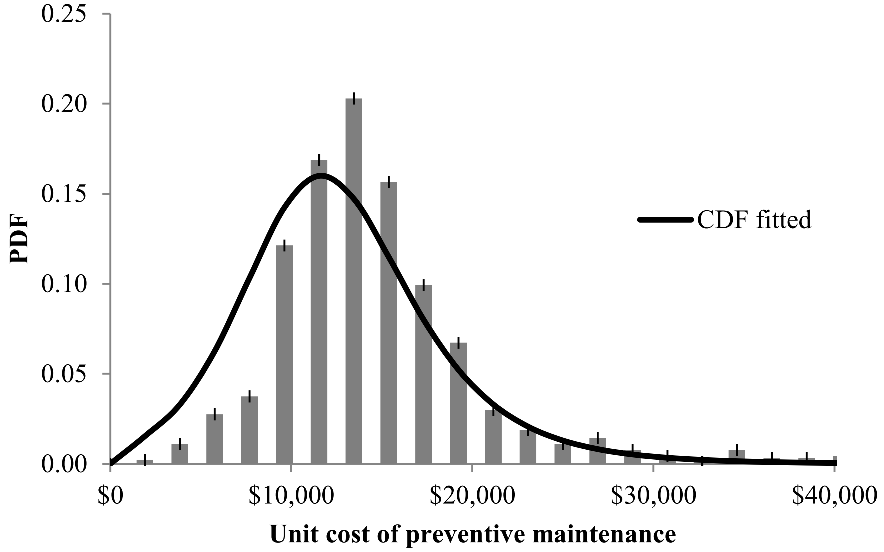

**Figure 29.** PM unit cost data PDF and fitted PDF

### *4.4.2. LR unit cost*

The LR unit cost PDF was obtained from 458 cases. A great variety of rehabilitation works are classified under this treatment classification. Among them, the most common are asphalt repair; base repair and sealing or patching; base and sub-base repair and sealing; base and subgrade repair and sealing; mill and overlay; and overlay. This variety of treatment is the main reason that the unit costs range from 10,020 USD to 528,916 USD with an average of 69,753 USD. The average value obtained by this model was less than the values used by the state of Texas as presented in Table 10. The equation that represents the best fitting PDF is the following.

$$f(x) = \frac{3.0063\left(\frac{x-6184.3}{48455.4}\right)^{3.0063-1}}{48455.4\left[1+\left(\frac{x-6184.3}{48455.4}\right)^{3.0063}\right]^{2}} \tag{4.2}$$

Figure 30presents a comparison between data distribution and fitted generated distribution. Though both distributions follow a similar tendency, but the fitted PDFwill generate more values below the mean than the real data. The LR budget was calculated from a randomly generated unit cost and multiplied by the number of lanes and the length of the segment.

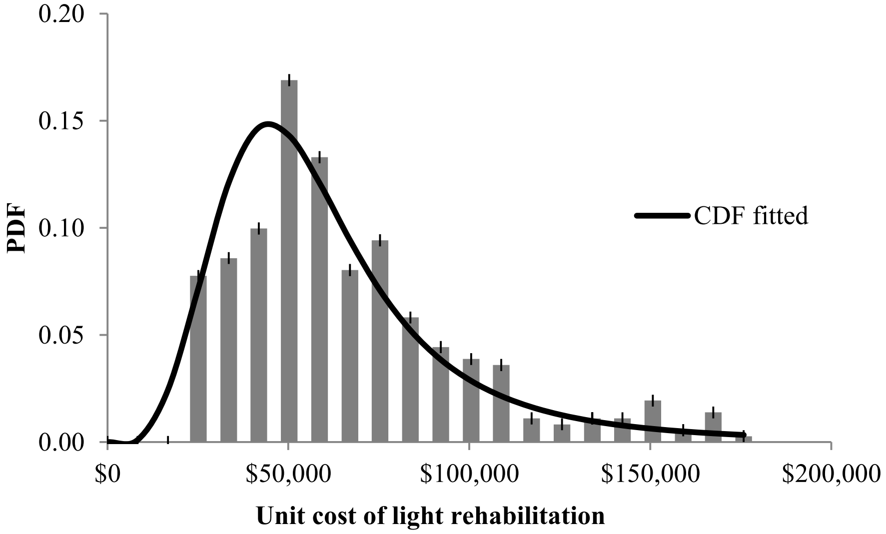

**Figure 30.** LR unit cost data PDF and fitted PDF

### *4.4.3. MR unit cost*

The MR unit cost PDF was obtained from 292 cases. A great variety of rehabilitation works fall in this treatment category. The most common are base repair, level up and seal coat; full depth repair; mill, seal and lay; subgrade repair with cement; mill and overlay; and in-place repair with geogrid and cement. Because of this variety, the unit costs range from 10,000 USD to 676,454 USD with an average of 75,612 USD. The average value obtained is similar to the value for this treatment category presented in Table 10. The equation that represents the best fitting PDF is the following.

$$f(x) = \frac{2.0\left(\frac{x-35863.4}{44915.7}\right)^{2.0-1}}{44915.7\left[1+\left(\frac{x-35863.4}{44915.7}\right)^{2.0}\right]^{2}} \tag{4.3}$$

Figure 31 presents a comparison between the data distribution and the fitted generated distribution. Fitted and data distributions have the same tendencies, being the log logistic PDF a good representation of analyzed information. The MR budget was calculated from a randomly generated unit cost and multiplied by the number of lanes and the length of the segment.

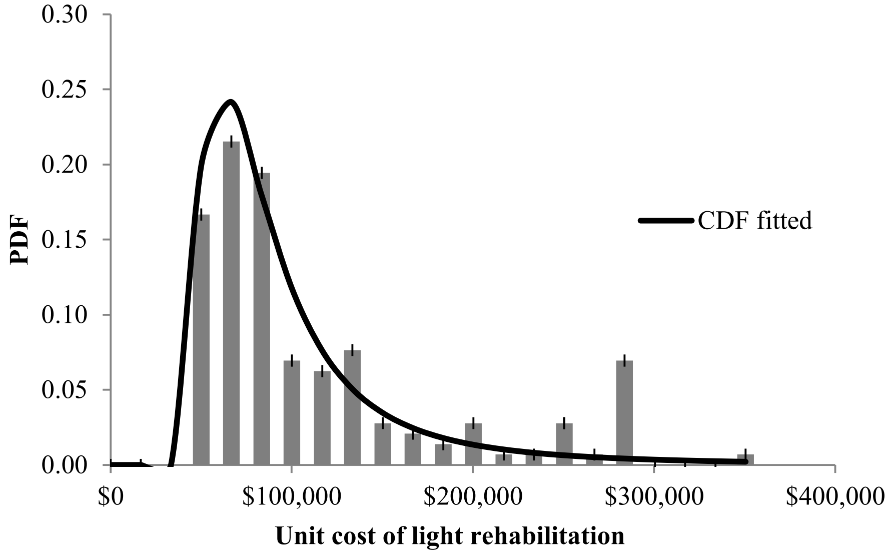

**Figure 31.** MR unit cost histogram and fitted PDF

### *4.4.4. HR unit cost*

The HR unit cost PDF was obtained from 128 cases. The most common repairs in this category are recycle, add base and seal; base repair and overlay; full depth base repair and seal; restoration of road; and scarify and add base and seal. Due to the vast variation in HR treatments, the unit costs range from 20,000 USD to 430,167 USD with an average of 193,727 USD. Obtained average value is less than the value presented in Table 10. The equation that represents the best fitting PDF is as follows.

$$f(x) = \frac{1.9647\left(\frac{x-41790.3}{75571.0}\right)^{1.9647-1}}{75571.0\left[1+\left(\frac{x-41790.3}{75571.0}\right)^{1.9647}\right]^{2}} \tag{4.4}$$

In Figure 32 fitted distribution and data distribution differed, because the number of cases was insufficient for a smooth distribution and the data contained numerous outliers. As a consequence, the log logistic PDF curve is skewed to the left. As with previously described M&R treatment budgets, the HR budget was calculated using a randomly generated unit cost and multiplied by the number of lanes and the length of the segments.

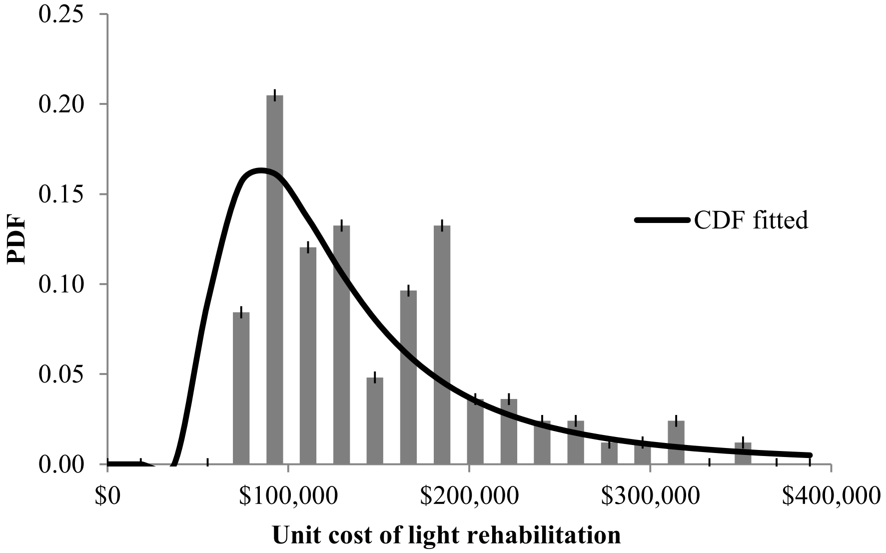

**Figure 32.** HR unit cost histogram and fitted PDF

Figure 33 compares the PDFs of each M&R treatment category. The PM budget was highly concentrated in the range of 5,000–20,000 USD, but the other treatment categories overlapped with each other in the range of 20,000 USD to 100,000 USD. HR is the category that covered the largest range of values among the rehabilitation treatments. Except in the case of PM, due to the random data generation, rehabilitation treatments in the other three categories could have similar unit cost values for a specific iteration. However, after the MCS iterations, resulting values will follow the distributions already presented.

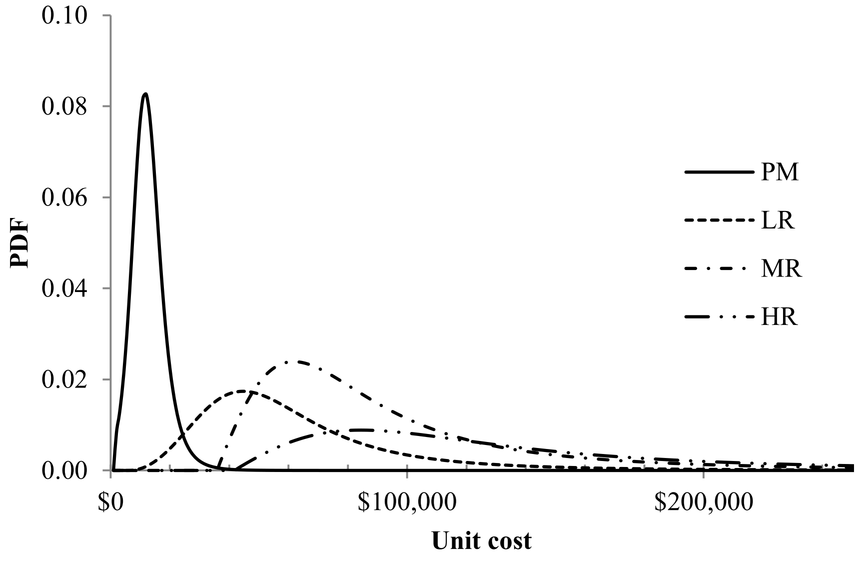

**Figure 33.** Comparison of M&R unit cost probability distributions

## 4.5 Performance prediction functions

The procedure for obtaining the simplified performance function was explained in section 3.3.2. According to this procedure, the initial step is calculating the utility values for each type of distress. Since only ACPs are included in the analysis, the failures considered in the calculation are shallow rutting, deep rutting, failures, block cracking, alligator cracking, longitudinal cracking, transverse cracking, and patching.

An example is shown in Figure 34, which presents the distress density and corresponding utility value for an alligator cracking distress in a road with light traffic. Distress density increases with time, having maintenance a faster distress utility growing compare with rehabilitation. In terms of utility value, the lowest utility corresponds to PM and the highest to HR, concluding that utility lost is proportional to the type of M&R.

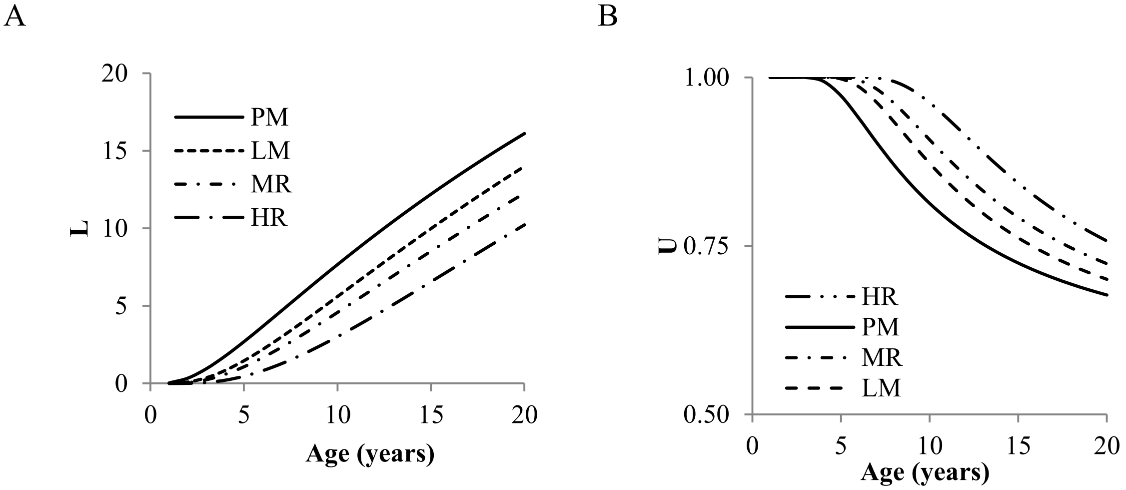

**Figure 34.** Alligator cracking with light traffic: (A) distress density, (B) utility value

The procedure was conducted for light, medium, and high traffic and for each type of treatment and each distress type. As a sample of the analysis performed, Figure 35 shows the utility values for each distress type for the PM treatment and light traffic. The type of distress that has the highest change over the time is the failure type.

Alligator cracking and patching also have an important change in utility value over time. All other types of distress present similar behavior over time.

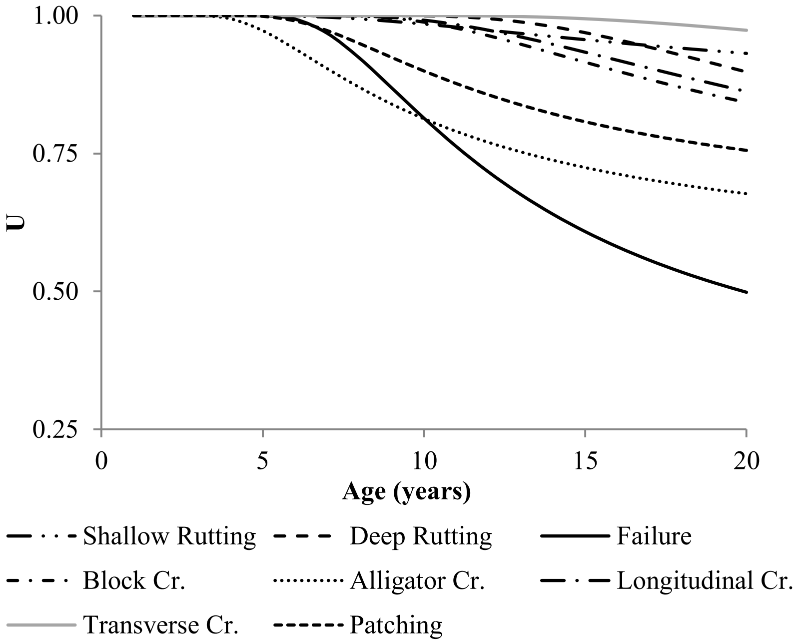

**Figure 35.** Utility values of each distress for PM with light traffic

After all the utility values were calculated, the DS was obtained as the product of the individual utility values. Using the DS, the ride quality utility is calculated over time. Finally, the CS score is obtained by multiplying ride utility by the DS as is presented in Figure 36.

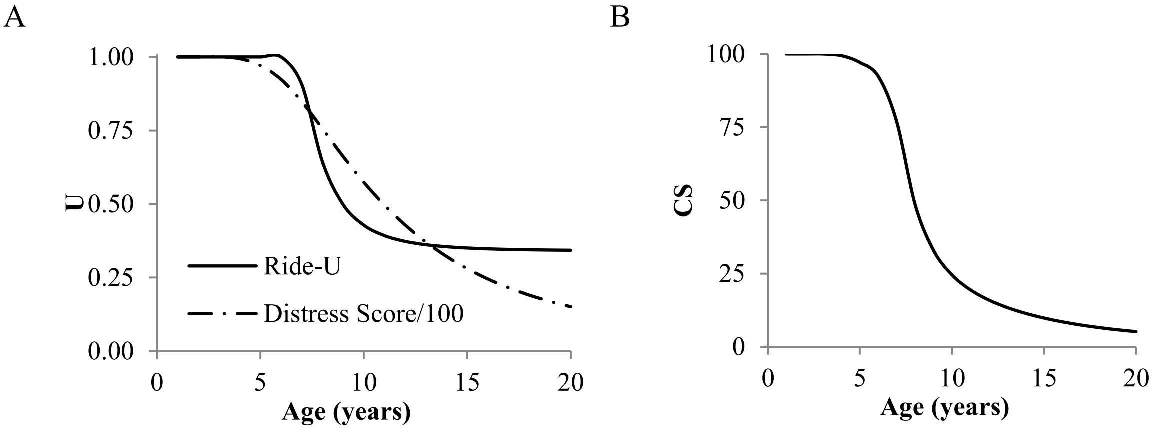

**Figure 36.** RS for PM with light traffic for pavement type 5: (A) utility value, (B) CS

After the previous step, DS and CS curves were generated for each M&R treatment, pavement family, zone, and traffic level. Figure 37 presents the DS and CS values for a pavement family A located in zone 2 with three different traffic levels. Figure 37 shows that the DS curves for all the treatment types are smooth and sigmoidal in shape. In contrast, CS curves show a sudden change in the slope after reaching certain number of years due to the way that utility value is calculated.

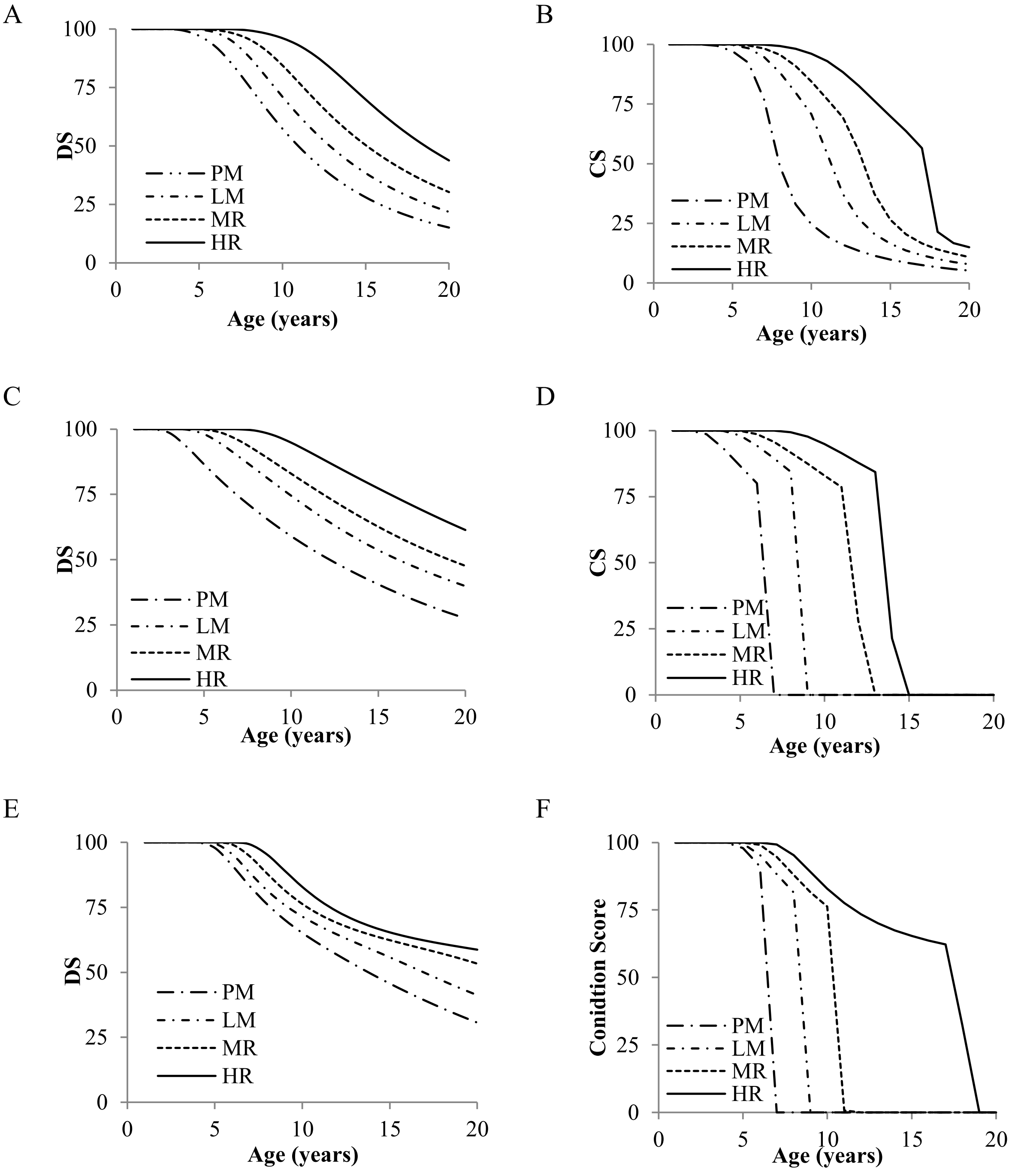

**Figure 37.** DS curves (left) and CS curves (right) for zone 2 pavement family: (A) and (B) show light traffic, (C) and (D) medium traffic, and (E) and (F) high traffic

A sigmoidal expression was fitted into the curves presented in Figure 37. The coefficients *β* and *A* were derived for different combinations of climate-subgrade zone, pavement family, traffic class (AADT × speed), and M&R treatment type. Coefficient values β and *A* for zone 2 (wet-warm climate and poor, very poor, or mixed subgrade) and pavement family A (pavement types 4, 5 and 9 according to TxDOT pavement classification) are shown in Table 12 for DS and CS.

**Table 12.** Performance curves parameters for pavement family A and climatic zone 2

| **Pavement type** | **Traffic type** | **Treatment type** | **DS** | | **CS** | |
|---|---|---|---|---|---|---|
| | | | ***β*** | ***A*** | ***β*** | ***A*** |
| 5 | Low Traffic | PM | 2.235 | 8.971 | 4.009 | 7.571 |
| | | LM | 2.235 | 10.901 | 4.009 | 10.327 |
| | | MR | 2.235 | 12.818 | 4.009 | 11.490 |
| | | HR | 2.455 | 16.077 | 4.009 | 15.050 |
| 5 | MediumTraffic | PM | 1.256 | 8.676 | 13.393 | 6.268 |
| | | LM | 1.405 | 12.438 | 21.864 | 8.227 |
| | | MR | 1.498 | 15.092 | 25.912 | 11.178 |
| | | HR | 1.807 | 18.868 | 29.265 | 13.283 |
| 5 | High Traffic | PM | 1.255 | 10.432 | 5.743 | 5.893 |
| | | LM | 1.255 | 12.467 | 9.924 | 7.776 |
| | | MR | 1.255 | 14.446 | 9.924 | 9.418 |
| | | HR | 1.255 | 16.664 | 62.000 | 16.000 |

Figure 38 presents a comparison between fitted curves and PMIS curves. For DS, there is a good match between fitted and PMIS curves. For CS, the match between curves is good, but not in high traffic conditions where curves coincide only for values below 60.

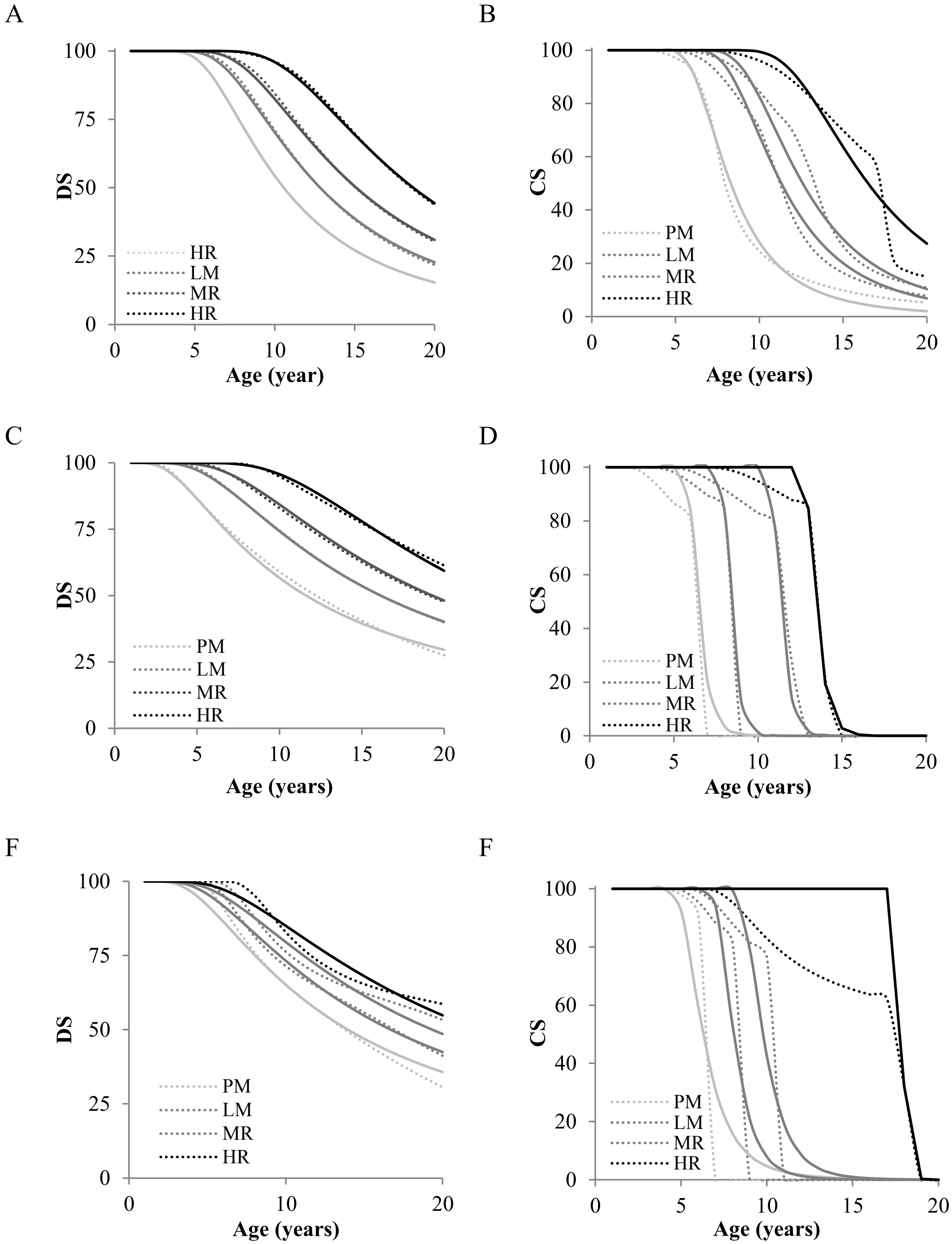

**Figure 38.** Fitted DS curves (left) and fitted CS (right): (A) and (B) show light traffic; (C) and (D) medium traffic; and (E) and (F) high traffic

As explained in the description of the model (section 3.4.2), reliability was incorporated into the performance prediction equations by modifying the objective function proposed by Gharaibeh et al. (2011) to include a term that considers the reliability level. After solving the optimization problem, a set of coefficients A and β were obtained for each reliability level included in the model. Those coefficients are presented in Appendix D.

The graphical representations of the reliability curves are presented in Figure 39. These curves were obtained after solving the objective function for pavement family A located in climate-subgrade zone 2. The 50% reliability level curve corresponds to the values shown in Table 12.

Performance curves at different reliability levels have sigmoidal shape having two coefficients, *A* and *β*, to define the curve. Since both coefficients were obtained for a range of reliability values, the probability distribution of each can be calculated. The best fit distribution for coefficient A is beta general, while β coefficient is a constant value for each traffic level. The mathematical expression for the beta general probability distribution is the following:

$$f(x) = \frac{(x - min)^{\alpha_1 - 1}(max - x)^{\alpha_2 - 1}}{B(\alpha_1 . \alpha_2)(max - min)^{\alpha_1 + \alpha_2 - 1}} \qquad (4.5)$$

where $\alpha_1$, $\alpha_2$ = shape parameters; $min$= boundary parameter; $max$ = boundary parameter; $B$ = beta function.

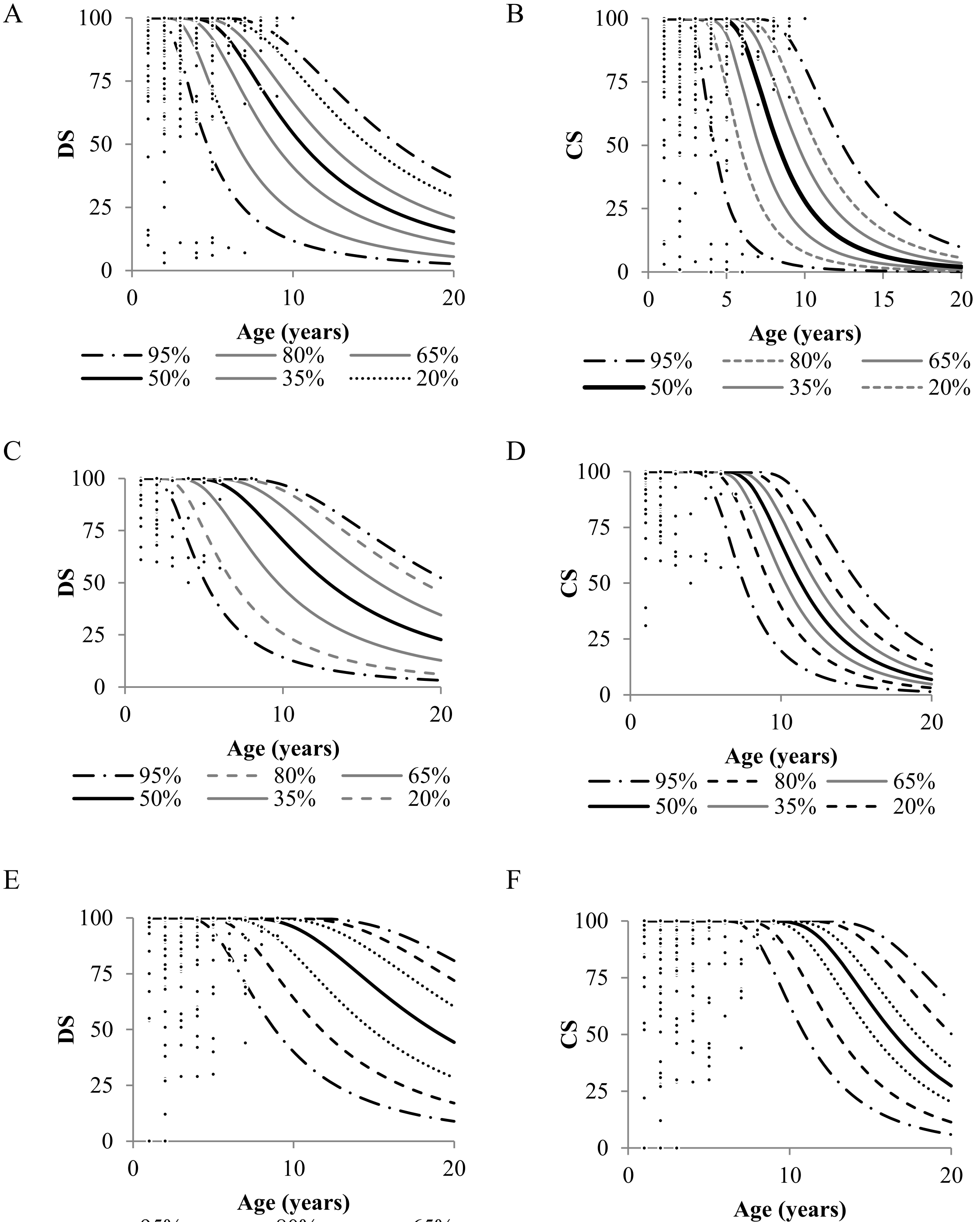

**Figure 39.** DS curves (left) and CS curves (right) for different reliability levels: (A) and (B) show PM light traffic, (C) and (D) LR low traffic, and (E) and (F) HR low traffic

Table 13 presents the resulting values for coefficients A and β for pavement family A located in climate-subgrade zone 2. Parameters $\alpha_1, \alpha_2, min$ are the same for each type of treatment; only the $max$ parameter changes. However, $\beta$ is not represented by a probability distribution since it has a constant value that depends only on traffic level and treatment type.

**Table 13.** DS and CS performance curve coefficient A

| Type of treatment | Parameter | Factor | DS | | | CS | | |
|---|---|---|---|---|---|---|---|---|
| | | | Low | Medium | High | Low | Medium | High |
| PM | A | α1 | 2.2413 | 2.2413 | 2.2413 | 2.448 | 2.448 | 2.448 |
| | | α2 | 2.2406 | 2.2406 | 2.2406 | 2.4457 | 2.4457 | 2.4457 |
| | | min | 1.4324 | 1.4324 | 1.4324 | 1.2466 | 1.2466 | 1.2466 |
| | | max | 17.11081 | 16.448 | 19.637 | 14.888 | 13.888 | 12.888 |
| | β | | 2.30 | 1.29 | 1.49 | 4.01 | 4.01 | 4.01 |
| LR | A | α1 | 0.60339 | 0.60339 | 0.60339 | 3.02 | 3.02 | 3.02 |
| | | α2 | 0.60338 | 0.60338 | 0.60338 | 3.0203 | 3.0203 | 3.0203 |
| | | min | 4.146 | 5.6831 | 19.193 | 4.7514 | 2.652 | 2.2007 |
| | | max | 17.656 | 5.7118 | 19.222 | 15.903 | 13.804 | 13.352 |
| | β | | 2.34 | 1.42 | 1.29 | 4.01 | 4.01 | 4.01 |
| MR | A | α1 | 0.52753 | 0.52753 | 0.52753 | 1.088 | 1.088 | 1.088 |
| | | α2 | 0.5275 | 0.5275 | 0.5275 | 1.0088 | 1.0088 | 1.0088 |
| | | min | 5.3059 | 7.5797 | 6.934 | 9.3315 | 5.4589 | 3.6995 |
| | | max | 20.33 | 22.604 | 21.958 | 20.769 | 16.896 | 15.138 |
| | β | | 2.37 | 1.47 | 1.14 | 4.01 | 4.01 | 4.01 |
| HR | A | α1 | 0.76683 | 0.76683 | 0.76683 | 1.7883 | 1.7883 | 1.7883 |
| | | α2 | 0.76673 | 0.76673 | 0.76673 | 1.7885 | 1.7885 | 1.7885 |
| | | min | 7.1387 | 9.9297 | 7.7253 | 8.2408 | 6.4949 | 11.003 |
| | | max | 25.015 | 27.806 | 25.601 | 21.86 | 20.057 | 24.622 |
| | β | | 2.56 | 1.61 | 1.61 | 4.01 | 4.01 | 4.01 |

Figure 40 presents a graphical comparison between the frequency distributions of coefficient A of the performance equation for DSs and CSs for a low traffic level. Those curves were obtained using the values presented in Table 13. The distribution for PM had the smallest variation among the treatment alternatives and the lowest mean value. As expected, the variation increased for the rehabilitation treatments, being highest for HR, which also had the maximum mean value.

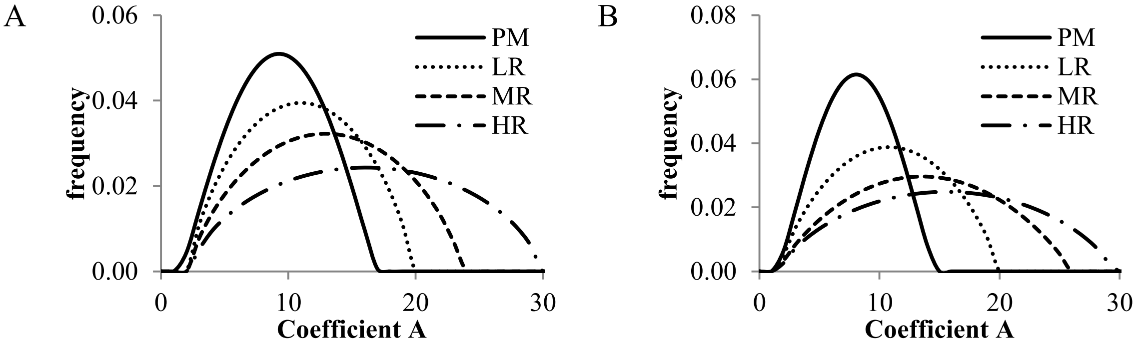

**Figure 40.** Frequency distribution of coefficient A: (A) DS, (B) CS

### 4.6 Budget allocation

Four budget allocation scenarios were analyzed. Each scenario was run with a budget availability that follows a triangular distribution. The average available budget was obtained from the projected budget in the Bryan district. Budget is distributed according to network type and length. Table 14 summarizes the Bryan maintenance budget from 2012 to 2015.

**Table 14.** Bryan district maintenance budget

| Year | Bryan district maintenance budget (in millions of USD) |
|---|---|
| 2012 | $12.5 |
| 2013 | $27.5 |
| 2014 | $26.0 |
| 2015 | $22.5 |
| **4-year average** | **≈$22.0** |

Additionally, historical data available in DISCOS for Bryan districts were analyzed. According to this information, non-contracted maintenance expenditures have only changed minimally over the years, averaging around 22 million USD annually, coincident with the value presented in the previous paragraph. Although the highway cost index is growing about 5.5% annually, maintenance spending capacity seems to be diminishing over time.

**Table 15.** Bryan district statistics

| Year | Non-contracted maintenance expenditures in USD$ | Highway cost index (1997 base) twelve month moving average |
|---|---|---|
| 2001 | 23,647,541.13 | 96.62 |
| 2004 | 21,151,899.88 | 103.25 |
| 2005 | 20,828,730.00 | 118.58 |
| 2006 | 21,527,797.19 | 124.82 |

The average budget is distributed to the entire Bryan district network proportionally to the length in miles and VTM. Table 16 presents the results of applying the distribution formula to the available budget resulting in a budget of 6.3 million USD for the network that was analyzed.

**Table 16.** Approximate Bryan district road maintenance and rehabilitation budget

| Road type | Center-line miles | Average AADT, veh/day | VMT in millions | Budget for whole network (million USD) | Budget for study network (million USD) |
|---|---:|---:|---:|---:|---:|
| Interstate Highways | 356.5 | 7,874 | 2.807 | 4.57 | - |
| U.S. Highways | 387.0 | 7,608 | 2.944 | 4.79 | - |
| State Highways | 750.0 | 4,847 | 3.635 | 5.91 | 5.91 |
| Farm to market roads | 1855.8 | 2,100 | 3.897 | 6.34 | - |
| Business Routes | 32.3 | 7,277 | 0.235 | 0.38 | 0.38 |
| Park and recreational Roads | 15.5 | 476 | 0.073 | 0.01 | 0.01 |
| **Total** | **3,397.1** | **n/a** | **13.526** | **22.0** | **6.3** |

As discussed in the model description, budget availability was included in the model. It is difficult to precisely estimate how much can change in future maintenance budgets. For this reason, a range of variation of 20% was assumed. Budget availability was represented by a triangular distribution with a minimum value of 5.04 million USD, a mean of 6.3 million USD, and a maximum of 7.56 million USD.

Table 17 summarizes the funds allocated to each alternative for an analysis period of 10 years. The benefit-cost scenario has a more balanced distribution between the M&R options, while the maintenance-first budget is mainly distributed in PM and HR. Rehabilitation-first divided the funds between rehabilitation alternatives but with more emphasis in HR, and worst-first concentrated the funds in LR and MR treatment.

**Table 17.** Allocated funds (in million USD) over a period of 10 years

| Allocation scenario | PM | LR | MR | HR | Total |
|---|---|---|---|---|---|
| Benefit-cost | 29.1 | 15.6 | 5.8 | 12.4 | 62.9 |
| Maintenance-first | 37.2 | 1.4 | 1.6 | 22.6 | 62.8 |
| Rehabilitation-first | 0.0 | 36.9 | 16.3 | 9.7 | 62.9 |
| Worst-first | 15.2 | 10.3 | 6.8 | 30.5 | 62.8 |

### 4.7 Ranking and optimization

The last step before the risk assessment is ranking and optimization. According to the model, ranking is done only for worst-first allocation method; all the other allocation methods are solved with an integer programming optimization. Figure 41 is a representation of M&R selected projects for the first year of analysis for each allocation scenario. For benefit-cost (B-C) and maintenance first (M-F) scenarios, project coverage is similar since primarily PM treatments are selected. Rehabilitation-first (R-F) has a small number of selected projects since rehabilitation costs are much higher than maintenance costs. Lastly, the worst-first allocation scenario (W-F) has intermediate network coverage.

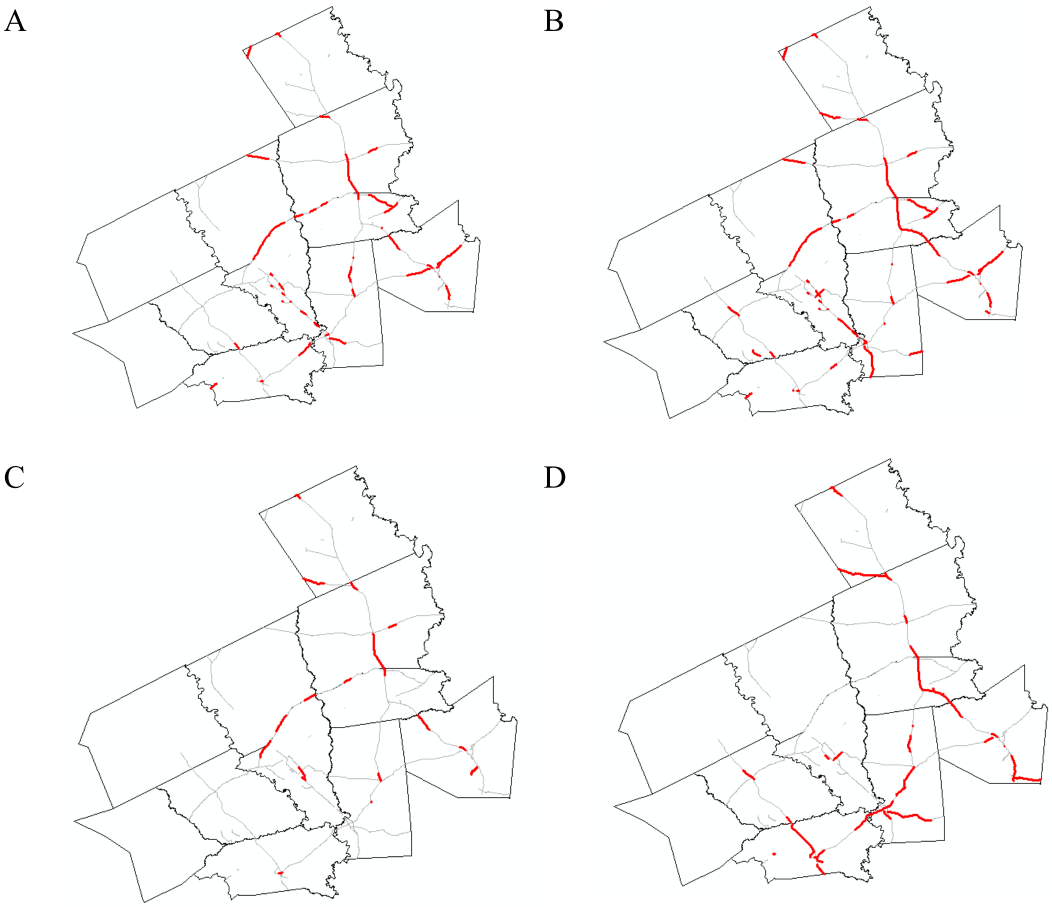

**Figure 41.** Map of M&R projects selected for the first year using the model; (A) B-C, (B) M-F, (C) R-F, and (D) W-F

Figure 42 presents the M&R cumulative project coverage after an analysis period of five years. The B-C scenario had the most extensive coverage, selecting projects over most of the network. P-F had extensive coverage also but less than B-C. The W-F scenario had an intermediate coverage concentrated mostly in segments with heavier traffic. The last alternative, R-H, showed the lowest level of coverage.

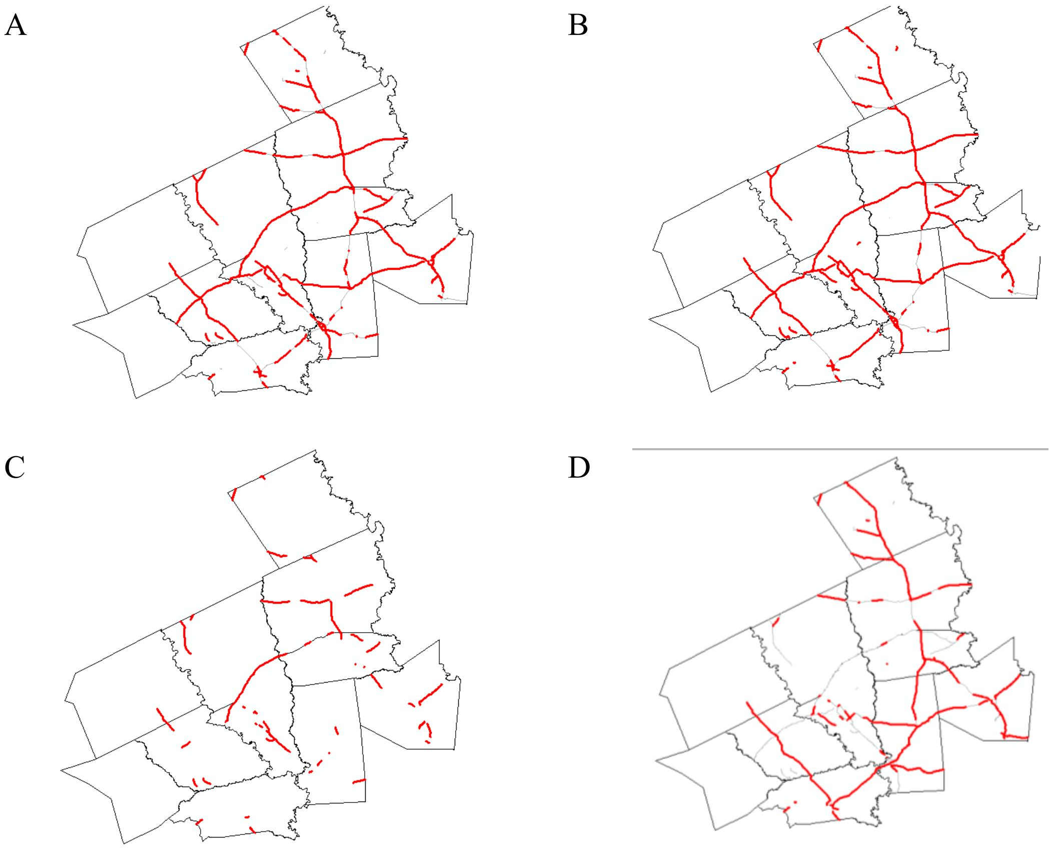

**Figure 42.** Map of M&R projects selected by the model for the various scenarios for a five-year period: (A) B-C, (B) M-F, (C) R-F, and (D) W-F

# 5. RISK ASSESSMENT

The risk was assessed for two variables: network in good condition and average CS. In the first case, risk is defined as the probability of failing to achieve Texas's goal of 90% of the network in good condition, with "good condition" defined as CS≥70. In the case of average CS, risk is defined as the probability of failing to sustain an average CS greater than or equal to 70. Risk assessment was performed annually for a period of 10 years.

## 5.1 Benefit-cost allocation method

The first option for budget allocation is the B-C. Under this approach, segments with highest benefit-cost relationship are selected. Table 18 presents the yearly average results for the key factors: CS, percent of network in "good" condition, and lane-miles of selected project for each type of treatment. This option allocated more funds for PM and LR than for other treatments. The CS remains constant over time, although the percent of network in good condition decreases with time.

**Table 18.** Yearly results for B-C allocation method

| Year | Risk average CS <70 | Risk %lane miles <90% | Lane-miles per treatment category | | | |
|---|---|---|---|---|---|---|
| | | | PM | LR | MR | HR |
| 1 | 2% | 88% | 320.0 | 23.3 | - | - |
| 2 | 11% | 87% | 327.3 | 18.4 | 3.6 | - |
| 3 | 18% | 86% | 134.3 | 17.3 | 17.6 | 12.6 |
| 4 | 22% | 82% | 405.6 | - | 7.8 | - |
| 5 | 27% | 79% | 10.6 | - | 26.2 | 30.6 |
| **Total** | **n/a** | **n/a** | **877.8** | **59.0** | **55.2** | **43.2** |

As described above, the model calculated annual risk for CS and percent of network. The CDF for year 5 is presented in Figure 43. The B-C allocation method risk for failing to maintain an average CS greater than or equal to 70 is 26.5%. The risk of succeeding in having the network in “good” condition is 79.3%.

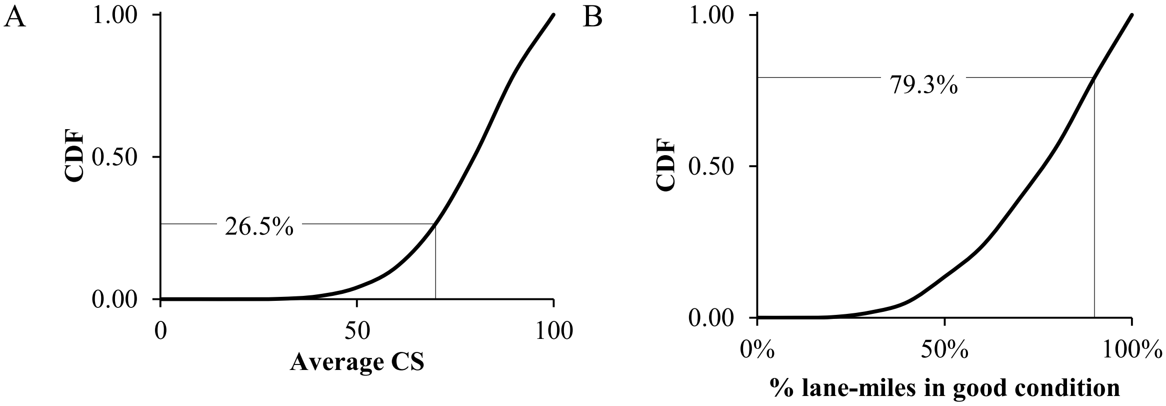

**Figure 43.** CDF at year 5 for B-C allocation method: (A) average CS, (B) percentage of lane-miles in “good” condition

## 5.2 Preventive maintenance first and then rehabilitation allocation method

The second budget allocation method is the M-F and then rehabilitation scenario. Under this approach, the budget is first allocated to maintenance projects, and rehabilitation projects are selected only if all the maintenance needs have been satisfied. Table 19 presents the yearly averages from the model for the following key results: CS, percent of network in good condition, and lane-miles of selected project for each type of treatment. As per its name, this option initially only allocated fund for PM, and after the second year progressively began to allocate funds for LR, MR and HR. Both risks assessed that of failing to maintain the CS and that of succeeding in maintaining the goal for network in "good" condition, have better averages than in the B-C approach.

**Table 19.** Yearly average results for M-F allocation method

| **Year** | **Risk average CS <70** | **Risk %lane miles <90%** | **Lane-miles per treatment category** | | | |
|---|---|---|---|---|---|---|
| | | | **PM** | **LR** | **MR** | **HR** |
| 1 | 2% | 89% | 449.9 | - | - | - |
| 2 | 10% | 96% | 347.3 | 18.4 | - | - |
| 3 | 16% | 97% | 160.6 | - | 14.0 | 22.0 |
| 4 | 22% | 96% | 432.4 | - | - | 1.8 |
| 5 | 34% | 95% | 5.4 | - | - | 46.4 |
| **Total** | **n/a** | **n/a** | **1395.6** | **18.4** | **14.0** | **70.2** |

Figure 44 present the CDF for the risk at year 5. For the M-F allocation method risk that average condition score is equal or greater than 70 is 34.2%. The risk of have the network in a good condition is 95.3%. Under this approach, the average CS was better than in the B-C approach, but the risk of not reaching the goal was higher with this approach.

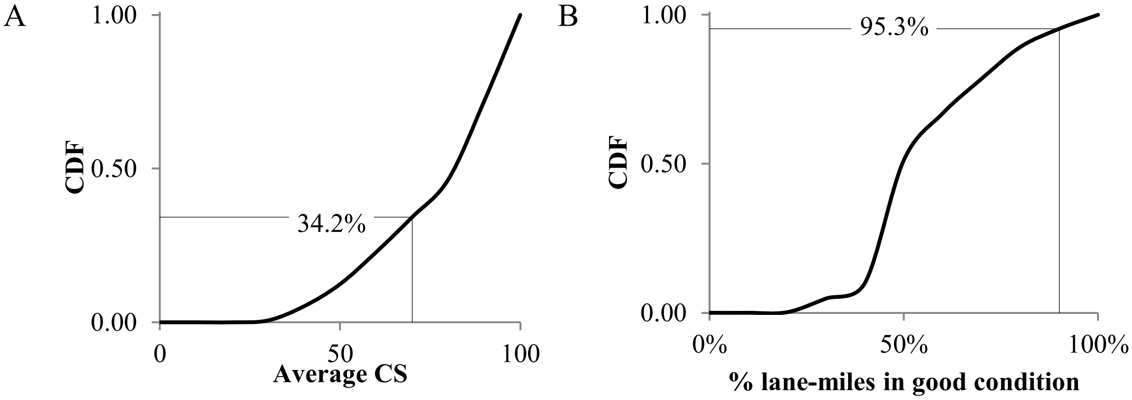

**Figure 44.** CDF at year 5 for M-F allocation method: (A) average CS, (B) percent of lane-miles in good condition

### 5.3 Rehabilitation first and then preventive maintenance allocation method

The third budget allocation method is R-F. Using this approach, the budget is allocated first to rehabilitation projects, and only if all the rehabilitation needs are satisfied are maintenance projects budgeted. Table 20 presents the yearly average results for the key results: CS, percent of network in “good” condition, and lane-miles of selected project for each type of treatment. Both the risk of failing to reach the goal for CSs and the risk of success in maintaining 90% of the network in “good” condition decrease substantially over the 5 year analysis period.

**Table 20.** Yearly average results for R-F allocation method

| Year | Risk average CS <70 | Risk %lane miles <90% | Lane-miles per treatment category | | | |
|---|---|---|---|---|---|---|
| | | | PM | LR | HR | MR |
| 1 | 5% | 89% | - | 70.9 | 8.0 | 1.0 |
| 2 | 22% | 96% | - | 80.6 | - | - |
| 3 | 39% | 97% | - | 65.5 | 15.2 | - |
| 4 | 53% | 96% | - | 37.4 | 42.2 | 0.6 |
| 5 | 61% | 95% | - | 57.4 | 23.2 | - |
| **Total** | **n/a** | **n/a** | **0.0** | **311.8** | **88.6** | **1.6** |

Figure 45 present the risk at the end of year 5. For the R-F allocation method, risk that average condition score is equal or greater than 70 is 61.0%. The risk that 90% of the network would be in "good" condition was 95.3%. This approach achieved a better average CS than did B-C, but it also produced the highest risk of failing to reach both goals.

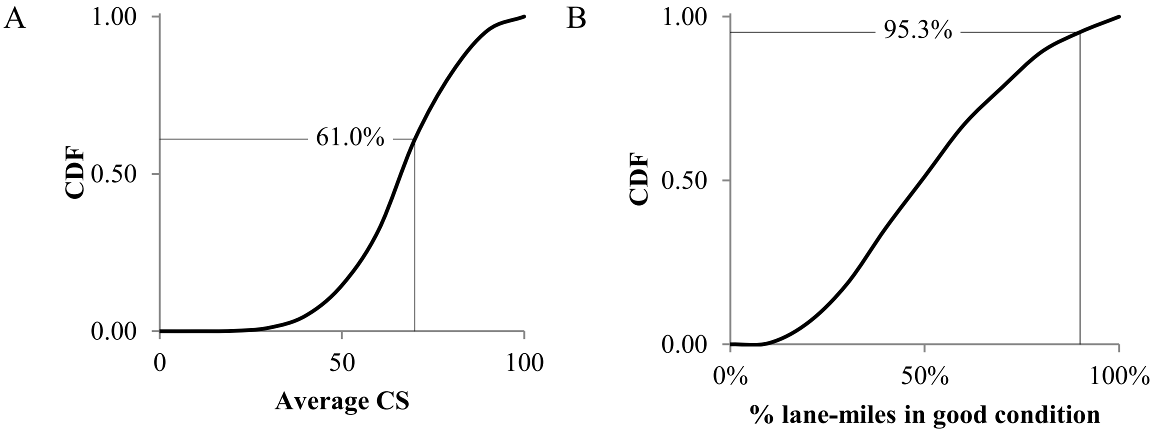

**Figure 45.** The CDF at year 5 for the R-F allocation method: (A) average CS, (B) percent of lane-miles in "good" condition

## 5.4 Worst-first allocation method

The last budget allocation method is the W-F. This approach ranks the segments according to their CSs and selects segments with the lowest CSs for M&R treatments first until the budget is depleted. Table 21 presents the annual average results for the key results. The budget is distributed among all types of M&R treatments since the benefit-cost relationship is not governing the allocation process. Average CSs decrease over time and the percent of the network in "good" condition has an important reduction over the years.

**Table 21.** Yearly average results for W-F allocation method

| Year | Risk average CS <70 | Risk %lane miles <90% | Lane-miles per treatment category | | | |
|---|---|---|---|---|---|---|
| | | | PM | LR | MR | HR |
| 1 | 2% | 89% | 186.8 | 30.6 | 12.8 | 2.2 |
| 2 | 9% | 96% | 129.7 | 5.0 | 37.0 | 9.0 |
| 3 | 19% | 97% | 59.9 | 60.0 | 10.0 | - |
| 4 | 28% | 96% | 131.8 | 26.0 | 5.0 | 15.2 |
| 5 | 34% | 95% | 4.4 | - | 2.1 | 45.3 |
| **Total** | **n/a** | **n/a** | **512.6** | **121.6** | **66.9** | **71.7** |

Figure 46 present the risk results at year 5. For the W-F approach, the risk that the average CS is not equal or greater than 70 is 33.6%. The risk of having the network in "good" condition is 95.3%. Risk assessment results are the same as with the M-F approach, but the average percent of the network in "good" condition is substantially less than with either M-F or B-C, because projects are selected only once the condition deteriorates enough.

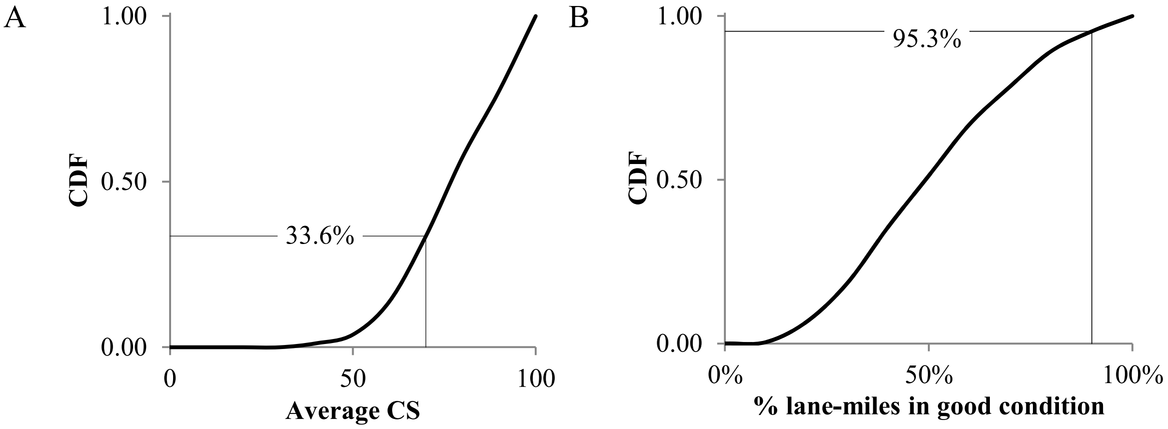

**Figure 46.** CDF at year 5 for W-F allocation method, (A) average CS; (B) % of lane-miles in good condition

## 5.5 Comparison or results

Annual PDF changes for a period of five years are compared. In Figure 47 results for the two allocation approaches B-C and R-F are shown. Clearly, the PDF of initial CS for B-C is concentrated around a value of 84, and with time it spreads out some, but it does not change significantly. In the R-F approach, the PDF becomes more spread, and also the average decreases over time.

In terms of succeeding in maintaining the goal of 90% of the network in “good” condition, there is a significant difference between the B-C and R-F approaches. Under B-C, the CS average improves over time and the PDF is slightly extended; with R-F, the mean decreases with time and the PDF also becomes more extended, meaning that the selected M&R treatments are not able to control the deterioration process.

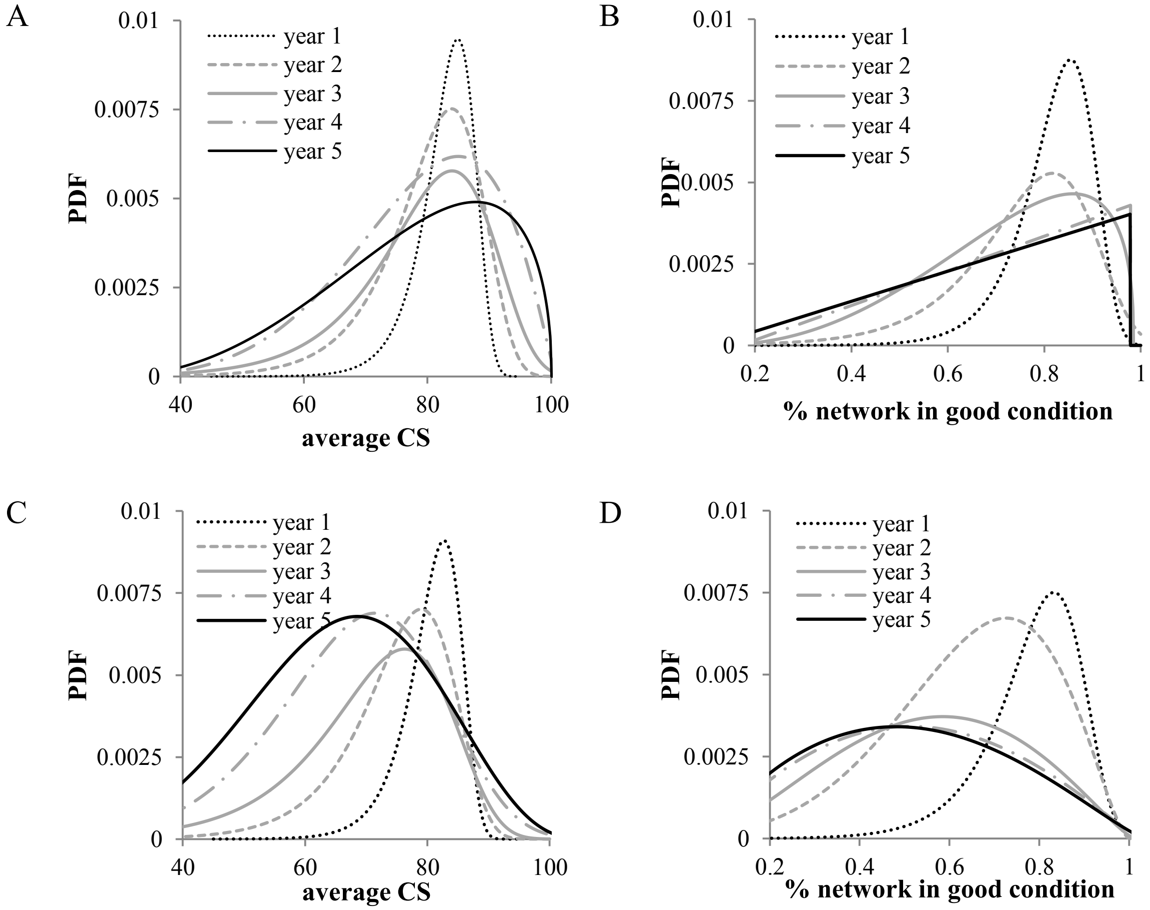

**Figure 47.** Yearly risk PDF for average condition score and percent of network in "good" condition: (A) and (B) B-C allocation method, (C) and (D) W-F allocation method

Figure 48 shows the CDF for the network average CS at year 5 of the planning period. The R-F allocation method has the highest risk of failing to achieve the average CS of 70. The B-C allocation method has the lowest risk of failing to achieve the goal for the same budget availability.

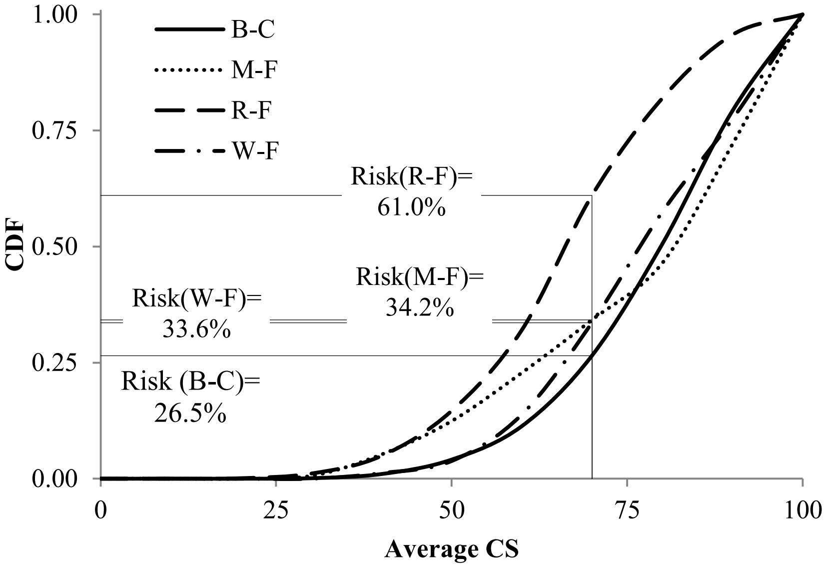

**Figure 48.** CDF for network average CS at year 5 of the planning period

Figure 49 presents the CDF of the percent of lane-miles in "good" condition for the four allocation methods at year 5. Similar to the risk assessment for not achieving CS, B-C has the lowest risk of failing to reach this goal. All the other alternatives have similar results of 95.3%.

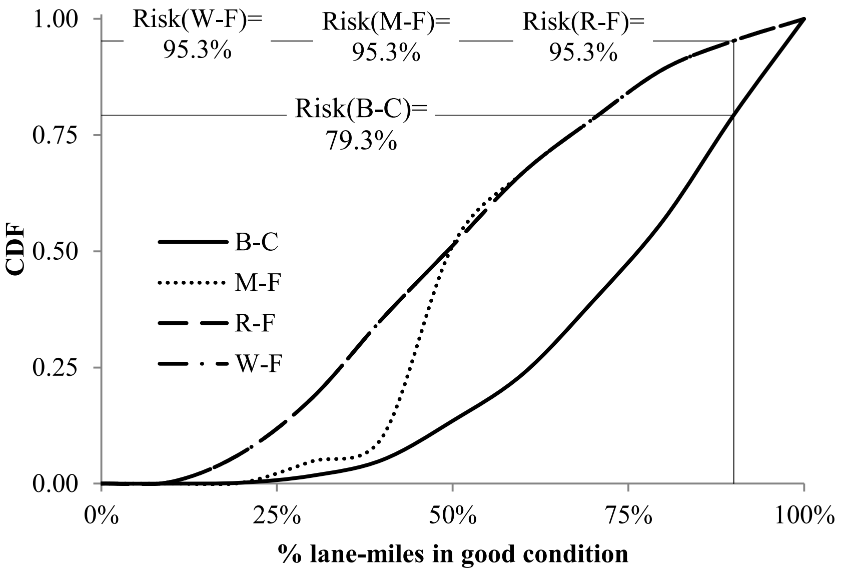

**Figure 49.** CDF for percent of lane-miles in good condition at year 5

For a more detailed explanation of which factors have the greatest influence on the results, the correlation factors were calculated. In this case, correlation factors were normalized regression coefficients associated with each input. A regression value of 0 indicates that there is no significant relationship between the input and the output, while a regression value of 1 or -1 indicates a 1 or -1 standard deviation change in the output for a 1 standard deviation change in the input.

Figure 50 shows the correlation coefficients for the five most influential factors in the average CS output. In all the cases, the coefficient A of the performance prediction function has the highest correlation to the output followed by M&R unit cost. This correlation calculation confirmed that the performance prediction model strongly influences the network analysis.

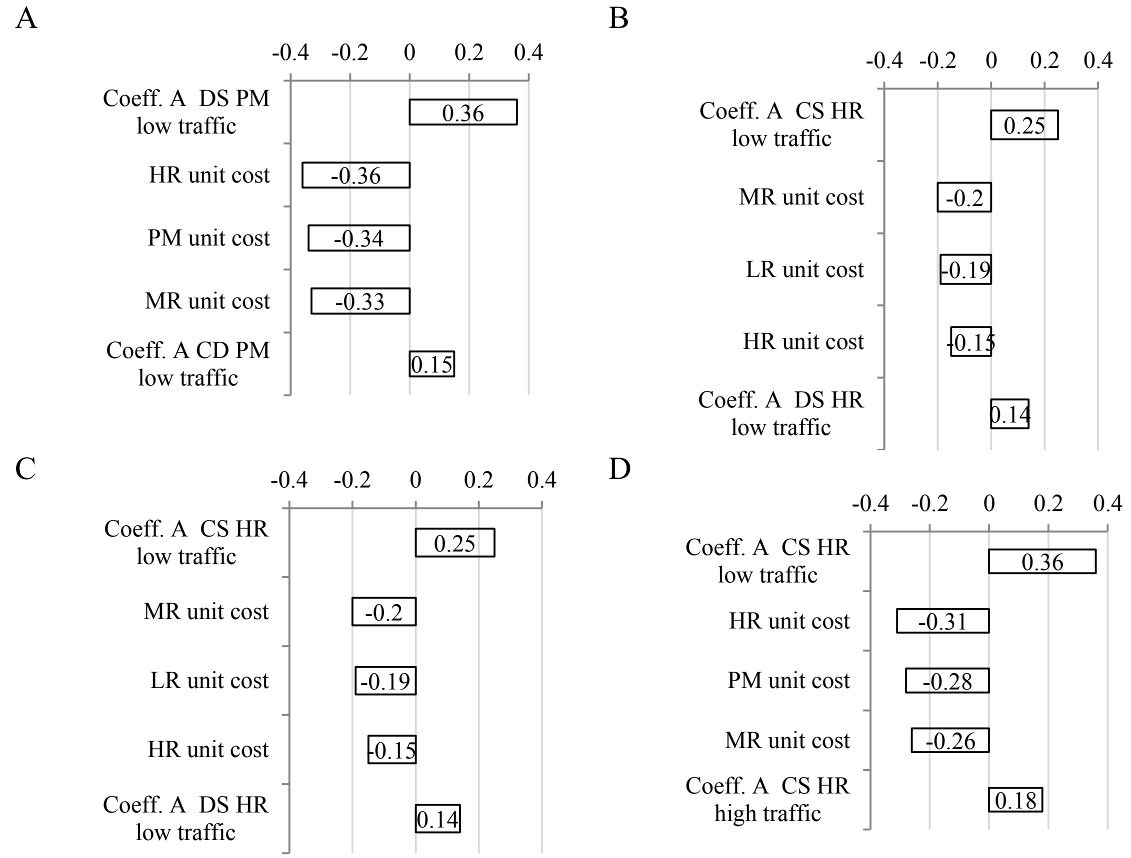

**Figure 50.** Correlation coefficients when risk is measured by average CS at year 5: (A) B-C, (B) M-F, (C) R-F, and (D) W-F

Figure 51 presents the correlation coefficients for the five most influential factors in the percent of network in good condition output. In all the cases unit cost has the highest correlation, followed by coefficient A of performance prediction function.

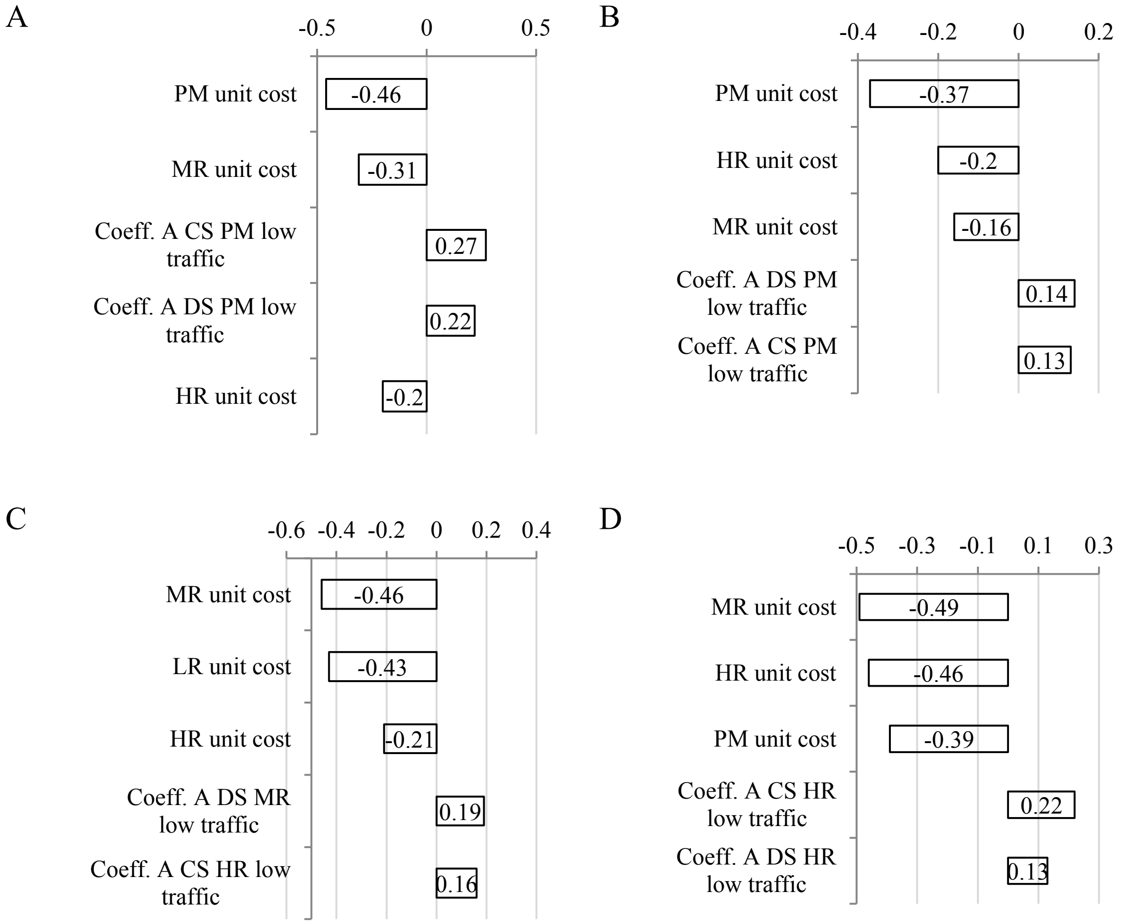

**Figure 51.** Correlation coefficients when risk is measured by percent of lane-miles in good condition at year 5: (A) B-C, (B) M-F, (C) R-F, and (D) W-F

The results show that the incorporation of uncertainty and risk into the budget allocation process gives decision makers a better understanding of which alternative provides the lowest risk of failing to fulfill the agency goal of having 90% of the network in “good” condition.

# 6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Summary

In 2012, the U.S. Congress passed the Moving Ahead for Progress in the 21st Century Act (MAP-21) to fund surface transportation programs for 2013–2014 and beyond. MAP-21 establishes a framework for federal transportation investments with the goal of preserving the highway system while improving its condition and performance. This law requires states to develop risk-based asset management plans. However, risk and uncertainty are not yet explicitly and extensively incorporated into current pavement management systems. In order to fulfill MAP-21 requirements, pavement management systems must be upgraded to incorporate risk management, permitting pavement management systems to serve as a more realistic decision support tool for pavement maintenance and rehabilitation planning and budget allocation.

In this dissertation, a framework was developed for incorporating risk and uncertainty into pavement network M&R budget allocation decisions at the planning stage. For risk assessment, uncertainty was incorporated into the analysis process, and factors influencing decisions were modeled as probability distributions. In applying this framework to a sample pavement network from Texas, risk is defined as the probability of failing to achieve the highway agency's goals, which are (1) to maintain an average network $CS \geq 70$ and (2) that 90% of the network is in good condition (i.e., $CS \geq 70$).

In summary, this budget allocation framework allows agencies to explore and compare various budget allocation options and their potential impacts on the network in advance of making decisions, providing agencies with a systematic approach to achieve road performance goals. This tool simulates all the possible outputs from a combinatorial analysis of different input probability distributions (namely pavement initial condition, predictions of future condition, M&R unit costs, and budget availability) using MCS.

## 6.2 Conclusions

In this work, a risk-based computational model was developed for allocating pavement funds and prioritizing pavement M&R projects at the planning stage. Specific conclusions drawn from the development and application of this computational model are:

- The frequency distribution of pavement condition varies from segment to segment. Thus, no single PDF can be generalized to fit the condition data of all segments.
- The PM unit cost PDF is distinctly different from the rehab unit cost PDFs. However, there is a noticeable overlap among the LR, MR, and HR unit cost PDFs.
- Uncertainty in the pavement condition predictions is controlled primarily by the uncertainty in the sigmoidal model's prolongation factor. Uncertainty in the sigmoidal model's slope factor does not translate to uncertainty in the model's predictions.

- The B-C and M-F allocation methods result in wider geographic distribution of M&R projects compared to the W-F and R-F methods. This pattern persists throughout the planning horizon.
- When compared to the W-F, R-F, and M-F methods, the B-C method results in lower risk and lower risk rate of increase over time. This pattern occurs in both risk assessment methods (i.e., probability of failing to achieve the target average CS, and probability of failing to achieve the target percent of lane-miles in good condition).
- When the performance goal is expressed in terms of the average CS, the uncertainty in the pavement condition predictions (i.e., uncertainty in the prediction models) has the greatest effect on the risk of failing to achieve the target performance.
- When the performance goal is expressed in terms of percent of lane-miles in good condition, the uncertainty in the M&R unit costs has the greatest effect on the risk of failing to achieve the target performance.

## 6.3 Recommendations

The network segmentation process has an important influence on the definition of M&R treatments. The model developed in this dissertation could potentially be improved by a) developing a dynamic segmentation module with the option to update the segments annually, b) incorporating a structural condition factor to identify segments that require major rehabilitation, and c) coordinating projects in closed proximity to avoid discontinuity in M&R projects, and d) adding the option of applying pre-treatments to localized failures.

Performance prediction models can be updated more frequently to reflect the actual behavior of certain M&R types. A factor that considers the loss of effectiveness of PM and LR when applied repeatedly could be included in the model. The ride score prediction function also needs to be improved to avoid unrealistic sudden drops in pavement condition for MR and HR treatments.

The unit cost PDFs could be improved by considering factors such as the intensity of the M&R work and the original condition of the pavement. This could improve the accuracy of budget estimates.

Finally, extending the risk assessment by incorporating an analysis of possible hazards that can affect the network would be useful. In the developed model, the only hazard considered was the budget availability. The traffic and environmental conditions that can also put the network components at risk could be analyzed.

# REFERENCES

AASHTO. (2011). *Transportation Asset Management Guide : A Focus on Implementation.* American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO. (1993). *AASHTO Guide for Design of Pavement Structures.* American Association of State Highway and Transportation Officials, Washington, DC.

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

Abaza, K. A., and Ashur, S. A. (2009). "Optimum Microscopic Pavement Management Model using Constrained Integer Linear Programming." *Journal of Transportation Engineering,* 10(3), 149-160.

Abaza, K. A., Ashur, S. A., and Al-Khatib, I. (2004). "Integrated Pavement Management System with a Markovian Prediction Model." *Journal of Transportation Engineering,* 130(1), 24-33.

ASCE. (2013). "2013 Report Card for America´s Infrastructure." http://www.infrastructurereportcard.org/a/#p/roads/overview (6/25, 2013).

Augeri, M. G., Colombrita, R., Greco, S., Lo Certo, A. L., Matarazzo, B., and Slowinski, R. (2011). "Dominance-Based Rough Set Approach to Budget Allocation in Highway Maintenance Activities." *Journal of Infrastructure Systems,* 17(2), 75-85.

Aven, T. (2003). *Foundation of Risk Analysis, a Knowledge and Decision-Oriented Perspective.* John Wiley & Sons Ltd., West Sussex, England.

Aven, T. (2008). "Risk Analysis in Maintenance." *Complex System Maintenance Handbook Vol. Part E,* K. A. H. Kobbacy, and D. N. P. Murthy, eds., Springer Series in Reliability Engineering, London, 437-458.

Bai, Q., Labi, S., and Sinha, K. C. (2012). "Trade-Off Analysis for Multiobjective Optimization in Transportation Asset Management by Generating Pareto Frontiers Using Extreme Points Nondominated Sorting Genetic Algorithm II." *Journal of Transportation Engineering,* 138(6), 798-808.

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.

Bennett, C. (2004). "Sectioning of Road Data for Pavement Management." *6th International Conference on Managing Pavements,* Brisbane, Australia, 1-11.

Boamah, P. A. (2010). "Development of Models for Optimal Road Maintenance Fund Allocation A case of Ghana". Ph.D. Dissertation. University of Birmingham, Birmingham, UK.

Bosurgi, G., D´Andrea, A., and Trifiro, F. (2005). "A Genetic Algorithm for Multiyear Pavement Maintenance Optimization." *3rd International SIIV Congress,* Bari, Italy, 1-7.

Bosurgi, G., and Trifiro, F. (2005). "A Model Based on Artificial Neural Networks and Genetic Algorithms for Pavement Maintenance Management." *The International Journal of Pavement Engineering,* 6(3), 201-209.

Bunn, D. W. (1982). *Analysis for Optimal Decisions.* John Wiley & Sons, New York, NY.

Cafiso, S., and Di Graziano, A. (2012). "Definition of Homogenous Sections in Road Pavement Measurements." *SIIV- 5th International Congress - Sustainability of Road Infrastructures, Procedia-Social and Behavioral Sciences 53,* Elsevier, 1069-1079.

Cafiso, S., Di Graziano, A., Kerali, H. G. R., and Odoki, J. B. (2002). "Multicriteria Analysis Method for Pavement Maintenance Management." *Transportation Research Record: Journal of the Transportation Research Board,* 1816(1), 73-84.

Cambridge Systematic, I., EVS Inc., and Markow, M. J. (2011). "Determining Highway Maintenance Costs." *Rep. No. NCHRP Report 688,* Transportation Research Board, Washington, D.C.

Cambridge Systematic, I., PB Consult, I., and System Metrics Group. (2005). "Analytical Tools for Asset Management." *Rep. No. NCHRP Report 545,* Transportation Research Board, Washington, D.C.

Chang, J. R., Chen, D. H., and Hung, C. T. (2005). "Selecting Preventive Maintenance Treatments in Texas: Using the Technique for Order Preference by Similarity to the Ideal Solution for Specific Pavement Study-3 sites." *Transportation Research Record: Journal of the Transportation Research Board,* 1933(1), 62-71.

Chassiakos, A. P., Vagiotas, P., and Theodorakopoulos, D. D. (2005). "A Knowledge-Based System for Maintenance Planning of Highway Concrete Bridges." *Advances in Engineering Software,* 36(1), 740-749.

Chen, D. H., Lin, D. F., and Luo, H. L. (2003). "Effectiveness of Preventative Maintenance Treatments using Fourteen SPS-3 Sites in Texas." *Journal of Performance of Constructed Facilities,* 17(3), 136-143.

Chou, J., and Le, T. (2011). "Reliability-based performance simulation for optimized pavement maintenance." *Reliability Engineering & System Safety,* 96(10), 1402-1410.

Chu, C. Y. (2007). "Dynamic Performance Models for Transportation Infrastructure Management". Ph.D. Dissertation. Northwestern University, Evanston, IL.

Chu, C. Y., and Durango-Cohen, P. L. (2008a). "Empirical Comparison of Statistical Pavement Performance Models." *Journal of Infrastructure Systems,* 14(2), 138-149.

Chu, C. Y., and Durango-Cohen, P. L. (2008b). "Incorporating Maintenance Effectiveness in the Estimation of Dynamic Infrastructure Performance Models." *Computer-Aided Civil and Infrastructure Engineering,* 23(3), 174-188.

Chu, C. Y., and Durango-Cohen, P. L. (2007). "Estimation of Infrastructure Performance Models Using State-Space Specifications of Time Series Models." *Transportation Research Part C,* 15(1), 17-32.

Colombrita, R., Augeri, M. G., Lo Certo, A. L., Greco, S., Matarazzo, B., and Laganà, G. (2004). "Development of a Multi-Criteria Decision Support System for Budget Allocation in Highway Maintenance Activities." Societa Italiana di Infrastrutture viarie, Firenze, 27-40.

Congress of the United States of America. (2012). "Moving Ahead for Progress in the 21st Century Act." *MAP-21,* H.R.4348(Second session), 1-584.

Cuelho, E. V., Mokwa, R. L., and Akin, M. (2006). "Preventive Maintenance Treatments of Flexible Pavements: A Synthesis of Highway Practice." *Rep. No. FHWA/MT-06-009/8117-26,* Western Transportation Institute, Bozeman, MT.

Dahl, G., and Minken, H. (2008). "Methods Based on Discrete Optimization for Finding Road Network Rehabilitation Strategies." *Computers & Operations Research,* 35(7), 2193-2208.

Deshpande, V., Damnjanovic, I. D., and Gardoni, P. (2010). "Reliability-Based Optimization Models for Scheduling Pavement Rehabilitation." *Computer-Aided Civil and Infrastructure Engineering,* 25(4), 227-237.

Dessouky, S., Krugler, P., Papagiannakis, A. T., and Freeman, T. J. (2011). "Review of Best Practices for the Selection of Rehab and Preventive Maintenance Projects:

Technical Report." *Rep. No. 0-6586-1,* Texas Transportation Institute, Texas A&M University System, College Station, TX.

Di Mino, G., and Nigrelli, J. (2007). "A Multi-Objective Approach Based on the Genetic Algorithm Technique for Road Pavement Maintenance." *4th International SIIV Congress,* ITA, Palermo, Italy, 1-17.

Feighan, K. J., Shahin, M. Y., Sinha, K. C., and White, T. D. (1988). "Application of Dynamic Programming and Other Mathematical Techniques to Pavement Management Systems." *Transportation Research Record,* 1200(1), 90-98.

Feldman, R. M., and Valdez-Flores, C. (2010). *Applied Probability and Stochastic Processes.* Springer, Heidelberg.

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

Ferreira, A., Picado-Santos, L., and Antunes, A. (2002b). "A Segment-Linked Optimization Model for Deterministic Pavement Management Systems." *Journal of Transportation Engineering,* 3(2), 95-105.

FHWA. (2007). *Asset Management Overview.* U.S. Dept. of Transportation, Federal Highway Administration, Office of Asset Management, Washington, D.C.

Foundation of Pavement Preservation. (2001). "Pavement Preventive Maintenance Guideliness." Foundation of Pavement Preservation, Federal Highway Administration, Washington, D.C.

Frangopol, D. M., and Liu, M. (2007). "Maintenance and Management of Civil Infrastructure based on Condition, Safety, Optimization, and Life-Cycle Cost." *Structure and Infrastructure Engineering,* 3(1), 29-41.

Galehouse, L., Moulthrop, J. S., and Hicks, R. G. (2003). "Principles of Pavement Preservation: Definitions, Benefits, Issues, and Barriers." *TR News,* 228(September/October), 4-9.

Gao, L., Zhang, Z., and Tighe, S. L. (2007). "Using Markov Process and Method of Moments for Optimizing Management Strategies of Pavement Infrastructure." *Transportation Research Board 86th Annual Meeting,* TRB, Washington, D.C., No.07-3355.

Gharaibeh, N., Wimsatt, A., Saliminejad, S., Menendez, J. R., Weissmann, A. J., Weissmann, J., and Chang-Albitres, C. (2012). "Implementation of New Pavement

Performance Prediction Models in PMIS: Report." *Rep. No. FHWA/TX-12/5-6386-01-1,* Texas Transportation Institute, The Texas A&M University System, College Station, TX.

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

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

Haas, R. C. G., Hudson, W. R., and Zaniewski, J. P. (1994). *Modern Pavement Management.* Krieger Pub. Co, Malabar, FL.

Haimes, Y. Y. (2004). *Risk Modeling, Assessment, and Management, Third Edition.* John Wiley & Sons, Inc., Hoboken, NJ.

Hall, K. T., Correa, C. E., Carpenter, S. H., and Elliott, R. P. (2003). "Guidelines for Life-Cycle Cost Analysis of Pavement Rehabilitation Strategies." *Transportation Research Record,* 51(1), 1-19.

Harper, W., and Majidzadeh, K. (1991). "Use of Expert Opinion in Two Pavement Management Systems." *Transportation Research Record: Journal of the Transportation Research Board,* 1311(1), 242-247.

Hicks, R. G., Dunn, K., and Moulthrop, J. S. (1997). "Framework for Selecting Effective Preventive Maintenance Treatments for Flexible Pavements." *Transportation Research Record: Journal of the Transportation Research Board,* 1597(1), 1-10.

Highway Research Board. (1962). "The AASHO Road Test, Report 5: Pavement Research." *Rep. No. Special Report,* National Academy of Science, National Research Council, Washington, D.C.

Hoff, P. D. (2009). *A First Course in Bayesian Statistical Methods.* Springer, New York.

ISO. (2009). *ISO 31000: 2009 Risk Management-Principles and Guidelines.* International Standards Organisation, Geneva.

Javed, F. (2010). "Integrated prioritization and optimization approach for pavement management". National University of Singapore, Singapore.

Johnson, A. M. (2000). "Best Practices Handbook on Asphalt Pavement Maintenance." *Rep. No. MN/RC-2000-04,* University of Minnesota Center for Transportation Studies, Minneapolis, MN.

Jordaan, G. J., and deBruin, P. W. (2002). "Advanced Use of the Cumulative Sum of Deviations Method to Identify Uniform Pavement Sections." *Recent Advances in Material Characterization and Modeling of Pavement Systems,* ASCE, Reston, VA, 193-208.

Juni, E., Adams, T. M., and Sokolowski, D. (2008). "Relating Cost to Condition in Routine Highway Maintenance." *Transportation Research Record: Journal of the Transportation Research Board,* 2044(1), 3-10.

Kobayashi, K., Kaito, K., and Lethanh, N. (2012). "A Statistical Deterioration Forecasting Method using Hidden Markov Model for Infrastructure Management." *Transportation Research Part B: Methodological,* 46(4), 544-561.

Koch, K. -. (2007). *Introduction to Bayesian Statistics.* Springer, New York.

Kreyszig, E. (2011). *Advanced Engineering Mathematics, 10th Edition.* John Wiley & Sons, Hoboken, NJ.

Kullback, S., and Leibler, R. A. (1951). "On Information and Sufficiency." *The Annals of Mathematical Statistics,* 22(1), 79-86.

Labi, S., and Sinha, K. C. (2003). "Measures of Short-Term Effectiveness of Highway Pavement Maintenance." *Journal of Transportation Engineering,* 129(6), 673-683.

Leitch, M. (2010). "ISO 31000: 2009—The New International Standard on Risk Management." *Risk Analysis,* 30(6), 887-892.

Li, N., Haas, R. C. G., and Huot, M. (1998). "Integer Programming of Maintenance and Rehabilitation Treatments for Pavement Networks." *Transportation Research Record: Journal of the Transportation Research Board,* 1629(1), 242-248.

Li, Z., Madanu, S., Zhou, B., Wang, Y., and Abbas, M. (2010). "A Heuristic Approach for Selecting Highway Investment Alternatives." *Computer-Aided Civil and Infrastructure Engineering,* 25(6), 427-439.

Li, Z., and Sinha, K. C. (2009). "Methodology for the Determination of Relative Weights of Highway Asset Management System Goals and of Performance Measures." *Journal of Infrastructure Systems,* 15(2), 95-105.

Liu, L., and Gharaibeh, N. G. (2013). "A Bayesian Model for Predicting the Performance of Pavements Treated with Thin HMA Overlays." *93rd Annual Meeting of the Transportation Research Board,* .

Liu, M., and Frangopol, D. M. (2006). "Optimizing Bridge Network Maintenance Management Under Uncertainty with Conflicting Criteria: Life-Cycle Maintenance, Failure, and User Costs." *Journal of Structural Engineering,* 132(11), 1835-1845.

Lytton, R. L. (1987). "Concepts of Pavement Performance Prediction and Modeling." *2nd North American Conference on Managing Pavements,* Ontario, Canada, 3-19.

Lytton, R. L. (1985). "From Ranking to True Optimization." *North American Pavement Management Conference,* Toronto, Canada, 5.3-5.17.

Magazine, M., and Oguz, O. (1984). "A Heuristic Algorithm for the Multidimensional Zero-One Knapsack Problem." *European Journal of Operational Research,* 16(3), 319-326.

Mahoney, J. P., Ahmed, N. U., and Lytton, R. L. (1978). "Optimization of Pavement Rehabilitation and Maintenance by use of Integer Programming." *Transportation Research Record,* 674(1), 15-22.

Markow, M. J. (1995). "Highway Management Systems: State of the Art." *Journal of Infrastructure Systems,* 1(3), 186-191.

Martello, S., and Toth, P. (1990). *Knapsack Problems, Algorithms and Computer Implementations.* John Wiley & Sons, West Sussex, England.

MathWorks. (2013). "MATLAB." R2013a.

Mikhail, M. (2012). "Next Generation Pavement Management System." *2012 Transportation short course: Maintenance and Pavement Management,* Texas Transportation Institute, Texas A&M University System, College Station, TX, 1-29.

Mild, P., and Salo, A. (2009). "Combining a Multiattribute Value Function with an Optimization Model: An Application to Dynamic Resource Allocation for Infrastructure Maintenance." *Decision Analysis,* 6(3), 139-152.

Mohseni, A. (1991). "Alternative Methods for Pavement Network Rehabilitation Management". Ph.D. Dissertation. University of Illinois at Urbana-Champaign, Urbana, Illinois.

Mrawira, D. M., and Amador, L. (2011). "Bayesian Regression in Pavement Deterioration Modeling: Revisiting the AASHO Road Test Rut Depth Model." *Transportation Research Board 90th Annual Meeting,* Transportation Research Board, Washington, D.C., 28-35.

Narciso, P. J. R. (2013). "Development of a Pavement Maintenance and Rehabilitation Project Formation and Prioritization Methodology that Reflects Agency Priorities and Improves Network Condition". M.Sc. Thesis. Texas A&M University, College Station, TX.

OECD Scientific Expert Group. (1994). *Road Maintenance and Rehabilitation: Funding and Allocation Strategies.* Organisation for Economic Co-operation and Development, Paris, France.

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(1), 62-70.

Palcic, I., and Lalic, B. (2009). "Analytical Hierarchy Process as a Tool for Selecting and Evaluating Projects." *International Journal of Simulation Modelling (IJSIMM),* 8(1), 16-26.

Palisade Corporation. (2012). "@RISK Risk Analysis Add-In for Microsoft Excel." 6.0.1: Industrial Edition.

Park, E. S., Smith, R. E., Freeman, T. J., and Spiegelman, C. H. (2008). "A Bayesian Approach for Improved Pavement Performance Prediction." *Journal of Applied Statistics,* 35(11), 1219-1238.

Pasupathy, R., Labi, S., and Sinha, K. C. (2007). "Optimal Reconstruction Periods for Stochastically Deteriorating Infrastructures." *Computer-Aided Civil and Infrastructure Engineering,* 22(6), 389-399.

Paterson, W. D. O. (1987). *Road Deterioration and Maintenance Effects: Models for Planning and Management.* World Bank Highway Design and Maintenance Standards Series, Washington, D.C.

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

Perkins-Smith, D. (2013). "Asset Management and MAP-21." *State Transportation Advisory Committee,* Division of Transportation Development, Colorado Department of Transportation, Denver, CO, 1-13.

Perrone, E., Clark, D., Ness, Q., Chen, X., and Hudson, S. (1998). "Risk Based Life Cycle Cost Analysis for Project Level Pavement Management." *Fourth International Conference on Managing Pavements,* Durban, South Africa, 1-15.

Peshkin, D. G., Hoerner, T. E., and Zimmerman, K. A. (2004). "Optimal Timing of Pavement Preventive Maintenance Treatment Applications." *Rep. No. NCHRP Report 523,* Transportation Research Board, Washington, D.C.

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(1), 42-48.

Reddy, B. B., and Veeraragavan, A. (2001). "Priority Ranking Model For Managing Flexible Pavements at Network Level." *Journal of Indian Roads Congress, December,* Paper Nº478, India, 379-394.

Ross, S. M. (2010). *Introduction to Probability Models, 10tn Edition.* Academic Press, Burlington, MA.

Salem, O., AbouRizk, S., and Ariaratnam, S. (2003). "Risk-Based Life-Cycle Costing of Infrastructure Rehabilitation and Construction Alternatives." *Journal of Infrastructure Systems,* 9(1), 6-15.

Senouci, A. B., and Adeli, H. (2001). "Resource Scheduling Using Neural Dynamics Model of Adeli and Park." *Journal of Construction Engineering and Management,* 127(1), 28-34.

Seyedshohadaie, S. R., Damnjanovic, I. D., and Butenko, S. I. (2010). "Risk-based maintenance and rehabilitation decisions for transportation infrastructure networks." *Transportation Research Part A: Policy and Practice,* 44(4), 236-248.

Shahin, M. Y. (2005). *Pavement Management for Airports, Roads, and Parking Lots.* Springer, New York, NY.

Sinha, K. C., Labi, S., Rodriguez, M., Tine, G. U., and Dutta, R. (2005). "Procedures for the Estimation of Pavement and Bridge Preservation Costs for Fiscal Planning and Programming." *Rep. No. FHWA/IN/JTRP-(2005)/17,* Joint Transportation Research Program, Purdue University, W. Lafayette, IN.

Sinha, K. C., Patidar, V., Li, Z., Labi, S., and Thompson, P. D. (2009). "Establishing the Weights of Performance Criteria: Case Studies in Transportation Facility Management." *Journal of Transportation Engineering,* 135(9), 619.

Sinha, P., and Zoltners, A. A. (1979). "The Multiple-Choice Knapsack Problem." *Operations Research,* 27(3), 503-515.

Sobanjo, J. O., Thompson, P. D., Lewis, M., and Kerr, R. (2002). "Estimating Agency Cost of Maintenance, Repair, and Rehabilitation for Florida Bridges." *Journal of Transportation Engineering,* 1795(1), 66-73.

Stampley, B. E., Miller, B., Smith, R. E., and Scullion, T. (1995). "Pavement Management Information System Concepts, Equations and Analysis Models." *Rep. No. TX-96/1989-1,* Texas Transportation Institute, Texas A&M University System, College Station, TX.

Tabatabaee, N., and Ziyadi, M. (2013). "Bayesian Approach to Updating Markov-Based Models for Predicting Pavement Performance." *Transportation Research Record: Journal of the Transportation Research Board,* 2366(1), 34-42.

Tack, J. N., and J. Chou, E. Y. (2002). "Multiyear Pavement Repair Scheduling Optimization by Preconstrained Genetic Algorithm." *Transportation Research Record: Journal of the Transportation Research Board,* 1816(1), 3-8.

Tavakoli, A., Lapin, M. S., and Figueroa, J. L. (1992). "PMSC: Pavement Management System for Small Communities." *Journal of Transportation Engineering,* 118(2), 270-280.

Thomas, F. (2003). "Statistical Approach to Road Segmentation." *Journal of Transportation Engineering,* 129(3), 300-308.

Thomas, O. S. A. A. (2011). "Stochastic Preservation Model for Transportation Infrastructure". Ph.D. Dissertation. The Florida State University, Florida.

Tighe, S. L. (2001). "Guidelines for Probabilistic Pavement Life Cycle Cost Analysis." *Transportation Research Record: Journal of the Transportation Research Board,* 1769(1), 28-38.

TxDOT. (2013). "Highway Cost Index (1997 Base) Index Report for October 2013." Construction Division, Texas Department of Transportation, Austin, TX.

TxDOT. (2011). *PMIS Technical Manual.* Construction Division, Materials and Pavement Section, Texas Department of Transportation, Austin, TX.

TxDOT. (2010). *Pavement Management Information System Rater′s Manual.* Texas Department of Transportation, Austin, TX.

U.S. Department of Transportation. (2005). "Intermodal Surface Transportation Efficiency Act (ISTEA)." www.dot.gov/ost/govtaffairs/istea/ (March, 25, 2014).

Vargas, S., de Solminihac, H., and Echaveguren, T. (2008). "Proposal of a Segmentation Procedure for Skid Resistance Data." *Arabian Journal for Science & Engineering,* 33(1B), 89-104.

Walls III, J., and Smith, M. R. (1998). "Life-Cycle Cost Analysis in Pavement Design-Interim Technical Bulletin." *Rep. No. FHWA-SA-98-079,* Federal Highway Administration, Washington, D.C.

Walsh, I. D. (2011). *ICE Manual of Highway Design and Management.* Institution of Civil Engineers (Great Britain), London.

Wang, F., Zhang, Z. M., and Machemehl, R. B. (2003). "Decision-Making Problem for Managing Pavement Maintenance and Rehabilitation Projects." *Transportation Research Record: Journal of the Transportation Research Board,* 1853(1), 21-28.

Wang, K. C. P., Way, G., Delton, J., and Zaniewski, J. P. (1993). "Pavement Network Optimization and Implementation." *Rep. No. AZ-SP-9301,* Arizona Department of Transportation, Phoenix, AZ.

Yeo, H., Yoon, Y., and Madanat, S. (2013). "Algorithms for Bottom-up Maintenance Optimisation for Heterogeneous Infrastructure Systems." *Structure and Infrastructure Engineering,* 9(4), 317-328.

Yoo, J., and Garcia-Diaz, A. (2008). "Cost-Effective Selection and Multi-Period Scheduling of Pavement Maintenance and Rehabilitation Strategies." *Engineering Optimization,* 40(3), 205-222.

Zaniewski, J. P., and Mamlouk, M. S. (1996). *Pavement Maintenance Effectiveness: Preventive Maintenance Treatments : Instructor's Guide.* Publication NºFHWA-SA-96-028, Federal Highway Administration, Washington, D.C.

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

# APPENDIX A: DISTRESS FUNCTIONS

**Table 22.** Distress utility factors

| Pavement Type | Distress Type | $\alpha_{ui}$ | $\beta_{ui}$ | $\rho_{ui}$ |
|---|---|---|---|---|
| 1 | Spalled Cracks | 1.000 | 0.690 | 106.000 |
| 1 | Punchouts | 0.985 | 1.000 | 5.140 |
| 1 | Asphalt Patches | 0.985 | 1.000 | 5.140 |
| 1 | Concrete Patches | 0.865 | 1.000 | 8.200 |
| 2 | Failed Joints and Cracks | 0.530 | 1.000 | 21.400 |
| 2 | JCP Failures | 1.456 | 1.000 | 22.150 |
| 2 | Slabs with Longitudinal Cracks | 1.006 | 1.000 | 47.800 |
| 2 | Shattered Slabs | 1.171 | 1.000 | 16.310 |
| 2 | Concrete Patching | 1.067 | 1.000 | 24.240 |
| 3 | Failed Joints and Cracks | 0.530 | 1.000 | 21.400 |
| 3 | JCP Failures | 1.456 | 1.000 | 22.150 |
| 3 | Slabs with Longitudinal Cracks | 1.006 | 1.000 | 47.800 |
| 3 | Shattered Slabs | 1.171 | 1.000 | 16.310 |
| 3 | Concrete Patching | 1.067 | 1.000 | 24.240 |
| 4 | Shallow Rutting | 0.310 | 1.000 | 19.720 |
| 4 | Deep Rutting | 0.690 | 1.000 | 16.270 |
| 4 | Patching | 0.450 | 1.000 | 10.150 |
| 4 | Failures | 1.000 | 1.000 | 4.700 |
| 4 | Block Cracking | 0.490 | 1.000 | 9.780 |
| 4 | Alligator Cracking | 0.530 | 1.000 | 8.010 |
| 4 | Longitudinal Cracking | 0.870 | 1.000 | 184.000 |
| 4 | Transverse Cracking | 0.690 | 1.000 | 10.390 |
| 5 | Shallow Rutting | 0.310 | 1.000 | 19.720 |
| 5 | Deep Rutting | 0.690 | 1.000 | 16.270 |
| 5 | Patching | 0.450 | 1.000 | 10.150 |
| 5 | Failures | 1.000 | 1.000 | 4.700 |
| 5 | Block Cracking | 0.490 | 1.000 | 9.780 |
| 5 | Alligator Cracking | 0.530 | 1.000 | 8.010 |
| 5 | Longitudinal Cracking | 0.870 | 1.000 | 184.000 |
| 5 | Transverse Cracking | 0.690 | 1.000 | 10.390 |
| 6 | Shallow Rutting | 0.310 | 1.000 | 19.720 |
| 6 | Deep Rutting | 0.690 | 1.000 | 16.270 |
| 6 | Patching | 0.450 | 1.000 | 10.150 |
| 6 | Failures | 1.000 | 1.000 | 4.700 |
| 6 | Block Cracking | 0.490 | 1.000 | 9.780 |
| 6 | Alligator Cracking | 0.530 | 1.000 | 8.010 |

| | | | | |
|---|---|---|---|---|
| 6 | Longitudinal Cracking | 0.870 | 1.000 | 184.000 |
| 6 | Transverse Cracking | 0.690 | 1.000 | 10.390 |
| 7 | Shallow Rutting | 0.230 | 1.000 | 17.550 |
| 7 | Deep Rutting | 0.320 | 1.000 | 9.040 |
| 7 | Patching | 0.320 | 1.000 | 17.280 |
| 7 | Failures | 1.000 | 1.000 | 4.700 |
| 7 | Block Cracking | 0.310 | 1.000 | 13.790 |
| 7 | Alligator Cracking | 0.420 | 1.000 | 18.770 |
| 7 | Longitudinal Cracking | 0.370 | 1.000 | 136.900 |
| 7 | Transverse Cracking | 0.430 | 1.000 | 9.560 |
| 8 | Shallow Rutting | 0.230 | 1.000 | 17.550 |
| 8 | Deep Rutting | 0.320 | 1.000 | 9.040 |
| 8 | Patching | 0.320 | 1.000 | 17.280 |
| 8 | Failures | 1.000 | 1.000 | 4.700 |
| 8 | Block Cracking | 0.310 | 1.000 | 13.790 |
| 8 | Alligator Cracking | 0.420 | 1.000 | 18.770 |
| 8 | Longitudinal Cracking | 0.370 | 1.000 | 136.900 |
| 8 | Transverse Cracking | 0.430 | 1.000 | 9.560 |
| 9 | Shallow Rutting | 0.310 | 1.000 | 19.720 |
| 9 | Deep Rutting | 0.690 | 1.000 | 16.270 |
| 9 | Patching | 0.450 | 1.000 | 10.150 |
| 9 | Failures | 1.000 | 1.000 | 4.700 |
| 9 | Block Cracking | 0.490 | 1.000 | 9.780 |
| 9 | Alligator Cracking | 0.530 | 1.000 | 8.010 |
| 9 | Longitudinal Cracking | 0.870 | 1.000 | 184.000 |
| 9 | Transverse Cracking | 0.690 | 1.000 | 10.390 |
| 10 | Shallow Rutting | 0.310 | 1.000 | 19.720 |
| 10 | Deep Rutting | 0.690 | 1.000 | 16.270 |
| 10 | Patching | 0.450 | 1.000 | 10.150 |
| 10 | Failures | 1.000 | 1.000 | 4.700 |
| 10 | Block Cracking | 0.490 | 1.000 | 9.780 |
| 10 | Alligator Cracking | 0.530 | 1.000 | 8.010 |
| 10 | Longitudinal Cracking | 0.870 | 1.000 | 184.000 |
| 10 | Transverse Cracking | 0.690 | 1.000 | 10.390 |

**Table 23.** Utility coefficients for ride quality

| Traffic Category | Alpha | Beta | Rho |
|---|---|---|---|
| Low | 1.18 | 1.00 | 58.50 |
| Medium | 1.76 | 1.00 | 48.10 |
| High | 1.73 | 1.00 | 41.00 |

**Table 24.** Coefficients of performance prediction equation for pavement types 4, 5, and 9

| Distress Type | Treatment Type | Low Traffic | | | Medium Traffic | | | High Traffic | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | α | β | A | α | β | A | α | β | A |
| Shallow Rutting | PM | 100 | 0.42 | 110.20 | 100 | 0.50 | 91.77 | 100 | 0.52 | 71.62 |
| | LR | 100 | 0.47 | 121.74 | 100 | 0.52 | 107.61 | 100 | 0.58 | 74.26 |
| | MR | 100 | 0.50 | 125.66 | 100 | 0.55 | 129.57 | 100 | 0.61 | 85.16 |
| | HR | 100 | 0.59 | 145.28 | 100 | 0.59 | 132.43 | 100 | 0.71 | 90.54 |
| Deep Rutting | PM | 100 | 0.62 | 85.47 | 100 | 0.70 | 76.20 | 100 | 0.89 | 44.97 |
| | LR | 100 | 0.75 | 95.17 | 100 | 0.83 | 83.33 | 100 | 1.05 | 46.10 |
| | MR | 100 | 0.89 | 104.45 | 100 | 0.88 | 89.09 | 100 | 1.18 | 54.08 |
| | HR | 100 | 1.03 | 112.31 | 100 | 1.53 | 93.10 | 100 | 1.28 | 61.40 |
| Failures | PM | 20 | 0.87 | 21.95 | 20 | 0.55 | 111.45 | 20 | 0.78 | 69.14 |
| | LR | 20 | 0.91 | 23.32 | 20 | 0.63 | 122.81 | 20 | 0.86 | 82.97 |
| | MR | 20 | 1.00 | 25.56 | 20 | 0.66 | 126.71 | 20 | 1.02 | 90.45 |
| | HR | 20 | 1.12 | 29.47 | 20 | 0.78 | 145.99 | 20 | 1.10 | 105.81 |
| Block Cracking | PM | 100 | 0.57 | 97.50 | 100 | 0.54 | 89.19 | 100 | 0.88 | 85.46 |
| | LR | 100 | 0.60 | 113.66 | 100 | 0.55 | 102.78 | 100 | 1.04 | 94.11 |
| | MR | 100 | 0.64 | 131.51 | 100 | 0.57 | 119.77 | 100 | 1.20 | 101.08 |
| | HR | 100 | 0.66 | 151.23 | 100 | 0.58 | 139.97 | 100 | 1.34 | 105.18 |
| Alligator Cracking | PM | 100 | 0.49 | 68.28 | 100 | 0.54 | 35.51 | 100 | 0.95 | 19.85 |
| | LR | 100 | 0.55 | 68.53 | 100 | 0.62 | 42.29 | 100 | 0.99 | 20.93 |
| | MR | 100 | 0.56 | 76.35 | 100 | 0.66 | 46.25 | 100 | 1.05 | 22.33 |
| | HR | 100 | 0.62 | 76.19 | 100 | 0.78 | 47.48 | 100 | 1.13 | 23.74 |
| Longitudinal Cracking | PM | 500 | 0.65 | 41.91 | 500 | 0.39 | 75.34 | 500 | 0.47 | 115.36 |
| | LR | 500 | 0.76 | 42.71 | 500 | 0.45 | 79.93 | 500 | 0.54 | 131.06 |
| | MR | 500 | 0.85 | 50.70 | 500 | 0.50 | 80.72 | 500 | 0.60 | 142.35 |
| | HR | 500 | 0.91 | 57.23 | 500 | 0.52 | 93.19 | 500 | 0.63 | 146.90 |

| Distress Type | Treatment Type | Low Traffic | | | Medium Traffic | | | High Traffic | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | α | β | A | α | β | A | α | β | A |
| Transverse Cracking | PM | 20 | 0.66 | 50.51 | 20 | 0.51 | 68.85 | 20 | 0.63 | 60.35 |
| | LR | 20 | 0.67 | 54.85 | 20 | 1.21 | 81.97 | 20 | 0.67 | 65.17 |
| | MR | 20 | 0.67 | 59.12 | 20 | 1.38 | 86.76 | 20 | 0.69 | 69.94 |
| | HR | 20 | 0.68 | 63.36 | 20 | 1.95 | 98.37 | 20 | 0.69 | 74.61 |
| Patching | PM | 100 | 0.58 | 54.80 | 100 | 0.42 | 110.20 | 100 | 0.60 | 67.13 |
| | LR | 100 | 0.61 | 61.13 | 100 | 0.47 | 121.74 | 100 | 0.66 | 79.75 |
| | MR | 100 | 0.64 | 69.17 | 100 | 0.50 | 125.66 | 100 | 0.79 | 86.73 |
| | HR | 100 | 0.70 | 80.26 | 100 | 0.59 | 145.28 | 100 | 0.85 | 101.63 |
| RS | PM | 100 | 5.35 | 7.53 | 100 | 42.24 | 6.19 | 100 | 25.01 | 6.36 |
| | LR | 100 | 5.78 | 11.51 | 100 | 43.80 | 8.47 | 100 | 34.52 | 8.65 |
| | MR | 100 | 7.94 | 13.56 | 100 | 49.03 | 11.94 | 100 | 37.72 | 10.67 |
| | HR | 100 | 42.65 | 17.26 | 100 | 49.50 | 13.86 | 100 | 45.51 | 18.06 |

**Table 25.** Coefficients of performance prediction equation for pavement types 7 & 8

| Distress Type | Treatment Type | Low Traffic | | | Medium Traffic | | | High Traffic | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | α | β | A | α | β | A | α | β | A |
| Shallow Rutting | PM | 100 | 0.49 | 93.49 | 100 | 0.74 | 46.21 | Not Enough Data | | |
| | LR | 100 | 0.51 | 110.67 | 100 | 1.01 | 53.71 | | | |
| | MR | 100 | 0.55 | 112.98 | 100 | 1.09 | 57.91 | | | |
| | HR | 100 | 0.61 | 118.76 | 100 | 1.40 | 68.24 | | | |
| Deep Rutting | PM | 100 | 0.82 | 55.66 | 100 | 0.59 | 118.61 | | | |
| | LR | 100 | 0.84 | 61.69 | 100 | 0.69 | 137.57 | | | |
| | MR | 100 | 0.88 | 69.12 | 100 | 0.78 | 153.66 | | | |
| | HR | 100 | 0.94 | 78.38 | 100 | 0.85 | 164.70 | | | |
| Failures | PM | 20 | 2.87 | 10.68 | 20 | 1.22 | 19.56 | | | |
| | LR | 20 | 3.20 | 11.67 | 20 | 1.25 | 20.57 | | | |
| | MR | 20 | 3.75 | 13.25 | 20 | 1.29 | 21.63 | | | |
| | HR | 20 | 3.86 | 15.73 | 20 | 1.33 | 22.69 | | | |
| Block Cracking | PM | 100 | 4.58 | 37.62 | 100 | 4.64 | 34.94 | | | |
| | LR | 100 | 5.44 | 44.08 | 100 | 5.43 | 39.55 | | | |
| | MR | 100 | 5.88 | 46.13 | 100 | 5.69 | 40.32 | | | |
| | HR | 100 | 6.93 | 52.43 | 100 | 6.41 | 43.43 | | | |
| Alligator Cracking | PM | 100 | 0.74 | 53.56 | 100 | 0.73 | 39.14 | | | |
| | LR | 100 | 0.76 | 59.13 | 100 | 0.83 | 46.76 | | | |
| | MR | 100 | 0.79 | 65.12 | 100 | 0.90 | 52.78 | | | |
| | HR | 100 | 0.82 | 72.21 | 100 | 0.92 | 56.47 | | | |

| Distress Type | Treatment Type | Low Traffic | | | Medium Traffic | | | High Traffic | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | α | β | A | α | β | A | α | β | A |
| Longitudinal Cracking | PM | 500 | 0.28 | 111.35 | 500 | 0.37 | 86.61 | | | |
| | LR | 500 | 0.32 | 124.55 | 500 | 0.37 | 99.37 | | | |
| | MR | 500 | 0.34 | 132.67 | 500 | 0.38 | 113.92 | | | |
| | HR | 500 | 0.35 | 159.94 | 500 | 0.39 | 131.58 | | | |
| Transverse Cracking | PM | 20 | 1.08 | 22.90 | 20 | 0.79 | 16.22 | | | |
| | LR | 20 | 1.14 | 24.49 | 20 | 0.81 | 16.46 | | | |
| | MR | 20 | 1.23 | 26.20 | 20 | 0.84 | 16.62 | | | |
| | HR | 20 | 1.36 | 28.91 | 20 | 0.89 | 17.79 | | | |
| Patching | PM | 100 | 0.34 | 102.28 | 100 | 0.71 | 94.44 | | | |
| | LR | 100 | 0.37 | 107.66 | 100 | 0.74 | 111.07 | | | |
| | MR | 100 | 0.43 | 123.83 | 100 | 0.78 | 111.41 | | | |
| | HR | 100 | 0.46 | 127.92 | 100 | 0.85 | 114.06 | | | |
| RS | PM | 100 | 18.25 | 6.38 | 100 | 6.32 | 7.72 | | | |
| | LR | 100 | 20.03 | 7.52 | 100 | 6.81 | 11.60 | | | |
| | MR | 100 | 21.16 | 9.67 | 100 | 9.02 | 13.65 | | | |
| | HR | 100 | 21.82 | 13.26 | 100 | 43.72 | 17.39 | | | |

**Table 26.** Coefficients of performance prediction equation for pavement types 6, 10

| Distress Type | Treatment Type | Low Traffic | | | Medium Traffic | | | High Traffic | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | α | β | A | α | β | A | α | β | A |
| Shallow Rutting | PM | 100 | 0.58 | 49.93 | 100 | 0.46 | 96.74 | Not Enough Data | | |
| | LR | 100 | 0.59 | 53.87 | 100 | 0.49 | 98.00 | | | |
| | MR | 100 | 0.60 | 58.23 | 100 | 0.54 | 104.16 | | | |
| | HR | 100 | 0.60 | 62.57 | 100 | 0.63 | 115.82 | | | |
| Deep Rutting | PM | 100 | 0.60 | 90.24 | 100 | 0.65 | 103.52 | | | |
| | LR | 100 | 0.60 | 101.52 | 100 | 0.71 | 108.86 | | | |
| | MR | 100 | 0.80 | 112.77 | 100 | 0.82 | 122.33 | | | |
| | HR | 100 | 1.01 | 123.06 | 100 | 0.86 | 145.53 | | | |
| Failures | PM | 20 | 0.78 | 100.18 | 20 | 4.36 | 90.05 | | | |
| | LR | 20 | 0.84 | 101.50 | 20 | 4.70 | 104.11 | | | |
| | MR | 20 | 0.93 | 108.45 | 20 | 5.11 | 121.38 | | | |
| | HR | 20 | 1.08 | 120.54 | 20 | 5.59 | 141.92 | | | |
| Block Cracking | PM | 100 | 3.17 | 42.00 | 100 | 9.87 | 33.50 | | | |
| | LR | 100 | 3.38 | 44.69 | 100 | 11.39 | 34.21 | | | |
| | MR | 100 | 3.61 | 48.17 | 100 | 12.65 | 39.69 | | | |

| Distress Type | Treatment Type | Low Traffic | | | Medium Traffic | | | High Traffic | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | α | β | A | α | β | A | α | β | A |
| | HR | 100 | 3.87 | 51.67 | 100 | 13.49 | 44.76 | | | |
| Alligator Cracking | PM | 100 | 0.62 | 65.51 | 100 | 0.47 | 92.92 | | | |
| | LR | 100 | 0.67 | 77.95 | 100 | 0.49 | 110.43 | | | |
| | MR | 100 | 0.79 | 82.99 | 100 | 0.52 | 111.54 | | | |
| | HR | 100 | 0.83 | 94.98 | 100 | 0.58 | 116.91 | | | |
| Longitudinal Cracking | PM | 500 | 0.48 | 117.56 | 500 | 0.48 | 105.14 | | | |
| | LR | 500 | 0.56 | 136.53 | 500 | 0.53 | 112.14 | | | |
| | MR | 500 | 0.63 | 152.26 | 500 | 0.63 | 129.81 | | | |
| | HR | 500 | 0.68 | 162.75 | 500 | 0.69 | 137.24 | | | |
| Transverse Cracking | PM | 20 | 0.84 | 49.84 | 20 | 0.77 | 111.83 | | | |
| | LR | 20 | 0.84 | 53.07 | 20 | 0.86 | 122.68 | | | |
| | MR | 20 | 1.00 | 55.46 | 20 | 0.90 | 124.05 | | | |
| | HR | 20 | 1.16 | 56.55 | 20 | 1.03 | 138.96 | | | |
| Patching | PM | 100 | 1.16 | 28.63 | 100 | 0.37 | 101.70 | | | |
| | LR | 100 | 1.25 | 31.85 | 100 | 0.44 | 120.93 | | | |
| | MR | 100 | 1.41 | 36.46 | 100 | 0.54 | 122.24 | | | |
| | HR | 100 | 1.67 | 36.09 | 100 | 0.68 | 125.78 | | | |
| RS | PM | 100 | 8.04 | 6.50 | 100 | 6.66 | 5.91 | | | |
| | LR | 100 | 8.27 | 7.80 | 100 | 8.00 | 8.73 | | | |
| | MR | 100 | 8.43 | 10.35 | 100 | 11.71 | 11.19 | | | |
| | HR | 100 | 11.11 | 12.49 | 100 | 29.15 | 19.68 | | | |

**Table 27.** Distress prediction functions

| Distress Type | α | β | ρ |
|---|---|---|---|
| Shallow Rutting | 0.31 | 1.00 | 19.72 |
| Deep Rutting | 0.69 | 1.00 | 16.27 |
| Patching | 0.45 | 1.00 | 10.15 |
| Failures | 1.00 | 1.00 | 4.70 |
| Block Cracking | 0.49 | 1.00 | 9.78 |
| Alligator Cracking | 0.53 | 1.00 | 8.01 |
| Longitudinal Cracking | 0.87 | 1.00 | 184.00 |
| Transverse Cracking | 0.69 | 1.00 | 10.39 |
| Alligator Cracking | 0.53 | 1.00 | 8.01 |
| Longitudinal Cracking | 0.87 | 1.00 | 184.00 |
| Transverse Cracking | 0.69 | 1.00 | 10.39 |

# APPENDIX B: MATLAB CODE FOR INTEGER OPTIMIZATION

```
years=10
sections=100
budget=400
iterations=years;
DECISION=ones(sections,years);
for x=1:iterations;
AGE=zeros(sections,1);
CEFF=zeros(sections,years);
CEFFPM=zeros(sections,years);
CEFFLR=zeros(sections,years);
CEFFMR=zeros(sections,years);
CEFFHR=zeros(sections,years);
CSOO=zeros(sections,years);
CSOF=zeros(sections,years);
SOLUTION=zeros(sections,years);
COST=zeros(sections,years);
COSTOTAL=zeros(years);
BENCOST=zeros(sections,years);
COSTTR=zeros(sections,years);
CSOT=zeros(sections, 1);
BETALAST=zeros(sections,1);
RHOLAST=zeros(sections,1);

for i=1:sections;
    CSOO(i,1)=CSO(i);
    BETALAST(i)=BETADN(i);
    RHOLAST(i)=RHODN(i);
    AGE(i)=AGEO(i);
end
for i=1:years;
   for j=1:sections;
        if DECISION(j,i)>=1;
      if CSOO(j,i)<70;
       CEFFPM(j,i)=COSTPM(j)/round((-log(1-70/(CSOO(j)+DCSPM(j))))^(1/BETAPM(j)));
       CEFFLR(j,i)=COSTLR(j)/round((-log(1-70/(CSOO(j)+DCSLR(j))))^(1/BETALR(j)));
       CEFFMR(j,i)=COSTMR(j)/round((-log(1-70/(CSOO(j)+DCSMR(j))))^(1/BETAMR(j)));
       CEFFHR(j,i)=COSTHR(j)/round((-log(1-70/(CSOO(j)+DCSHR(j))))^(1/BETAHR(j)));
       if CSOO(j,i)+DCSPM(j)>70;
          if CEFFPM(j,i)<CEFFLR(j,i)&CEFFPM(j,i)<CEFFMR(j,i)&CEFFPM(j,i)<CEFFHR(j,i);
             SOLUTION(j,i)=1;
             CSOO(j,i)=CSOO(j,i)+DCSPM(j);
              BETALAST(j)=BETAPM(i);
             RHOLAST(j)=RHOPM(i);
             AGE(j)=1;
             CSOF(j,i)=CSOO(j,i)*(1-exp(-((RHOPM(j)/AGE(j))^BETAPM(j))));
             COST(j,i)=length(j)*width(j)/24*COSTPM(j);
             BENCOST(j,i)=(CSOO(j,i)+CSOF(j,i))/2*AADT(j)/width(j)/24/COSTPM(j);
            else if CEFFLR(j,i)<CEFFMR(j,i)&CEFFLR(j,i)<CEFFHR(j,i);
               SOLUTION(j,i)=2;
```

```
            CSOO(j,i)=CSOO(j,i)+DCSLR(j);
            AGE(j)=1;
            BETALAST(j)=BETALR(i);
            RHOLAST(j)=RHOLR(i);
            CSOF(j,i)=CSOO(j,i)*(1-exp(-((RHOLAST(j)/AGE(j))^BETALAST(j))));
            COST(j,i)=length(j)*width(j)/24*COSTLR(j);
            BENCOST(j,i)=(CSOO(j,i)+CSOF(j,i))/2*AADT(j)/width(j)/24/COSTLR(j);
          else if (CEFFMR(j,i)<CEFFHR(j,i));
                SOLUTION(j,i)=3;
                CSOO(j,i)=100;
                BETALAST(j)=BETAMR(i);
                 RHOLAST(j)=RHOMR(i);
                 AGE(j)=1;
                 CSOF(j,i)=CSOO(j,i)*(1-exp(-((RHOLAST(j)/i)^BETALAST(j))));
                  COST(j,i)=length(j)*width(j)/24*COSTMR(j);
                 BENCOST(j,i)=(CSOO(j,i)+CSOF(j,i))/2*AADT(j)/width(j)/24/COSTMR(j);

            else SOLUTION(j,i)=4 ;
                CSOO(j,i)=100;
                 BETALAST(j)=BETAHR(i);
                 RHOLAST(j)=RHOHR(i);
                 AGE(j)=1;
                 CSOF(j,i)=CSOO(j,i)*(1-exp(-((RHOLAST(j)/i)^BETALAST(j))));
                  COST(j,i)=length(j)*width(j)/24*COSTHR(j);
                 BENCOST(j,i)=(CSOO(j,i)+CSOF(j,i))/2*AADT(j)/width(j)/24/COSTHR(j);
             end
        end
    end
else if CSOO(j,i)+DCSLR(j)>70;
        if CEFFLR(j,i)<CEFFMR(j,i)&CEFFLR(j,i)<CEFFHR(j,i);
         SOLUTION(j,i)=2;
          CSOO(j,i)=CSOO(j,i)+DCSLR(j);
          BETALAST(j)=BETALR(i);
             RHOLAST(j)=RHOLR(i);
             AGE(j)=1;
           CSOF(j,i)=CSOO(j,i)*(1-exp(-((RHOLAST(j)/i)^BETALAST(j))));
            COST(j,i)=length(j)*width(j)/24*COSTLR(j);
           BENCOST(j,i)=(CSOO(j,i)+CSOF(j,i))/2*AADT(j)/width(j)/24/COSTLR(j);

        else if (CEFFMR(j,i)<CEFFHR(j,i));
                SOLUTION(j,i)=3;
                CSOO(j,i)=100;
                  BETALAST(j)=BETAMR(i);
                   RHOLAST(j)=RHOMR(i);
                   AGE(j)=1;
                  CSOF(j,i)=CSOO(j,i)*(1-exp(-((RHOLAST(j)/i)^BETALAST(j))));
                    COST(j,i)=length(j)*width(j)/24*COSTMR(j);
                   BENCOST(j,i)=(CSOO(j,i)+CSOF(j,i))/2*AADT(j)/width(j)/24/COSTMR(j);

            else SOLUTION(j,i)=4;
                CSOO(j,i)=100;
                   BETALAST(j)=BETAHR(i);
```

```
                         RHOLAST(j)=RHOHR(i);
                         AGE(j)=1;
                         CSOF(j,i)=CSOO(j,i)*(1-exp(-((RHOLAST(j)/i)^BETALAST(j))));
                          COST(j,i)=length(j)*width(j)/24*COSTHR(j);
                         BENCOST(j,i)=(CSOO(j,i)+CSOF(j,i))/2*AADT(j)/width(j)/24/COSTHR(j);

                       end
                     end
                   else if (CEFFMR(j,i)<CEFFHR(j,i));
                         SOLUTION(j,i)=3;
                         CSOO(j,i)=100;
                         BETALAST(j)=BETAMR(i);
                           RHOLAST(j)=RHOMR(i);
                           AGE(j)=1;
                           CSOF(j,i)=CSOO(j,i)*(1-exp(-((RHOLAST(j)/i)^BETALAST(j))));
                          BENCOST(j,i)=(CSOO(j,i)+CSOF(j,i))/2*AADT(j)/width(j)/24/COSTMR(j);
                           COST(j,i)=length(j)*width(j)/24*COSTMR(j);

                       else SOLUTION(j,i)=4 ;
                         CSOO(j,i)=100;
                         BETALAST(j)=BETAHR(i);
                          RHOLAST(j)=RHOHR(i);
                          AGE(j)=1;
                         CSOF(j,i)=CSOO(j,i)*(1-exp(-((RHOLAST(j)/i)^BETALAST(j))));
                          COST(j,i)=length(j)*width(j)/24*COSTHR(j);
                          BENCOST(j,i)=(CSOO(j,i)+CSOF(j,i))/2*AADT(j)/width(j)/24/COSTHR(j);

                     end
                   end
                 end
         else CSOF(j,i)=CSOO(j,i)*(1-exp(-((RHOLAST(j)/(AGE(j)+i))^BETALAST(j))));
                    BENCOST(j,i)=0;
         end
         else CSOF(j,i)=CSOO(j,i)*(1-exp(-((RHOLAST(j)/(AGE(j)+i))^BETALAST(j))));
                    BENCOST(j,i)=0;
             end
        CSOO(j,i+1)=CSOF(j,i);
         end
end
H=zeros(1,years);
I=zeros(years,sections*years);
f=zeros(1,sections*years);
k=0;
n=1;
m=years;
for i=1:years;
   H(1,i)=budget;
end
for o=1:years;
   for j=1:sections;
      k=k+1;
    f(1,k)=BENCOST(j,o);
```

```
    end
end
k=0;
for o=1:years;
    for j=1:sections;
        k=k+1;
        I(o,k)=COST(j,o);
    end
end
M=bintprog(-f,I,H);
k=0;
for o=1:i;
    for j=1:sections;
        k=k+1;
     DECISION(j,o)=M(k,1);
    end
end
  end
```

# APPENDIX C: BRYAN DISTRICT INFORMATION

**Table 28.** Bryan district statistics information from TxDOT DISCOS

| Year | Population | Daily vehicles miles | Miles center | Lane miles | Construction expenditures in $ | Non-contracted maintenance expenditures in $ | Highway cost index (1997 base) twelve month moving average |
|---|---|---|---|---|---|---|---|
| 2001 | 370,948.00 | 11,823,947.00 | 3,110.39 | 6,898.13 | 2,297,771.40 | 23,647,541.13 | 96.62 |
| 2004 | 387,501.00 | 13,455,582.00 | 3,116,279.00 | 6,920.92 | 80,653,136.74 | 21,151,899.88 | 103.25 |
| 2005 | 388,565.00 | 12,711,508.00 | 3,121,388.00 | 6,931.85 | 101,561,908.00 | 20,828,730.00 | 118.58 |
| 2006 | 389,965.00 | 14,186,372.00 | 3,125.22 | 6,954.62 | 134,668,657.98 | 21,527,797.19 | 124.82 |
| 2011 | 431,881.00 | 14,024,544.00 | 3,142.35 | 7,121.77 | 62,147,220.61 | 30,549,545.13 | 114.48 |
| 2012 | 431,881.00 | 14,054,258.00 | 3,143.52 | 7,136.33 | 95,935,911.97 | 32,715,247.74 | 138.27 |
| 2013 | 431,881.00 | 13,434,878.00 | 3,145.37 | 7,154.56 | 83,655,148.72 | 32,189,475.11 | 143.03 |

**Table 29.** Segment information of analyzed network

| **Seg.** | **code** | **begin marker** | **end marker** | **average DS** | **average CS** | **average RS** | **length (miles)** | **AADT** | **Pav. type** | **speed limit** |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | BS0006RK | 406.4 | 410.0 | 99.7 | 96.4 | 3.4 | 3.4 | 8985.7 | 5.0 | 51 |
| 2 | BS0006RK | 410.0 | 414.6 | 90.8 | 69.2 | 2.8 | 4.6 | 20127.3 | 5.0 | 40 |
| 3 | BS0006RK | 417.4 | 418.5 | 89.3 | 89.3 | 3.8 | 1.1 | 25133.3 | 5.0 | 50 |
| 4 | BS0006RL | 0.0 | 406.4 | 100.0 | 100.0 | 3.1 | 0.6 | 1850.0 | 5.0 | 55 |
| 5 | BS0006RL | 414.6 | 415.7 | 85.0 | 77.0 | 3.1 | 1.1 | 19250.0 | 5.0 | 40 |
| 6 | BS0006RR | 0.0 | 406.4 | 100.0 | 100.0 | 3.8 | 0.6 | 1850.0 | 5.0 | 55 |
| 7 | BS0006RR | 414.6 | 415.7 | 85.0 | 85.0 | 3.6 | 1.1 | 19250.0 | 5.0 | 40 |
| 8 | BS0006SK | 0.0 | 429.0 | 87.9 | 87.5 | 3.5 | 2.8 | 5642.9 | 5.0 | 52 |
| 9 | BS0006SK | 429.0 | 432.2 | 77.6 | 77.6 | 3.9 | 3.2 | 3257.1 | 5.0 | 59 |
| 10 | BS0006SL | 432.2 | 432.6 | 87.0 | 87.0 | 3.6 | 0.4 | 800.0 | 5.0 | 70 |
| 11 | BS0006SR | 432.2 | 432.6 | 96.0 | 96.0 | 3.3 | 0.4 | 800.0 | 5.0 | 70 |
| 12 | BS0021HK | 0.0 | 686.1 | 100.0 | 81.3 | 2.8 | 1.3 | 400.0 | 5.0 | 66 |
| 13 | BS0036JK | 442.0 | 443.8 | 94.0 | 80.3 | 3.3 | 1.8 | 6750.0 | 5.0 | 49 |
| 14 | BS0036JK | 444.1 | 446.0 | 84.5 | 81.0 | 3.4 | 1.7 | 13725.0 | 5.0 | 38 |
| 15 | BS0036JL | 443.8 | 444.1 | 94.0 | 94.0 | 3.2 | 0.3 | 4125.0 | 5.0 | 35 |
| 16 | BS0036JR | 443.8 | 444.1 | 92.0 | 87.0 | 3.1 | 0.3 | 4125.0 | 5.0 | 35 |
| 17 | BU0084RK | 0.0 | 346.0 | 87.0 | 68.0 | 2.8 | 1.8 | 4650.0 | 8.0 | 55 |
| 18 | BU0084RK | 346.0 | 346.3 | 94.0 | 61.0 | 2.6 | 0.3 | 4900.0 | 5.0 | 55 |
| 19 | BU0290FK | 0.0 | 444.7 | 100.0 | 94.7 | 3.4 | 1.0 | 6600.0 | 5.0 | 55 |
| 20 | BU0290FK | 446.0 | 448.5 | 96.0 | 89.2 | 3.4 | 2.4 | 7800.0 | 10.0 | 43 |
| 21 | BU0290FK | 448.5 | 448.8 | 100.0 | 100.0 | 3.4 | 0.3 | 3800.0 | 5.0 | 50 |
| 22 | BU0290FL | 444.7 | 445.6 | 74.0 | 39.0 | 2.4 | 0.9 | 3650.0 | 5.0 | 55 |

| Seg. | code | begin marker | end marker | average DS | average CS | average RS | length (miles) | AADT | Pav. type | speed limit |
|---|---|---|---|---|---|---|---|---|---|---|
| 23 | BU0290FR | 444.7 | 445.6 | 74.0 | 36.0 | 2.3 | 0.9 | 3650.0 | 5.0 | 55 |
| 24 | PR0012 K | 0.0 | 633.1 | 100.0 | 82.0 | 2.3 | 0.3 | 210.0 | 5.0 | 70 |
| 25 | PR0040 K | 0.1 | 0.5 | 85.0 | 71.0 | 2.4 | 0.4 | 960.0 | 5.0 | 55 |
| 26 | PR0040 K | 0.5 | 413.6 | 100.0 | 100.0 | 3.1 | 3.1 | 481.4 | 10.0 | 39 |
| 27 | PR0040AK | 0.0 | 413.2 | 97.0 | 87.8 | 2.1 | 1.3 | 110.0 | 10.0 | 55 |
| 28 | PR0057 K | 432.0 | 435.0 | 82.0 | 81.8 | 3.1 | 2.9 | 926.7 | 5.0 | 60 |
| 29 | PR0057 K | 435.0 | 437.9 | 99.3 | 98.5 | 2.8 | 2.9 | 180.0 | 5.0 | 44 |
| 30 | PR0064 K | 632.0 | 633.4 | 96.7 | 87.0 | 2.2 | 1.4 | 350.0 | 5.0 | 55 |
| 31 | RE0004 K | 432.0 | 435.3 | 100.0 | 96.7 | 2.8 | 3.2 | 640.0 | 5.0 | 70 |
| 32 | SH0006 A | 584.0 | 587.5 | 97.0 | 84.0 | 3.0 | 2.4 | 2610.0 | 5.0 | 51 |
| 33 | SH0006 A | 587.5 | 589.5 | 94.3 | 94.3 | 3.4 | 2.0 | 4980.0 | 5.0 | 54 |
| 34 | SH0006 A | 589.5 | 591.5 | 96.8 | 59.5 | 2.5 | 2.0 | 5792.5 | 5.0 | 49 |
| 35 | SH0006 A | 591.5 | 594.0 | 97.8 | 91.3 | 3.3 | 2.5 | 7676.7 | 5.0 | 51 |
| 36 | SH0006 A | 594.0 | 600.8 | 100.0 | 87.1 | 3.4 | 6.8 | 13874.0 | 5.0 | 54 |
| 37 | SH0006 A | 601.0 | 606.0 | 100.0 | 99.0 | 3.6 | 5.0 | 360.0 | 5.0 | 55 |
| 38 | SH0006 A | 606.5 | 608.7 | 100.0 | 100.0 | 4.7 | 2.1 | 360.0 | 5.0 | 55 |
| 39 | SH0006 A | 611.6 | 612.4 | 100.0 | 100.0 | 3.7 | 0.8 | 60.0 | 10.0 | 45 |
| 40 | SH0006 A | 612.4 | 614.5 | 99.4 | 95.2 | 3.1 | 2.1 | 2730.0 | 5.0 | 47 |
| 41 | SH0006 K | 554.1 | 561.5 | 94.9 | 94.9 | 4.7 | 7.4 | 9766.7 | 5.0 | 55 |
| 42 | SH0006 L | 542.0 | 547.5 | 100.0 | 100.0 | 4.9 | 5.5 | 3731.8 | 5.0 | 55 |
| 43 | SH0006 L | 547.5 | 554.1 | 100.0 | 100.0 | 4.8 | 6.6 | 4219.2 | 5.0 | 55 |
| 44 | SH0006 L | 584.0 | 586.0 | 77.5 | 77.5 | 4.0 | 0.9 | 20122.5 | 5.0 | 70 |
| 45 | SH0006 L | 586.0 | 593.5 | 100.0 | 100.0 | 4.8 | 7.5 | 25713.3 | 8.0 | 70 |
| 46 | SH0006 L | 593.5 | 602.5 | 100.0 | 100.0 | 4.3 | 9.0 | 12976.9 | 5.0 | 70 |
| 47 | SH0006 L | 609.9 | 610.0 | 100.0 | 100.0 | 4.8 | 0.1 | 11500.0 | 5.0 | 70 |
| 48 | SH0006 L | 610.0 | 616.5 | 100.0 | 100.0 | 4.6 | 6.5 | 8233.6 | 10.0 | 70 |
| 49 | SH0006 L | 616.5 | 626.0 | 100.0 | 100.0 | 4.8 | 8.1 | 8735.9 | 10.0 | 70 |
| 50 | SH0006 R | 542.0 | 547.5 | 100.0 | 100.0 | 4.7 | 5.5 | 3731.8 | 5.0 | 70 |
| 51 | SH0006 R | 547.5 | 554.1 | 100.0 | 100.0 | 4.8 | 6.6 | 4219.2 | 5.0 | 70 |
| 52 | SH0006 R | 584.0 | 586.0 | 76.0 | 76.0 | 3.9 | 0.9 | 20122.5 | 5.0 | 70 |
| 53 | SH0006 R | 586.0 | 593.5 | 96.8 | 96.8 | 4.6 | 7.5 | 25713.3 | 8.0 | 70 |
| 54 | SH0006 R | 593.5 | 602.5 | 99.3 | 99.3 | 4.2 | 9.0 | 12976.9 | 5.0 | 70 |
| 55 | SH0006 R | 609.9 | 616.5 | 100.0 | 100.0 | 4.4 | 6.6 | 8451.3 | 5.0 | 70 |
| 56 | SH0006 R | 616.5 | 626.0 | 100.0 | 100.0 | 4.8 | 8.1 | 8735.9 | 5.0 | 70 |
| 57 | SH0006 X | 584.0 | 588.0 | 98.3 | 96.7 | 3.5 | 2.9 | 6630.0 | 5.0 | 46 |
| 58 | SH0006 X | 588.0 | 591.0 | 89.3 | 67.3 | 2.9 | 3.0 | 3756.7 | 5.0 | 51 |
| 59 | SH0006 X | 591.0 | 600.9 | 96.6 | 95.2 | 3.7 | 9.9 | 11340.0 | 5.0 | 53 |
| 60 | SH0006 X | 601.0 | 603.0 | 100.0 | 100.0 | 3.4 | 2.0 | 360.0 | 5.0 | 55 |
| 61 | SH0006 X | 603.5 | 606.0 | 100.0 | 92.8 | 3.0 | 2.5 | 360.0 | 5.0 | 55 |

| Seg. | code | begin marker | end marker | average DS | average CS | average RS | length (miles) | AADT | Pav. type | speed limit |
|---|---|---|---|---|---|---|---|---|---|---|
| 62 | SH0006 X | 606.5 | 609.2 | 100.0 | 100.0 | 4.4 | 2.6 | 1196.7 | 5.0 | 55 |
| 63 | SH0006 X | 611.1 | 611.6 | 100.0 | 100.0 | 4.8 | 0.5 | 3370.0 | 5.0 | 55 |
| 64 | SH0006 X | 612.4 | 614.3 | 100.0 | 85.8 | 3.1 | 1.9 | 5320.0 | 5.0 | 55 |
| 65 | SH0007 K | 610.0 | 616.5 | 100.0 | 100.0 | 4.1 | 6.5 | 3084.6 | 10.0 | 70 |
| 66 | SH0007 K | 616.5 | 618.9 | 100.0 | 90.6 | 3.2 | 2.4 | 3420.0 | 10.0 | 70 |
| 67 | SH0007 K | 618.9 | 628.5 | 96.8 | 95.9 | 3.8 | 8.5 | 3616.7 | 5.0 | 56 |
| 68 | SH0007 K | 628.5 | 632.0 | 77.3 | 77.3 | 4.0 | 3.5 | 2485.7 | 5.0 | 55 |
| 69 | SH0007 K | 632.0 | 641.0 | 97.7 | 97.2 | 3.3 | 9.0 | 3044.4 | 5.0 | 55 |
| 70 | SH0007 K | 641.0 | 644.0 | 94.0 | 90.3 | 3.2 | 3.0 | 4666.7 | 5.0 | 53 |
| 71 | SH0007 K | 644.0 | 646.0 | 75.0 | 51.0 | 2.6 | 2.0 | 3900.0 | 5.0 | 55 |
| 72 | SH0007 K | 646.0 | 648.0 | 91.8 | 84.5 | 3.2 | 2.0 | 3900.0 | 5.0 | 55 |
| 73 | SH0007 K | 648.0 | 651.0 | 73.3 | 68.2 | 2.9 | 3.0 | 2816.7 | 5.0 | 55 |
| 74 | SH0007 K | 651.0 | 655.0 | 89.3 | 89.1 | 3.2 | 4.0 | 2287.5 | 5.0 | 55 |
| 75 | SH0007 K | 655.0 | 661.8 | 92.6 | 92.6 | 3.7 | 6.8 | 2135.7 | 5.0 | 55 |
| 76 | SH0014 K | 334.0 | 340.0 | 96.4 | 96.3 | 3.8 | 4.3 | 4522.2 | 5.0 | 56 |
| 77 | SH0014 K | 384.0 | 386.0 | 99.8 | 99.8 | 3.8 | 2.0 | 2575.0 | 5.0 | 51 |
| 78 | SH0014 K | 386.0 | 389.6 | 100.0 | 100.0 | 3.7 | 3.6 | 2385.7 | 10.0 | 55 |
| 79 | SH0019 K | 420.0 | 421.8 | 99.0 | 99.0 | 4.0 | 1.8 | 10550.0 | 5.0 | 58 |
| 80 | SH0019 K | 431.9 | 435.3 | 99.1 | 99.1 | 4.1 | 3.8 | 10288.9 | 5.0 | 60 |
| 81 | SH0019 L | 421.8 | 431.9 | 100.0 | 100.0 | 4.2 | 10.0 | 5821.4 | 5.0 | 69 |
| 82 | SH0019 L | 435.3 | 436.1 | 88.0 | 88.0 | 3.9 | 0.8 | 4200.0 | 5.0 | 60 |
| 83 | SH0019 R | 421.8 | 431.9 | 100.0 | 100.0 | 4.2 | 10.0 | 5821.4 | 5.0 | 69 |
| 84 | SH0019 R | 435.3 | 436.1 | 100.0 | 92.0 | 3.3 | 0.8 | 4200.0 | 5.0 | 60 |
| 85 | SH0021 K | 619.3 | 622.5 | 90.7 | 87.7 | 3.3 | 3.2 | 13200.0 | 5.0 | 57 |
| 86 | SH0021 K | 628.3 | 629.0 | 100.0 | 99.5 | 3.5 | 0.7 | 12900.0 | 5.0 | 60 |
| 87 | SH0021 K | 633.8 | 634.5 | 100.0 | 100.0 | 3.8 | 0.7 | 11800.0 | 5.0 | 70 |
| 88 | SH0021 K | 639.4 | 642.2 | 99.4 | 99.4 | 3.8 | 2.8 | 12850.0 | 5.0 | 59 |
| 89 | SH0021 K | 643.8 | 644.7 | 99.0 | 98.7 | 3.6 | 0.8 | 17933.3 | 5.0 | 43 |
| 90 | SH0021 K | 681.3 | 686.0 | 87.5 | 87.0 | 4.3 | 5.0 | 4600.0 | 5.0 | 70 |
| 91 | SH0021 K | 686.0 | 691.0 | 95.7 | 95.7 | 4.1 | 5.0 | 4040.0 | 5.0 | 63 |
| 92 | SH0021 K | 691.0 | 694.6 | 96.9 | 96.9 | 3.9 | 3.6 | 2300.0 | 5.0 | 68 |
| 93 | SH0021 L | 608.9 | 619.3 | 99.3 | 97.8 | 4.1 | 9.3 | 3872.5 | 5.0 | 70 |
| 94 | SH0021 L | 622.5 | 628.3 | 100.0 | 100.0 | 4.0 | 5.8 | 6195.8 | 5.0 | 68 |
| 95 | SH0021 L | 629.0 | 633.8 | 98.2 | 98.2 | 3.8 | 4.8 | 6450.0 | 5.0 | 70 |
| 96 | SH0021 L | 634.5 | 639.4 | 100.0 | 100.0 | 3.8 | 6.3 | 5226.9 | 5.0 | 70 |
| 97 | SH0021 R | 608.9 | 619.3 | 98.3 | 97.3 | 3.7 | 9.3 | 3872.5 | 5.0 | 70 |
| 98 | SH0021 R | 622.5 | 628.3 | 98.9 | 98.9 | 3.9 | 5.8 | 6195.8 | 5.0 | 68 |
| 99 | SH0021 R | 629.0 | 633.8 | 100.0 | 100.0 | 3.9 | 4.8 | 6450.0 | 5.0 | 70 |
| 100 | SH0021 R | 634.5 | 639.4 | 99.7 | 98.4 | 3.7 | 6.3 | 5226.9 | 5.0 | 70 |

| Seg. | code | begin marker | end marker | average DS | average CS | average RS | length (miles) | AADT | Pav. type | speed limit |
|---|---|---|---|---|---|---|---|---|---|---|
| 101 | SH0030 K | 622.0 | 625.5 | 94.6 | 85.3 | 3.1 | 3.5 | 12442.9 | 10.0 | 51 |
| 102 | SH0030 K | 625.5 | 629.0 | 96.3 | 96.3 | 4.0 | 3.4 | 11900.0 | 10.0 | 68 |
| 103 | SH0030 K | 629.0 | 632.9 | 100.0 | 100.0 | 4.0 | 3.7 | 6900.0 | 10.0 | 70 |
| 104 | SH0030 K | 634.0 | 641.0 | 100.0 | 100.0 | 4.1 | 7.0 | 6414.3 | 5.0 | 70 |
| 105 | SH0030 K | 641.0 | 649.0 | 99.9 | 99.9 | 4.2 | 8.0 | 4125.0 | 5.0 | 70 |
| 106 | SH0030 K | 649.0 | 656.5 | 88.8 | 86.7 | 3.3 | 7.5 | 5020.0 | 5.0 | 70 |
| 107 | SH0030 K | 656.5 | 667.0 | 96.6 | 96.6 | 3.8 | 9.8 | 4780.0 | 5.0 | 70 |
| 108 | SH0030 K | 667.0 | 671.0 | 100.0 | 100.0 | 4.2 | 4.0 | 10200.0 | 5.0 | 70 |
| 109 | SH0030 K | 673.8 | 674.5 | 98.0 | 97.5 | 3.7 | 0.7 | 19300.0 | 5.0 | 53 |
| 110 | SH0030 K | 676.3 | 678.9 | 91.5 | 91.5 | 3.6 | 2.7 | 3708.3 | 5.0 | 52 |
| 111 | SH0030 L | 671.0 | 673.8 | 100.0 | 99.8 | 3.8 | 2.8 | 6516.7 | 5.0 | 61 |
| 112 | SH0030 R | 671.0 | 673.8 | 100.0 | 100.0 | 4.2 | 2.8 | 6516.7 | 5.0 | 60 |
| 113 | SH0036 K | 522.7 | 533.0 | 96.6 | 96.1 | 4.0 | 9.1 | 5557.9 | 5.0 | 55 |
| 114 | SH0036 K | 533.0 | 536.0 | 85.2 | 85.2 | 4.4 | 3.0 | 6000.0 | 5.0 | 55 |
| 115 | SH0036 K | 536.0 | 540.0 | 85.5 | 85.5 | 4.1 | 4.1 | 7862.5 | 5.0 | 54 |
| 116 | SH0036 K | 540.0 | 543.5 | 81.4 | 81.4 | 3.8 | 3.4 | 5571.4 | 5.0 | 55 |
| 117 | SH0036 K | 543.5 | 553.5 | 96.7 | 96.7 | 4.4 | 10.0 | 4775.0 | 5.0 | 56 |
| 118 | SH0036 K | 553.5 | 556.0 | 74.2 | 74.2 | 4.5 | 2.5 | 7980.0 | 5.0 | 56 |
| 119 | SH0036 K | 556.0 | 558.0 | 91.5 | 85.0 | 3.3 | 2.0 | 8150.0 | 5.0 | 53 |
| 120 | SH0036 K | 559.0 | 566.0 | 100.0 | 100.0 | 4.5 | 6.0 | 7269.2 | 5.0 | 70 |
| 121 | SH0036 K | 566.0 | 573.1 | 92.6 | 92.6 | 4.5 | 7.1 | 9114.3 | 5.0 | 70 |
| 122 | SH0036 K | 576.1 | 577.3 | 100.0 | 100.0 | 3.7 | 1.5 | 14450.0 | 5.0 | 53 |
| 123 | SH0036 L | 558.0 | 559.0 | 100.0 | 100.0 | 3.6 | 1.0 | 3850.0 | 5.0 | 55 |
| 124 | SH0036 L | 573.1 | 573.6 | 100.0 | 100.0 | 3.7 | 0.4 | 5650.0 | 5.0 | 70 |
| 125 | SH0036 L | 577.3 | 580.4 | 100.0 | 100.0 | 4.1 | 3.1 | 3335.7 | 5.0 | 70 |
| 126 | SH0036 R | 558.0 | 559.0 | 100.0 | 99.5 | 3.3 | 1.0 | 3850.0 | 5.0 | 55 |
| 127 | SH0036 R | 573.1 | 573.6 | 100.0 | 100.0 | 3.6 | 0.4 | 5650.0 | 5.0 | 70 |
| 128 | SH0036 R | 577.3 | 580.4 | 100.0 | 100.0 | 3.9 | 3.1 | 3335.7 | 5.0 | 70 |
| 129 | SH0040 K | 0.0 | 0.2 | 100.0 | 43.0 | 2.2 | 0.2 | 5300.0 | 5.0 | 60 |
| 130 | SH0040 K | 624.2 | 624.5 | 100.0 | 78.0 | 2.8 | 0.3 | 4300.0 | 5.0 | 50 |
| 131 | SH0040 L | 0.2 | 624.2 | 100.0 | 100.0 | 4.2 | 2.6 | 2316.7 | 5.0 | 60 |
| 132 | SH0040 R | 0.2 | 624.2 | 97.5 | 97.5 | 4.0 | 2.6 | 2316.7 | 5.0 | 60 |
| 133 | SH0047 L | 0.0 | 418.7 | 99.4 | 99.1 | 4.1 | 7.1 | 2793.3 | 5.0 | 70 |
| 134 | SH0047 R | 0.0 | 414.0 | 95.0 | 95.0 | 4.4 | 2.4 | 2550.0 | 5.0 | 70 |
| 135 | SH0047 R | 414.0 | 418.7 | 96.8 | 96.8 | 4.3 | 4.7 | 2915.0 | 5.0 | 70 |
| 136 | SH0075 K | 325.1 | 328.0 | 83.6 | 78.0 | 3.0 | 2.1 | 808.0 | 5.0 | 55 |
| 137 | SH0075 K | 328.0 | 330.5 | 93.0 | 74.4 | 2.3 | 2.5 | 550.0 | 5.0 | 55 |
| 138 | SH0075 K | 330.5 | 333.5 | 88.3 | 88.3 | 3.2 | 3.0 | 621.7 | 5.0 | 55 |
| 139 | SH0075 K | 333.5 | 335.5 | 70.5 | 66.0 | 2.6 | 2.0 | 980.0 | 5.0 | 55 |

| Seg. | code | begin marker | end marker | average DS | average CS | average RS | length (miles) | AADT | Pav. type | speed limit |
|---|---|---|---|---|---|---|---|---|---|---|
| 140 | SH0075 K | 335.5 | 338.0 | 86.8 | 81.4 | 2.6 | 2.5 | 980.0 | 5.0 | 55 |
| 141 | SH0075 K | 338.0 | 340.5 | 87.0 | 81.6 | 2.7 | 2.5 | 1876.0 | 5.0 | 55 |
| 142 | SH0075 K | 340.5 | 346.0 | 97.9 | 89.9 | 2.9 | 5.5 | 2850.0 | 5.0 | 54 |
| 143 | SH0075 K | 346.0 | 356.0 | 90.3 | 87.4 | 2.9 | 10.0 | 1402.5 | 5.0 | 55 |
| 144 | SH0075 K | 356.0 | 360.0 | 84.0 | 76.6 | 2.6 | 2.5 | 1200.0 | 5.0 | 55 |
| 145 | SH0075 K | 360.0 | 363.0 | 92.2 | 85.7 | 2.7 | 3.0 | 2433.3 | 5.0 | 54 |
| 146 | SH0075 K | 363.0 | 368.0 | 97.4 | 85.6 | 2.7 | 5.0 | 1320.0 | 5.0 | 58 |
| 147 | SH0075 K | 368.0 | 375.5 | 93.8 | 89.7 | 2.8 | 7.5 | 1010.0 | 5.0 | 55 |
| 148 | SH0075 K | 375.5 | 378.0 | 87.0 | 77.4 | 2.5 | 2.5 | 1660.0 | 5.0 | 52 |
| 149 | SH0075 K | 378.0 | 385.5 | 96.9 | 95.5 | 3.0 | 7.5 | 1054.7 | 5.0 | 55 |
| 150 | SH0075 K | 385.5 | 390.0 | 88.1 | 85.9 | 2.8 | 4.3 | 760.0 | 5.0 | 57 |
| 151 | SH0075 K | 390.0 | 392.0 | 98.5 | 98.5 | 3.7 | 2.0 | 887.5 | 10.0 | 70 |
| 152 | SH0075 K | 392.0 | 398.5 | 95.6 | 95.6 | 4.0 | 6.5 | 1839.2 | 10.0 | 70 |
| 153 | SH0075 K | 398.5 | 402.0 | 87.6 | 64.4 | 2.9 | 3.5 | 5814.3 | 5.0 | 58 |
| 154 | SH0075 K | 402.0 | 407.5 | 98.4 | 98.4 | 3.9 | 5.5 | 1870.0 | 10.0 | 70 |
| 155 | SH0075 K | 407.5 | 410.0 | 95.8 | 95.8 | 4.1 | 2.2 | 870.0 | 10.0 | 70 |
| 156 | SH0075 K | 410.0 | 415.5 | 92.6 | 92.6 | 3.9 | 5.5 | 1385.5 | 8.0 | 70 |
| 157 | SH0075 K | 415.5 | 422.0 | 96.5 | 96.5 | 4.2 | 6.5 | 1500.0 | 8.0 | 70 |
| 158 | SH0075 K | 422.0 | 425.5 | 97.6 | 97.6 | 4.3 | 3.5 | 6800.0 | 8.0 | 70 |
| 159 | SH0075 K | 425.8 | 428.2 | 100.0 | 88.6 | 3.4 | 2.4 | 10700.0 | 5.0 | 48 |
| 160 | SH0075 K | 428.7 | 434.0 | 88.7 | 80.2 | 3.1 | 4.5 | 11100.0 | 5.0 | 42 |
| 161 | SH0075 K | 434.0 | 436.5 | 94.4 | 76.6 | 2.9 | 2.5 | 2520.0 | 5.0 | 70 |
| 162 | SH0075 K | 436.5 | 441.5 | 96.5 | 94.0 | 3.5 | 5.0 | 4020.0 | 5.0 | 70 |
| 163 | SH0075 K | 441.5 | 446.0 | 91.1 | 87.4 | 3.4 | 3.5 | 5228.6 | 5.0 | 60 |
| 164 | SH0090 K | 0.0 | 392.5 | 85.2 | 85.2 | 3.8 | 2.3 | 3600.0 | 5.0 | 55 |
| 165 | SH0090 K | 392.5 | 397.0 | 57.1 | 55.7 | 3.8 | 4.5 | 2888.9 | 5.0 | 55 |
| 166 | SH0090 K | 397.0 | 402.5 | 71.1 | 71.1 | 3.6 | 5.0 | 2463.6 | 5.0 | 55 |
| 167 | SH0090 K | 402.5 | 406.5 | 79.8 | 79.8 | 3.6 | 4.0 | 2125.0 | 5.0 | 55 |
| 168 | SH0090 K | 406.5 | 412.0 | 60.6 | 60.6 | 3.3 | 5.5 | 1927.3 | 5.0 | 55 |
| 169 | SH0090 K | 412.0 | 414.5 | 63.6 | 63.6 | 3.3 | 2.5 | 2200.0 | 5.0 | 55 |
| 170 | SH0090 K | 414.5 | 417.0 | 72.8 | 72.8 | 3.5 | 2.5 | 2500.0 | 5.0 | 55 |
| 171 | SH0090 K | 417.0 | 424.5 | 99.1 | 96.6 | 3.3 | 7.5 | 3753.3 | 5.0 | 56 |
| 172 | SH0090 K | 424.5 | 428.0 | 62.3 | 61.7 | 3.5 | 3.5 | 4985.7 | 5.0 | 54 |
| 173 | SH0090 K | 428.0 | 430.0 | 100.0 | 100.0 | 3.8 | 2.0 | 4800.0 | 5.0 | 70 |
| 174 | SH0090 K | 430.0 | 432.9 | 98.8 | 98.8 | 3.7 | 2.9 | 12200.0 | 5.0 | 68 |
| 175 | SH0105 K | 620.1 | 623.0 | 93.7 | 83.2 | 3.2 | 2.9 | 11333.3 | 5.0 | 55 |
| 176 | SH0105 K | 623.0 | 625.5 | 90.8 | 90.8 | 3.9 | 2.5 | 7600.0 | 5.0 | 64 |
| 177 | SH0105 K | 625.5 | 632.0 | 92.8 | 92.8 | 3.9 | 6.5 | 5261.5 | 10.0 | 70 |
| 178 | SH0105 K | 632.0 | 634.0 | 79.0 | 79.0 | 3.7 | 2.0 | 4550.0 | 5.0 | 70 |

| Seg. | code | begin marker | end marker | average DS | average CS | average RS | length (miles) | AADT | Pav. type | speed limit |
|---|---|---|---|---|---|---|---|---|---|---|
| 179 | SH0105 K | 634.0 | 639.5 | 99.8 | 99.8 | 4.3 | 5.5 | 5000.0 | 5.0 | 70 |
| 180 | SH0105 K | 639.5 | 647.7 | 96.8 | 91.4 | 3.5 | 5.3 | 6607.7 | 5.0 | 58 |
| 181 | SH0105 K | 647.8 | 648.8 | 81.0 | 78.7 | 3.2 | 1.0 | 13133.3 | 5.0 | 37 |
| 182 | SH0105 K | 650.2 | 655.2 | 99.9 | 99.9 | 4.0 | 5.0 | 8840.0 | 5.0 | 55 |
| 183 | SH0105 K | 655.2 | 659.0 | 100.0 | 100.0 | 3.8 | 3.7 | 7087.5 | 5.0 | 55 |
| 184 | SH0105 K | 659.0 | 663.5 | 100.0 | 100.0 | 3.6 | 4.5 | 7600.0 | 5.0 | 55 |
| 185 | SH0105 K | 663.5 | 668.0 | 99.8 | 99.8 | 4.1 | 3.9 | 6100.0 | 5.0 | 70 |
| 186 | SH0105 L | 0.0 | 620.1 | 91.5 | 78.5 | 2.8 | 0.3 | 4050.0 | 5.0 | 35 |
| 187 | SH0105 L | 647.7 | 647.8 | 75.0 | 74.0 | 3.2 | 0.1 | 5800.0 | 5.0 | 30 |
| 188 | SH0105 R | 0.0 | 620.1 | 74.5 | 72.5 | 2.8 | 0.3 | 4050.0 | 5.0 | 35 |
| 189 | SH0105 R | 647.7 | 647.8 | 70.0 | 37.0 | 2.4 | 0.1 | 5800.0 | 5.0 | 30 |
| 190 | SH0150 K | 670.0 | 671.2 | 93.3 | 79.3 | 3.2 | 1.2 | 3900.0 | 5.0 | 60 |
| 191 | SH0150 K | 671.3 | 679.3 | 97.4 | 83.0 | 3.2 | 8.0 | 3741.2 | 5.0 | 70 |
| 192 | SH0164 K | 619.5 | 626.0 | 99.8 | 99.8 | 4.1 | 6.1 | 2103.8 | 5.0 | 57 |
| 193 | SH0164 K | 626.0 | 631.0 | 90.0 | 88.7 | 3.7 | 5.2 | 2627.3 | 5.0 | 66 |
| 194 | SH0164 K | 631.0 | 634.5 | 70.2 | 68.8 | 3.1 | 3.0 | 2766.7 | 5.0 | 63 |
| 195 | SH0179 K | 620.5 | 629.0 | 91.4 | 91.4 | 3.8 | 7.7 | 2675.0 | 8.0 | 68 |
| 196 | SH0237 K | 0.0 | 448.0 | 100.0 | 100.0 | 3.9 | 2.4 | 2100.0 | 5.0 | 70 |
| 197 | SH0308 K | 412.0 | 412.4 | 87.0 | 78.0 | 3.0 | 0.4 | 13000.0 | 5.0 | 50 |
| 198 | SH0308 L | 412.4 | 413.3 | 87.5 | 73.0 | 2.9 | 0.9 | 5015.0 | 5.0 | 43 |
| 199 | SH0308 R | 412.4 | 413.3 | 89.5 | 85.5 | 3.2 | 0.9 | 5015.0 | 5.0 | 43 |
| 200 | SHOSR K | 0.0 | 607.5 | 100.0 | 95.8 | 2.9 | 3.5 | 580.0 | 5.0 | 70 |
| 201 | SHOSR K | 607.5 | 613.5 | 95.9 | 90.8 | 2.8 | 6.0 | 1531.7 | 5.0 | 70 |
| 202 | SHOSR K | 613.5 | 617.0 | 90.4 | 76.6 | 2.7 | 3.5 | 2285.7 | 5.0 | 70 |
| 203 | SHOSR K | 617.0 | 622.5 | 77.6 | 68.0 | 3.0 | 5.6 | 3190.9 | 5.0 | 70 |
| 204 | SHOSR K | 622.5 | 625.0 | 99.4 | 93.2 | 2.8 | 2.5 | 1460.0 | 5.0 | 70 |
| 205 | SHOSR K | 625.0 | 629.5 | 96.7 | 94.8 | 3.0 | 4.5 | 1000.0 | 5.0 | 70 |
| 206 | SHOSR K | 629.5 | 634.0 | 95.3 | 80.8 | 2.6 | 3.4 | 1062.5 | 5.0 | 70 |
| 207 | SHOSR K | 634.0 | 636.5 | 79.8 | 79.6 | 2.9 | 2.5 | 1050.0 | 10.0 | 55 |
| 208 | SHOSR K | 636.5 | 639.0 | 75.6 | 58.2 | 2.3 | 2.4 | 1050.0 | 10.0 | 55 |
| 209 | SHOSR K | 639.0 | 641.0 | 94.0 | 92.5 | 2.9 | 2.0 | 1050.0 | 10.0 | 55 |
| 210 | SHOSR K | 641.0 | 643.0 | 73.5 | 65.3 | 2.5 | 2.0 | 1475.0 | 10.0 | 55 |
| 211 | SHOSR K | 643.0 | 645.0 | 84.0 | 83.3 | 2.9 | 2.0 | 1750.0 | 10.0 | 55 |
| 212 | SHOSR K | 645.0 | 648.5 | 72.1 | 60.7 | 2.4 | 3.5 | 1150.0 | 10.0 | 55 |
| 213 | SHOSR K | 648.5 | 651.0 | 78.2 | 78.2 | 3.0 | 2.5 | 1150.0 | 10.0 | 55 |
| 214 | SHOSR K | 651.0 | 653.0 | 100.0 | 100.0 | 3.4 | 2.0 | 1100.0 | 10.0 | 55 |
| 215 | SHOSR K | 653.0 | 655.5 | 85.0 | 83.6 | 2.7 | 2.5 | 522.0 | 10.0 | 55 |
| 216 | SHOSR K | 655.5 | 658.5 | 68.2 | 55.5 | 2.4 | 3.0 | 570.0 | 10.0 | 55 |
| 217 | SHOSR K | 658.5 | 662.5 | 66.1 | 63.5 | 2.6 | 4.0 | 465.0 | 10.0 | 55 |

| Seg. | code | begin marker | end marker | average DS | average CS | average RS | length (miles) | AADT | Pav. type | speed limit |
|---|---|---|---|---|---|---|---|---|---|---|
| 218 | SHOSR K | 662.5 | 667.3 | 79.7 | 66.4 | 2.5 | 4.8 | 569.0 | 10.0 | 55 |
| 219 | SL0083 K | 598.0 | 598.5 | 100.0 | 71.0 | 2.2 | 0.5 | 2600.0 | 5.0 | 55 |
| 220 | SL0160 K | 632.0 | 633.0 | 84.0 | 60.0 | 2.2 | 0.5 | 980.0 | 5.0 | 30 |
| 221 | SL0208 K | 622.0 | 623.0 | 90.0 | 52.0 | 1.5 | 0.5 | 410.0 | 5.0 | 55 |
| 222 | SL0262 K | 616.0 | 617.0 | 84.0 | 43.0 | 1.4 | 0.6 | 310.0 | 5.0 | 55 |
| 223 | SL0361 K | 402.0 | 403.0 | 100.0 | 90.0 | 3.0 | 0.2 | 280.0 | 5.0 | 55 |
| 224 | SL0429 K | 422.0 | 422.1 | 100.0 | 100.0 | 2.8 | 0.1 | 170.0 | 5.0 | 55 |
| 225 | SL0429 L | 422.1 | 422.2 | 100.0 | 46.0 | 1.3 | 0.1 | 185.0 | 5.0 | 55 |
| 226 | SL0429 R | 422.1 | 422.2 | 100.0 | 90.0 | 3.0 | 0.1 | 185.0 | 5.0 | 55 |
| 227 | SS0059 K | 404.0 | 405.0 | 88.0 | 88.0 | 3.9 | 0.2 | 1400.0 | 5.0 | 55 |
| 228 | SS0067 K | 650.0 | 651.0 | 66.0 | 31.0 | 1.8 | 0.3 | 720.0 | 10.0 | 55 |
| 229 | SS0104 K | 0.0 | 389.0 | 100.0 | 83.0 | 1.9 | 1.0 | 250.0 | 10.0 | 55 |
| 230 | SS0104 K | 389.0 | 389.1 | 100.0 | 90.0 | 2.0 | 0.1 | 250.0 | 5.0 | 55 |
| 231 | SS0113 K | 354.0 | 354.9 | 100.0 | 100.0 | 2.6 | 0.9 | 140.0 | 5.0 | 35 |
| 232 | SS0114 K | 616.0 | 617.1 | 100.0 | 100.0 | 2.8 | 0.6 | 120.0 | 5.0 | 55 |
| 233 | SS0125 K | 604.0 | 605.0 | 85.0 | 85.0 | 3.9 | 0.5 | 1100.0 | 10.0 | 40 |
| 234 | SS0174 K | 0.0 | 391.0 | 100.0 | 100.0 | 3.4 | 0.4 | 2900.0 | 5.0 | 55 |
| 235 | SS0231 K | 612.0 | 613.0 | 100.0 | 64.0 | 1.6 | 0.6 | 330.0 | 5.0 | 55 |
| 236 | SS0234 K | 432.0 | 433.0 | 85.0 | 66.0 | 2.3 | 0.4 | 860.0 | 10.0 | 55 |
| 237 | SS0515 K | 636.0 | 636.8 | 97.5 | 94.0 | 3.2 | 0.8 | 5400.0 | 10.0 | 45 |

# APPENDIX D: DISTRESS FUNCTIONS COEFFICIENTS

**Table 30.** DS performance function coefficients for different reliability levels

| Type of treatment | type of traffic | Coeff. | DS | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 95% | 80% | 65% | 50% | 35% | 20% | 5% |
| PM | Low | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 2.235 | 2.235 | 2.235 | 2.235 | 2.235 | 2.235 | 2.235 |
| | | A | 3.950 | 5.520 | 7.514 | 8.971 | 10.429 | 12.423 | 13.993 |
| | Medium | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 1.256 | 1.256 | 1.256 | 1.256 | 1.256 | 1.256 | 1.256 |
| | | A | 3.654 | 5.224 | 7.218 | 8.676 | 10.133 | 12.127 | 13.697 |
| | High | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 1.255 | 1.255 | 1.255 | 1.255 | 1.255 | 1.255 | 1.255 |
| | | A | 5.410 | 6.980 | 8.974 | 10.432 | 11.889 | 13.883 | 15.453 |
| LR | Low | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 2.235 | 2.235 | 2.235 | 2.235 | 2.235 | 2.235 | 2.235 |
| | | A | 4.320 | 5.800 | 8.200 | 10.901 | 13.602 | 16.002 | 17.482 |
| | Medium | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 1.405 | 1.405 | 1.405 | 1.405 | 1.405 | 1.405 | 1.405 |
| | | A | 5.857 | 7.337 | 9.737 | 12.438 | 15.139 | 17.539 | 19.019 |
| | High | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 1.255 | 1.255 | 1.255 | 1.255 | 1.255 | 1.255 | 1.255 |
| | | A | 5.886 | 7.366 | 9.766 | 12.467 | 15.168 | 17.568 | 19.048 |
| MR | Low | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 2.235 | 2.235 | 2.235 | 2.235 | 2.235 | 2.235 | 2.235 |
| | | A | 5.420 | 6.910 | 9.410 | 12.818 | 16.225 | 18.725 | 20.215 |
| | Medium | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 1.498 | 1.498 | 1.498 | 1.498 | 1.498 | 1.498 | 1.498 |
| | | A | 7.694 | 9.184 | 11.684 | 15.092 | 18.499 | 20.999 | 22.489 |
| | High | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 1.255 | 1.255 | 1.255 | 1.255 | 1.255 | 1.255 | 1.255 |
| | | A | 7.048 | 8.538 | 11.038 | 14.446 | 17.854 | 20.354 | 21.844 |
| HR | Low | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 2.455 | 2.455 | 2.455 | 2.455 | 2.455 | 2.455 | 2.455 |
| | | A | 7.610 | 10.100 | 12.800 | 16.077 | 19.354 | 22.054 | 24.544 |
| | Medium | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 1.807 | 1.807 | 1.807 | 1.807 | 1.807 | 1.807 | 1.807 |
| | | A | 10.401 | 12.891 | 15.591 | 18.868 | 22.145 | 24.845 | 27.335 |

| Type of treatment | type of traffic | Coeff. | DS | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 95% | 80% | 65% | 50% | 35% | 20% | 5% |
| | High | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 1.255 | 1.255 | 1.255 | 1.255 | 1.255 | 1.255 | 1.255 |
| | | A | 8.197 | 10.687 | 13.387 | 16.664 | 19.941 | 22.641 | 25.131 |

**Table 31.** CS performance function coefficients for different reliability levels

| Type of treatment | type of traffic | Coeff. | CS | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 95% | 80% | 65% | 50% | 35% | 20% | 5% |
| PM | Low | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 4.009 | 4.009 | 4.009 | 4.009 | 4.009 | 4.009 | 4.009 |
| | | A | 3.820 | 5.340 | 6.430 | 7.571 | 8.711 | 9.801 | 11.321 |
| | Medium | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 13.393 | 13.393 | 13.393 | 13.393 | 13.393 | 13.393 | 13.393 |
| | | A | 2.517 | 4.037 | 5.127 | 6.268 | 7.408 | 8.498 | 10.018 |
| | High | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 5.743 | 5.743 | 5.743 | 5.743 | 5.743 | 5.743 | 5.743 |
| | | A | 2.143 | 3.663 | 4.753 | 5.893 | 7.034 | 8.124 | 9.644 |
| LR | Low | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 4.009 | 4.009 | 4.009 | 4.009 | 4.009 | 4.009 | 4.009 |
| | | A | 6.860 | 8.420 | 9.400 | 10.327 | 11.254 | 12.234 | 13.794 |
| | Medium | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 21.864 | 21.864 | 21.864 | 21.864 | 21.864 | 21.864 | 21.864 |
| | | A | 4.761 | 6.321 | 7.301 | 8.227 | 9.154 | 10.134 | 11.694 |
| | High | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 9.924 | 9.924 | 9.924 | 9.924 | 9.924 | 9.924 | 9.924 |
| | | A | 4.309 | 5.869 | 6.849 | 7.776 | 8.703 | 9.683 | 11.243 |
| MR | Low | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 4.009 | 4.009 | 4.009 | 4.009 | 4.009 | 4.009 | 4.009 |
| | | A | 9.910 | 11.650 | 13.320 | 15.050 | 16.780 | 18.450 | 20.190 |
| | Medium | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 25.912 | 25.912 | 25.912 | 25.912 | 25.912 | 25.912 | 25.912 |
| | | A | 6.037 | 7.777 | 9.447 | 11.178 | 12.908 | 14.578 | 16.318 |
| | High | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 9.924 | 9.924 | 9.924 | 9.924 | 9.924 | 9.924 | 9.924 |
| | | A | 4.278 | 6.018 | 7.688 | 9.418 | 11.149 | 12.819 | 14.559 |
| HR | Low | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 4.009 | 4.009 | 4.009 | 4.009 | 4.009 | 4.009 | 4.009 |

| **Type of treatment** | **type of traffic** | **Coeff.** | **CS** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | **95%** | **80%** | **65%** | **50%** | **35%** | **20%** | **5%** |
| | | A | 9.970 | 11.810 | 13.800 | 15.050 | 16.300 | 18.290 | 20.130 |
| | Medium | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 29.265 | 29.265 | 29.265 | 29.265 | 29.265 | 29.265 | 29.265 |
| | | A | 8.203 | 10.043 | 12.033 | 13.283 | 14.533 | 16.523 | 18.363 |
| | High | α | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| | | β | 90.157 | 90.157 | 90.157 | 90.157 | 90.157 | 90.157 | 90.157 |
| | | A | 12.732 | 14.572 | 16.562 | 17.812 | 19.062 | 21.052 | 22.892 |