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A Stochastic Approach for Pavement Condition Projections and Budget Needs for the MTC Pavement Management System

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Dedication

To my wife Carmen that helped me and supported me to obtain my Ph.D. and to my daughters Irene and Patricia who also supported me. Thank You

A STOCHASTIC APPROACH FOR PAVEMENT CONDITION PROJECTIONS AND BUDGET NEEDS FOR THE MTC PAVEMENT MANAGEMENT SYSTEM

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Abstract

Pavement management decision-making is the most important task for officials in transportation agencies, who develop maintenance and rehabilitation programs. Information about historical pavement network performance is needed for decision-making; pavement management systems (PMS) provide means to organize road network data to improve the pavement network condition. PMS have prediction performance models to forecast the future condition of the pavement networks with information required for decision-making; these models can be deterministic or probabilistic. Pavement performance deterministic models are commonly used in PMS, but they do not consider the uncertainty in forecasting pavement performance. Pavement performance depends on many random factors like traffic loads and environmental effects.

This research presents a stochastic approach to address the variability of the random factors involved in pavement performance prediction. The stochastic approach consists in two methods: probability-based performance curves and probabilistic performance-based scenarios considering different pavement deterioration rates over time. Data form PMS of the Metropolitan Transportation Commission (MTC) in the San Francisco, California Bay Area was used to develop the stochastic approach.

The new approach will aid transportation agencies to be aware of the possible performance scenarios which will affect treatment selection and budget needs estimate in the planning horizon for maintenance and rehabilitation programs.

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Chapter 1: Introduction

Transportation agencies need large amounts of money to preserve their pavement networks in good condition. The development of cost-effective maintenance and rehabilitation programs requires reliable information on pavement performance in order to select the right treatment for the pavement sections.

Pavement management is an approach that assists decision-makers finding cost-effective maintenance and rehabilitation strategies to preserve the pavement network in a functional condition over time. In pavement management there are three main levels of practice: strategic, network (tactical), and project (operational) level. At the strategic level, decisions are made at the highest level within the agency, by individuals in the upper management, long-term goal and policies are set for the entire pavement network at this level. At the network level, multi-year maintenance and rehabilitation programs are prepared for the entire network considering different strategies, results of network level analysis are presented to the decision-makers at the strategic level to assist them in setting goals and policies for the pavement network. At the project level, pavement sections are individually studied to determine the most cost-effective maintenance or rehabilitation treatment for each section and decisions are focused over a short period of time (AASHTO 2012).

In the past, managers made pavement management decisions based on personal judgment and experience (Sundin and Braban-Ledoux 2001). However, due to the complexity of pavement management practices and the large amount of data involved in the analysis, pavement management systems (PMS) are used by the

agencies to support their decision making process. PMS uses performance models to forecast pavement condition to identify treatment needs, to prioritize funding allocation when budgets are constrained, and to determine the impact of maintenance and rehabilitation strategies on the pavement network.

1.1 Pavement Performance Models

Pavement performance models forecast pavement network condition and are used in the pavement management decision-making process to determine where, what, and when maintenance and rehabilitation treatments should be applied. Performance models are classified in two groups: deterministic and probabilistic. In a deterministic performance model, every predicted set of variables is uniquely determined by parameters defined by single values in previous states. Therefore, deterministic models always result in the same values for a given set of initial conditions. Conversely, in a stochastic model, randomness is present, and variable states are not described by single values, but rather by probability distributions.

In deterministic performance models, the future pavement condition is predicted using mechanistic, empirical, or mechanistic-empirical methods (Abaza 2004). The mechanistic model is based on mechanistic rational principles that govern pavement behavior under load; while the empirical model is based on site observations and statistical techniques. A combination of these two models is known as mechanistic-empirical (Li 2005).

Probabilistic prediction models predict the future pavement condition using probabilities. Markovian, and Bayesian are examples of probabilistic models (Abaza et al 2004). The Markovian model uses a probability transition matrix to describe the

probabilities of a particular change in pavement state that is applied to the initial pavement condition to forecast the future condition. The Bayesian approach involves a prior probability distribution to express the uncertainty of pavement performance prediction. The prior probability distribution is normally developed from expert knowledge. With data obtained from field observations, the prior distribution is modified and becomes a posterior distribution. The posterior distribution represents a pavement performance conditional state given a prior pavement performance state (Aven and Kvaloy 2002, Park et al 2008).

1.2 Research Problem

Agencies often have budget constraints for pavement maintenance and rehabilitation programs, and must allocate their funds in a cost-effective manner to preserve their pavement networks in good condition. Pavement performance prediction models are required to determine the treatment needs over the planning horizon.

However, uncertainty is always present in pavement performance predictions. Uncertainty is inherent in traffic projections, weather prediction, and changes in the pavement structural capacity. Deterministic performance models do not take into account this uncertainty and predict future pavement condition scenarios with single values (Abaza 2004). Hence, the problem to address in this dissertation is how to model the uncertainty that is present when forecasting pavement condition and how to incorporate this model into the pavement management decision-making process. The level of uncertainty in pavement performance prediction can be addressed using probability functions to determine the likelihood of a certain pavement condition scenario to occur in the future. Therefore, a stochastic approach based on chance or

probability of occurrence of a future pavement condition will better model the inherent uncertainty that is present when forecasting the pavement condition.

1.3 MTC Pavement Performance Model

The Metropolitan Transportation Commission (MTC) in the San Francisco California Bay Area uses a deterministic pavement performance prediction model based on the pavement condition index (PCI).

PCI projections follow a curve plotted with equation 1.1, as shown in Figure 1.1.

$$PCI_{PRO} = 100 - \frac{\rho}{\left(\ln\left(\frac{\alpha}{AGE}\right)\right)^{\frac{1}{\beta}}} \quad (1.1)$$

PCI_{PRO} = Projected PCI value at a given year

ρ = regression constant that controls the age at which the inflection point in the curve occurs. As an example, Figure 1.1 shows ρ with the inflection point at age 7.

α = regression constant that controls the age at which the curve becomes asymptotic. As an example, Figure 1.1 shows that the asymptote begins at age 29, the PCI value at this age is negative and it is not taken into account in the practice because when PCI reaches the value of 0, it means that the pavement has already failed completely.

β = regression constant that controls how sharply the curve bends, β represents the slope of PCI over time at the point of inflection as shown in Figure 1.1

AGE = number of years since construction.

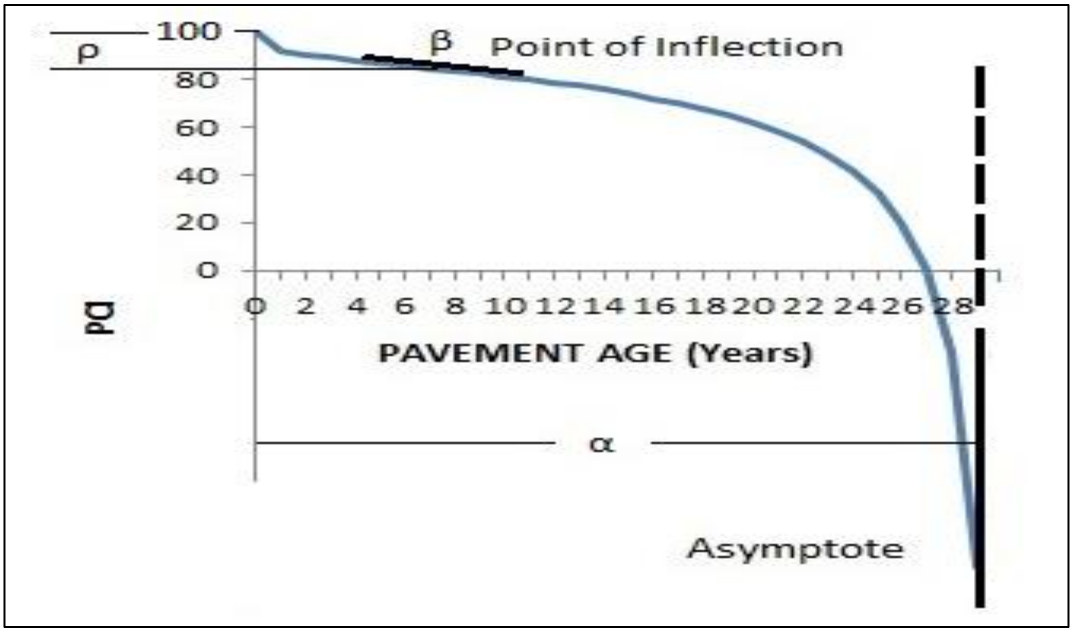

Figure 1.1 PCI Performance Curve Parameters from equation 1.1

The PCI projection equation was developed in 1981 by a group of experts working for MTC (MTC 1987). Each functional class and pavement type has a set of alpha, beta, and rho parameters that are used in equation 1.1 to project the pavement condition. However, pavement sections of the same functional class and surface type may show different PCI projections varying the alpha, beta, and rho parameters.

As shown in Figure 1.2, the variability in the expected pavement performance generates uncertainty in the prediction of PCI values, which can vary significantly at the same pavement age. The average PCI curve is plotted using the default α, β, and ρ parameters in equation 1.1; the optimistic or high performance PCI (above the average) and the pessimistic or low performance PCI (below the average) curves are plotted using different α, β, and ρ parameters. In this example, the variability of PCI at age 10 is 29 points (PCI values vary from 84 to 55). More pavement performance curves, between the pessimistic PCI and the optimistic PCI curves, can be developed for a set of pavement performance scenarios.

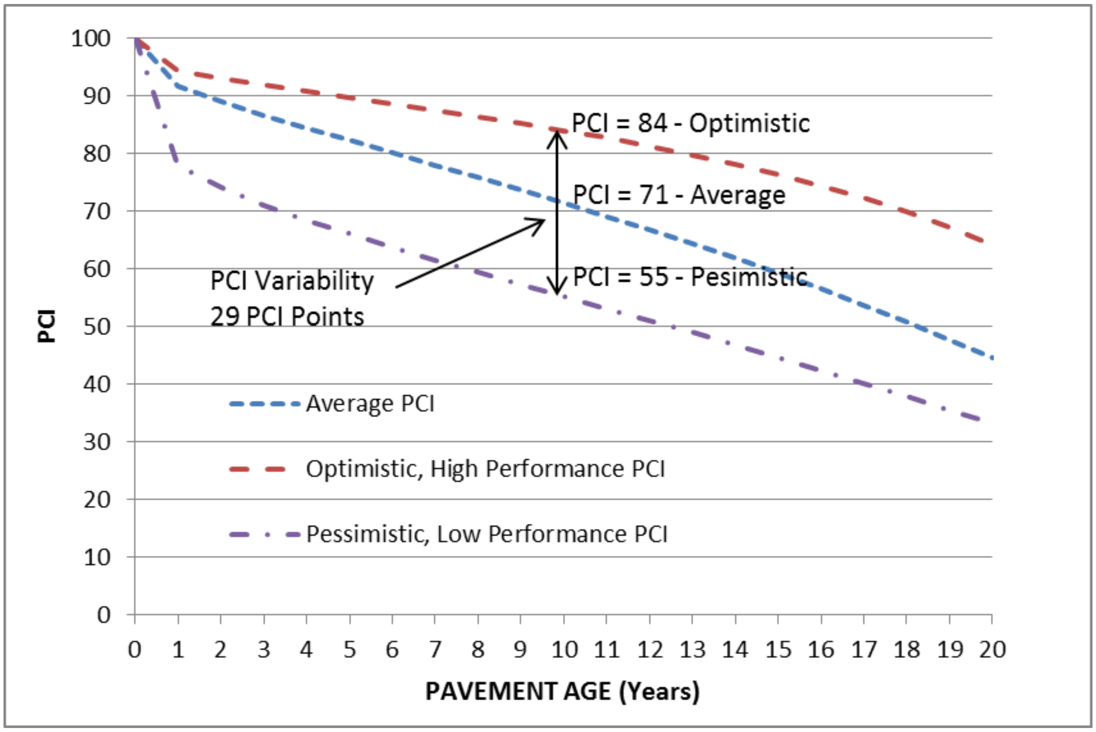

Figure 1.2 Variability of the PCI Over Time

In a deterministic approach, maintenance and rehabilitation funding decisions are based on a set of single values for the pavement condition over time without addressing the uncertainty of PCI future values when forecasting pavement performance. At present, decision-makers that use the MTC Pavement Management System (MTC-PMS), have a narrow perspective of the expected pavement network performance over time, because the forecasting model delivers a single value for pavement condition, as shown in the average PCI curve in Figure 1.2.

1.4 Research Objectives

The purpose of this research is to develop a stochastic approach to address the uncertainty in pavement performance predictions to enhance the current pavement management decision making process at the network level. The first objective of this

research is to study the behavior of PCI values over time to develop probability-based pavement performance curves (PBPPC). The second objective is to apply the probability-based performance curves in a target-driven approach, to maintain an agency's PCI target value over the planning period and to obtain the corresponding budget needs at different probability levels. Finally, a third objective is to develop a probabilistic pavement performance-based scenario (PPPBS) approach using probability distributions to account for different pavement performance deterioration rates.

Due to the large amount of historical pavement performance data available in the system, the MTC-PMS was selected to develop the stochastic approach. With the implementation of a stochastic approach, transportation agencies will know better the variability of pavement condition projections as well as their impact in the treatment prioritization process and budget estimates.

1.5 Research Methodology

The research methodology is shown in Figure 1.3 and includes the following tasks:

- Task 1 is identifying the research problem as already described in 1.1.
- Task 2 is formulating the research objectives as explained in 1.2.
- Task 3 is performing a literature review on pavement management, pavement performance models, decision trees, and scenario analysis.
- Task 4 is the development of probability-based pavement performance curves. PCI inspection data is collected, sorted by age, and clustered in yearly bins.

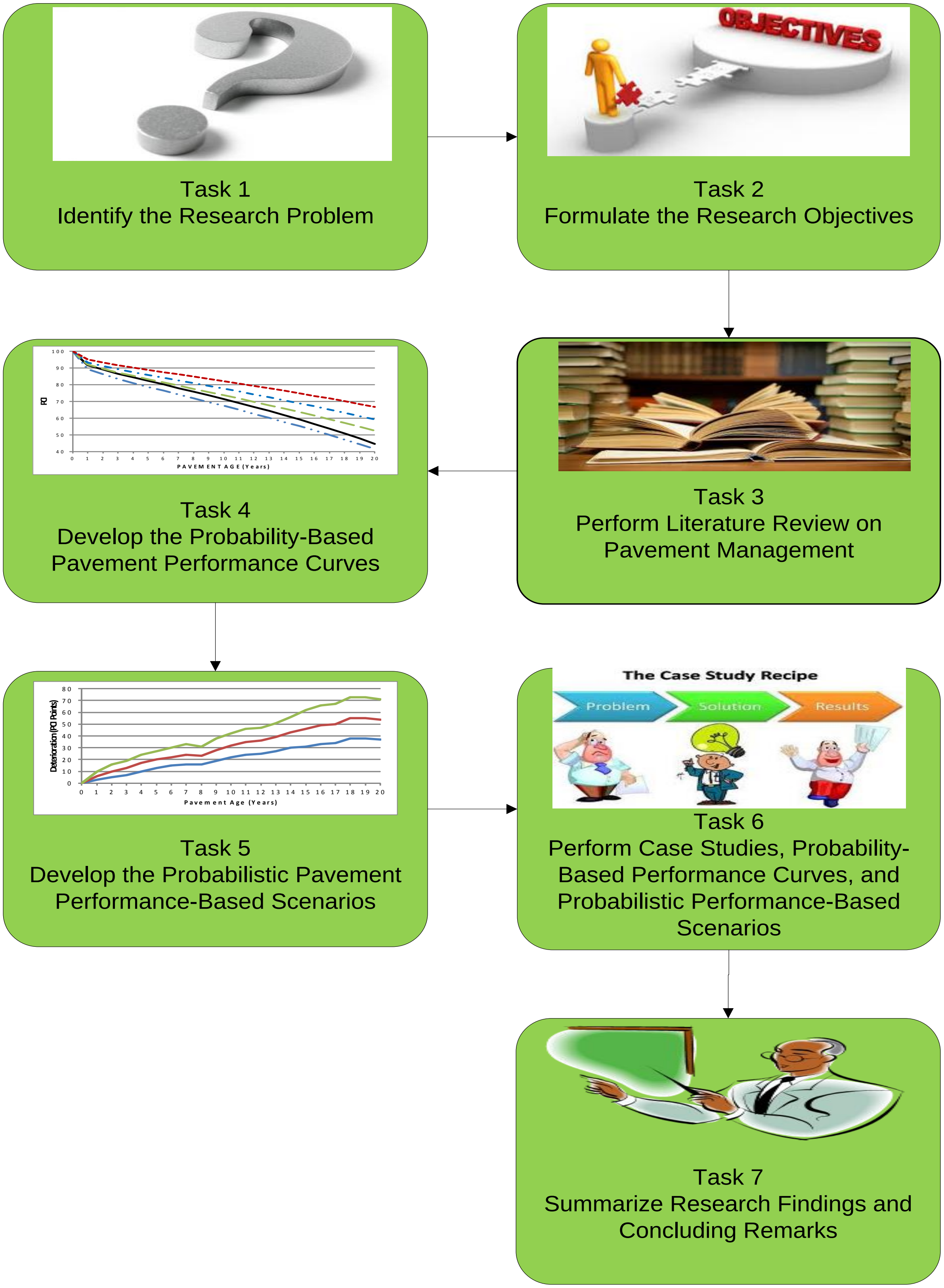

Figure 1.3 Summary of the Research Methodology Approach

Data collected include: PCI observed values at inspection dates, and construction and maintenance treatment dates. These data are extracted from the Cities of Belmont, San Carlos, Milpitas, San Ramon, San Anselmo, and Santa Rosa in California; and from the Marion County in Oregon.

A filter process is conducted to clean the data from possible errors in the records; for example very low PCI values at early ages and very high PCI values near the end of the pavement service life are carefully reviewed and removed if they are markedly different from other values in the yearly bins.

Using the PCI filtered values, probability distributions are fitted for each year and means and standard deviations are calculated to compute PCI percentile values at different probability performance levels. The PCI points obtained for a probability performance level are joined to build a probability-based pavement performance curve (PBPPC). Regression analysis is used to find the alpha, beta and rho parameters for each PBPPC.

- Task 5 is the development of the probabilistic pavement performance-based scenario approach based on the cumulative pavement deterioration. A new pavement has a PCI value of 100; therefore the cumulative pavement deterioration of a pavement section at the inspection date can be established as 100 minus PCI value obtained from the inspection. The pavement cumulative deterioration, in terms of PCI points, is calculated for each section and clustered by age. Probability distributions are fitted to the cumulative deterioration PCI points for each year of the service life. Low, medium, and high deterioration bands are established, and annual cumulative deterioration probability

distributions are truncated, using the limits for each deterioration band, to calculate only cumulative deterioration PCI points within the limits in each deterioration band.

- Task 6 is the application of the PBPPCs conducting needs analyses to identify pavement sections for maintenance and rehabilitation, and to estimate budget needs to preserve the pavement network in good condition. It also presents target driven analyses at different probability levels, with the corresponding budgets to achieve a desired target PCI value. The probabilistic pavement performance-based scenarios approach (PPPBS) is applied to a needs analysis using truncated Normal distributions of the cumulative pavement deterioration to model low, medium, and high pavement deterioration scenarios.
- Task 7 is summarizing conclusions and recommendations as a result of the research study.

1.6 Organization of the Dissertation

The dissertation is organized in five chapters as shown in Figure 1.4

Chapter 1 is an introduction to the research work, outlining pavement management fundamental concepts, presenting the research problem and objectives, and describing a brief outline of the methodology used in the study.

Chapter 2 presents a literature review on pavement management concepts and elements. Different types of performance models used in pavement management systems are discussed as well as the use of decision trees and scenario analysis to identify treatment needs and formulate budgets for maintenance and rehabilitation programs.

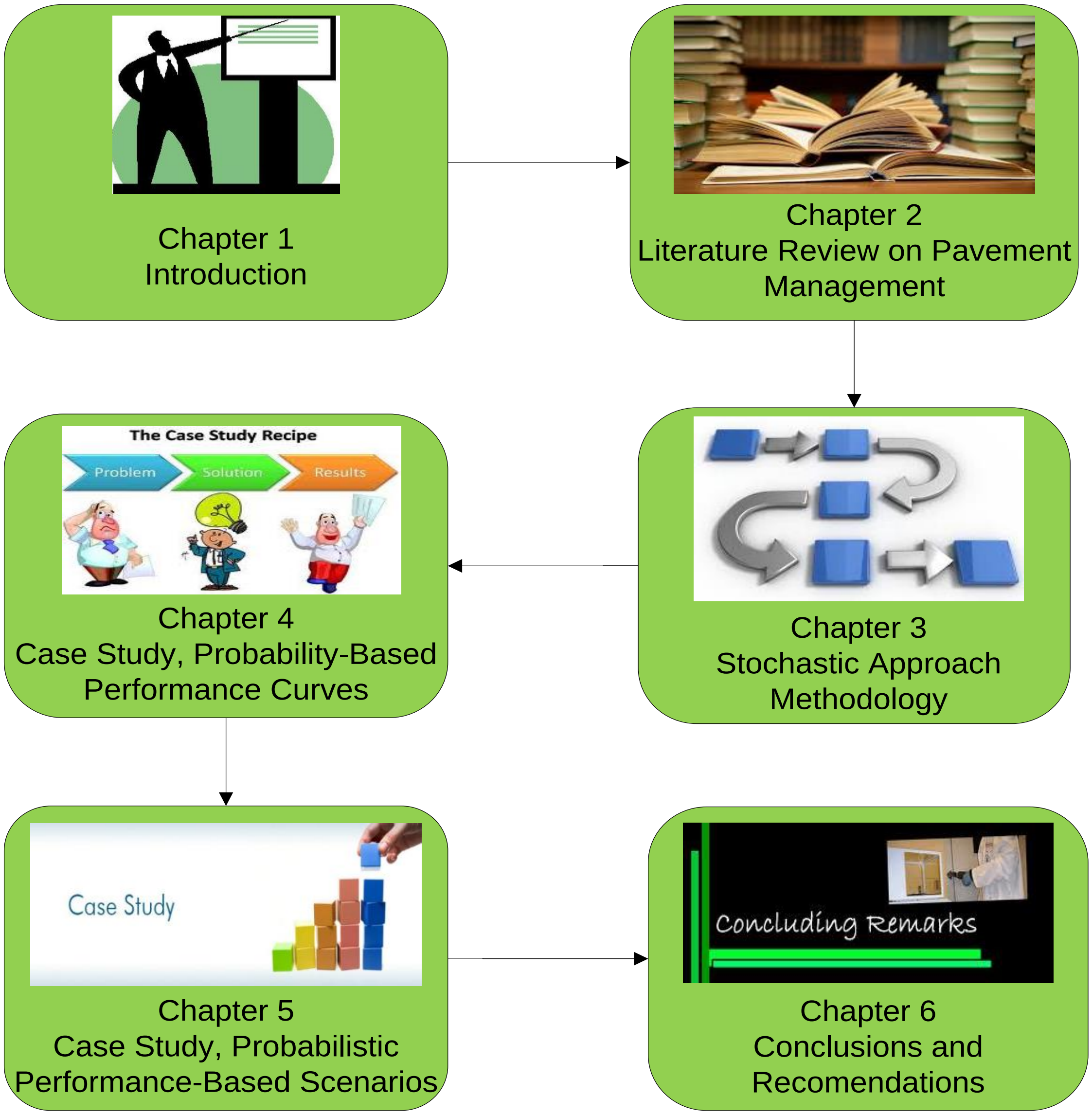

Figure 1.4 Overall Organization of the Dissertation

Chapter 3 describes the development of the stochastic approach for pavement condition projections and budget needs estimates. The process to develop the probability-based pavement performance curves and the probabilistic pavement performance-based scenario methodology is presented. The implementation of this new approach in the pavement management process is also discussed in this Chapter.

Chapter 4 presents two case studies to illustrate the application of the stochastic approach developed in Chapter 3. In the first case study, PBPPCs are used to perform a needs analysis. The needs analysis consists on identifying pavement sections for treatment and formulating a budget estimate to preserve the pavement network in an optimum condition. In the second case study, a PCI target driven analysis is conducted setting a desired target PCI value for the pavement network through the analysis period, and determining treatments and budget needed to achieve the targeted PCI.

Chapter 5 presents one case study that illustrates the application of the probabilistic pavement performance-based scenario approach in a needs analysis for low, medium, and high pavement performance deterioration scenarios.

Chapter 6 summarizes the conclusions of the study with major findings and recommendations for implementation; emphasizes the significance of the research and its contributions to the pavement management decision-making process; and presents ideas for future research work.

Chapter 2: Literature Review on Pavement Management

2.1 Pavement Management Concepts

Pavement management is a systematic approach to manage a pavement network in order to develop cost-effective maintenance and rehabilitation strategies to preserve the network at the desired level of service. To implement this approach, highway agencies use pavement management systems (PMS) as a tool to decide on what sections to apply treatments, and to formulate the corresponding budget. According to AASHTO, "A pavement management system (PMS) is a set of tools or methods that assist decision-makers in finding optimum strategies for providing, evaluating, and maintaining pavements in a serviceable condition over a period of time" (AASHTO 2012).

According to AASHTO, the fundamental elements of a network-level pavement management system are:

- An inventory of the pavement sections with information about location, functional class, number of lanes, pavement type, dates of construction, and maintenance and rehabilitation treatment history.
- Condition assessment, collecting pavement distress data (e.g. type, amount, and severity), ride quality, structural integrity, and skid resistance.
- Determination of future treatment and budget needs based on performance models. After the inventory and condition assessment is completed, a forecast of the future pavement section condition is made over a specified planning period, recommending maintenance and rehabilitation treatments over time to preserve the pavement network in optimal condition without funding constraints.

- Once the needs analysis is performed, candidate sections are prioritized to allocate available funds.
- As a last element, the impact of funding allocation scenarios and maintenance programs is compared to identify the most cost-effective strategy among the alternatives (AASHTO 2001).

Establishing a sound PMS with well-documented information about future pavement condition, improves the efficiency of the decision-making process on maintenance and rehabilitation actions, helping preserve the pavement network in a serviceable and safe condition at a minimum cost (George 2000). PMS should be capable of projecting the future pavement condition to identify future treatment needs and to forecast annual maintenance and rehabilitation budgets (AASHTO 2002). Many agencies use PMS with the aim to maximize the overall performance of the pavement network while minimizing the overall budget (Chang-Albitres 2007). The key of pavement management decisions is having reliable information available about pavement performance.

Pavement management is performed in three main management levels: strategic, network, and project. At the strategic management level long-term goal and policies are set for the entire pavement network. At the network management level, overall needs for the whole pavement network are determined, maintenance and rehabilitation programs are developed, and budget needs to achieve pavement performance goals are established. Decisions on how to allocate available funds are made based on the agency's criteria and policies. Data collected for the prediction of the future pavement condition is limited in detail at the network management level, but it

is considered sufficient to assess the pavement condition to identify treatment needs and budget (AASHTO 2012). At the project management level, officials are responsible for implementing the maintenance and rehabilitation work plan. Data collected at this level is very detailed and includes surveys to evaluate the pavement structural capacity, traffic, and environmental conditions for individual sections (AASHTO 2012, Schram 2008).

The determination of needs and the prioritization of candidate sections for funding allocation are very important tasks in the pavement management decision-making process. These decisions should be backed up by information about the future pavement condition and corresponding budget estimates. Therefore, the prediction of the pavement condition using either a deterministic or probabilistic pavement performance model is a key factor in PMS to establish maintenance and rehabilitation programs.

There are two kinds of pavement condition prediction models used in PMS: deterministic and probabilistic. Deterministic models predict pavement life, distress level, or future pavement condition as a single number; probabilistic models predict these events as a range of values with probability distributions (Lytton 1987). Deterministic models include structural and functional performance models. Probabilistic models include survivor curves and Markov process models. A brief description of these models from the literature is presented in the next sections.

2.2 Deterministic Models to Predict Pavement Performance

In deterministic models, a mathematical function derived from observed or measured pavement deterioration, predicts the future pavement condition as a single

value (Abaza 2004). Examples of deterministic models are primary response models, structural performance models, functional performance models, and damage models. Primary response models predict pavement deflection, stress, or strain due to traffic loads and climatic conditions, and they can be mechanistic, empirical or mechanistic-empirical models. Structural performance models predict pavement distress and pavement condition using pavement condition index, and they can be empirical or mechanistic-empirical models. Functional performance models predict the present serviceability index or the International Roughness Index (IRI). Damage models are derived from either functional or structural models. Damage is a normalized measure of distress or some other measure of pavement condition; damage starts at zero and becomes one when the level of distress is unacceptable (Lytton 1987).

The mathematical model is based on mechanistic, regression, or mechanistic-empirical models. These models do not contemplate the variability of the parameters used in the prediction. The mechanistic model relies upon the soil mechanistic theory, mechanical properties of pavement materials under load, and multilayer structural analysis technics, establishing relationships among stress, strain, and deflection (Li 2005, Li et al 1997). The mechanistic-empirical models contrast the results from theory with field observations to predict roughness, and cracking due to environmental and traffic loads which are used to calibrate the models. (Schram 2008).

Pavement performance deterministic models are commonly developed using regression analysis to establish a relationship between observed parameters such as riding comfort index (RCI) with pavement material properties, pavement thickness, traffic loads, or age (Li et al 1997). Abaza (2004) developed a deterministic performance

prediction model using an incremental analysis of the AASHTO basic design equation for flexible pavements, to generate a single performance curve for a given pavement structure. This curve provides a simple tool to project the future condition of the pavement using the present serviceability index (PSI) and 80kN equivalent single axle load (ESAL) in the AASHTO basic pavement design equation, obtaining a required structural number (SN). After determining the required SN, it is used in an equation that includes layer thickness for surface, base, and sub-base, layer strength coefficients and layer drainage coefficients. The method defines a pavement performance curve as a function of the PSI and 80kN ESAL applications. A logarithmic relation was stablished between service time and load applications to construct a performance curve. This method needs information for each section about the construction material, weather conditions, and traffic information. This model can be applied at the project management level.

A deterministic prediction model for county roads in the state of Alabama was constructed applying regression analysis to predict the time needed for a road surface to reach a point of failure. This point of failure is defined as the condition where the only way to restore a good pavement condition is through a total reconstruction. This method considers that pavement deterioration is due to daily traffic and time passed since the last resurfacing. A regression analysis is conducted to establish the deterioration equation based on the average daily traffic that is divided in average daily trucks and average daily cars. The model was recommended for the PMS used in Alabama’s state counties (Wilson 2005).

A deterministic pavement performance model using an exponential equation was developed in China, based on the pavement condition index, or road quality index that reflects pavement deterioration process as age increases, or as cumulative axle load increases. Parameters in this model are a function of traffic, structure, and environment. This model was integrated into a pavement management system software developed by the Shanghai Municipal Engineering Design Institute (Bai et al 2013).

A mechanistic-empirical deterioration prediction model was developed for the Nebraska DOT. The model is based on the Mechanistic Empirical Pavement Design Guide (MEPDG) from the National Cooperative Highway Research Program (NCHRP) and has 75 user inputs including design life, construction date, pavement type, traffic, climate, materials, and structure (Schram 2008). However, the large number of parameter data needed in the model makes it difficult to implement, since structural and materials data were incomplete in the databases.

An empirical-mechanistic model was developed for the Delaware Department of Transportation using simple and multiple regression analyses, the model includes an overall pavement condition rating in a scale from 0 to 100 as a dependent variable; and age, average annual daily traffic, and pavement distresses as independent variables (Mills et al 2012).

The Linear Mixed Effects Model predicts pavement condition mixing average daily traffic, loading, thickness, climate and environmental conditions, and pavement condition prior to the last treatment. Pavement characteristics are shared by all pavements in the same pavement family. Initial condition and pavement deterioration rate for a particular section are also considered to develop a regression equation to

predict the future pavement condition (Yu et al 2007). This method was tested using data from the Ohio Department of Transportation (ODOT). ODOT measures the pavement condition using the Pavement Condition Rating (PCR) on a scale from 0 to 100 rating the best pavements with a PCR of 100 and the worst pavements with 0. The model prediction accuracy increases with a large number of historical observed conditions, but the accuracy decreases as the variability of the observed conditions increases.

Mississippi Department of Transportation (MDOT) developed pavement condition prediction models for their PMS. MDOT's PMS defines five pavement families: original flexible, overlaid flexible, composite, jointed concrete, and continuously reinforced concrete pavements. For flexible and composite pavements prediction models were developed for alligator cracking, other types of cracks (e.g. longitudinal and transverse cracks), rutting, roughness, and Pavement Condition Rating (PCR). For concrete pavements, prediction condition models were developed for cracks, punch-out, roughness, and pavement condition rating. The prediction models were developed using regression techniques, multiple linear forms, nonlinear regression, and Bayesian regression. The data used in the models include pavement layer thicknesses, type of material, type of subgrade, construction year, maintenance treatment type, and year of treatment application, traffic details per section, and pavement distress data (George 2000).

Pavement performance prediction can be done with deterministic models using regression analysis models. However, these methods produce uncertainty in the

performance prediction because they do not consider the variability inherent in the parameters used in the model.

2.3 Probabilistic Models to Predict Pavement Performance

The prediction of pavement performance involves a certain degree of uncertainty. The models for predicting long-term pavement performance should ideally include a procedure to address the reliability of historical data due to errors in the registration process or incomplete data. The variability of parameters such as pavement strength, ESALs, and IRIs employed in these models influences the variability of pavement performance predictions. Probability distributions are used to model the variability of the parameters for predicting pavement performance (Suherman, 2009). Probabilistic models are more common at the network pavement management level to forecast the pavement performance using probability distributions for the predictions (Hedfi and Stephanos 2001).

Probabilistic prediction models take into account the probability associated with the future pavement performance as a random variable, predicting the pavement condition at a certain probability level based on engineering judgment or analyses of historical data (Abaza 2004, Montgomery and Runger 2011).

Probabilistic models used for modeling pavement deterioration can be state-based or time-based. State-based models predict the probability that a pavement will change its condition in a given time, whereas time-based models predict the probability distribution of the time needed for a pavement to change its present condition. Examples of state-based models are Markovian chain-based prediction models that state that the probability of a future pavement condition depends on the present

pavement condition state. Time-based models are also known as duration models and survival models, broadly used to predict the time for the initiation of fatigue cracking in pavements (Lee et al 2012).

A probabilistic approach is useful to quantify the uncertainty in the performance predictions. Suherman (2009) developed a probabilistic prediction model based on the International Roughness Index (IRI), calculating the predicted IRI as a function of cumulative ESALs, pavement strength, and initial IRI. A failure state is defined by the transportation agency as an IRI failure value, pavement reliability is defined “as the probability that the pavement roughness (IRI_p), predicted at any traffic level will be less than the pavement roughness at failure, IRI_f”.

Methods used to address the reliability of the probabilistic prediction models are sensitivity analysis and Monte Carlo simulation. All the parameters are assumed to follow a normal distribution. The value of pavement roughness at failure is set by the transportation agency, and the probability of failure is calculated using Monte Carlo simulation as:

$$P_f = \frac{\text{the number of trials with } Z \geq 0}{\text{total number of trials}}$$

P_f = Probability of Failure

$Z = IRI_p - IRI_f$

IRI_p = Predicted pavement surface roughness

IRI_f = Pavement surface roughness at failure

And the reliability is given by $R = 1.0 - P_f$

Li (2005) proposed ordered probit and sequential logit probabilistic models for pavement performance prediction. These models are based on condition states and use structural, traffic, and environmental parameters to predict future pavement condition in terms of a pavement condition index or pavement serviceability index. The probability distribution assumption in the models is normal in the ordered probit model and logistic in the sequential logit model.

Zhang and Damnjanovici (2006) proposed a structural reliability theory considering a stress-strength inference method stating failure when the stress exceeds the pavement strength. The probability of failure is calculated using various approximation techniques including Monte Carlo simulation (MCS) and the first order reliability method (FORM). The method was developed using AASHTO 1993 Pavement Design Method (Zhang and Damnjanovici 2006). A difficulty for this method is that the agencies must record project level design data of all the pavement sections in their network to obtain the pavement strength in order to predict future condition.

Another probabilistic pavement performance model for planning maintenance and rehabilitation programs for a pavement network is a survivor curve. A survivor curve is a graph of the probability of pavement expected service life versus age or versus traffic loads. The construction, maintenance, and rehabilitation history of the pavement network is the source to develop survivor curves by determining the pavement sections that must be maintained or rehabilitated each year after major repair or new construction. Probability of surviving is 1.0 at construction time, age 0, or at the initial designed traffic load, it drops to 0 as age increases at the end of the service life, or as traffic loads increase. It represents the probability in percentage of pavement remaining

in service after a number of years or after a number of passes of a standard load (Lytton 1987).

Markov Decision Process (MDP) is a discrete time stochastic process, in which a decision-maker can choose an action in some state of the process; it is another modeling framework to support the development of pavement maintenance and rehabilitation policies. The Markovian assumption implies that the condition of the pavement at time t_1 is the consequence of the pavement condition and the actions applied at time t_0. Deterioration is usually modeled as an exponential function of time. As an example the model for pavement roughness can be written as:

$s = s^0 \exp(\xi\tau)$

where

s = roughness at the end of the planning horizon

s^0 = roughness at the beginning of the planning horizon

ξ = deterioration parameter

τ = length of the planning horizon, $t_1 - t_0$, $t_1 > t_0$

The deterioration parameter ξ is random and normally distributed, another random variable is also introduced as $\eta = s/s^0$ with a lognormal probability distribution. The pavement deterioration process is represented by transitional probabilities estimated from expert knowledge or from empirical data, which are used to determine the distribution of future states and transitional probabilities; a level of risk is introduced and is measured by a Value at Risk. The model is solved for a long term period to determine the budget required, if the available budget is less than the budget needed, then the model is solved for a short term period (Seyedshohadaie et al 2010).

Markov chain models predict the probability that a facility will change its condition state given a fixed time interval. The condition of any future state is independent of past events, and only depends on its present state (Zhang et al 2006). The model developed by Zhang includes pavement deterioration rates and improvement rates to optimize maintenance and rehabilitation interventions. The transition matrix includes five condition states labeled 1,…, 5 representing sections in excellent, good, fair, poor, and very poor condition. Maintenance can be applied to sections in states 2, 3, 4, and 5, expecting that the section will improve by one state. Rehabilitation actions can be applied to sections in states 3, 4, and 5, expecting that the section will improve to state 1. With these elements, two 5 x 5 transition matrices are constructed, one matrix for the present state and another matrix for the future state. The study presents three alternatives: (1) to maximize pavements in good condition, (2) to minimize pavements in bad condition and (3) to select sections in worst condition for treatment as first priority.

Tack and Chou (2001) developed a probabilistic Markov chain performance model for Ohio DOT based on existing data. The pavement condition rating (PCR) and lane miles from years 1995 to 1999 were used to develop a transition probability matrix by separating in 10 classes the PCR values, then calculating the probability of the number of miles changing from one range to another in a one year period (Tack and Chou 2001).

A probabilistic pavement performance prediction model was developed for China's expressways combining the Grey System Prediction (GSP) model with a Markov Probability Prediction (MPP) model. The GSP model predicts four indexes of pavement performance: Riding Quality Index, Pavement Structure Strength Index,

Pavement Surface Condition Index, and Skidding Resistance Index. The transition probability matrix combines the GSP prediction results with the initial time probability distribution results. The initial time probability distribution represents the present pavement condition. This model was developed with limited data due to the short period of China's expressway development (Mao and Yu 2009).

Bayesian performance models combine objective data and subjective data such as engineering knowledge to develop prediction equations using regression analysis (FHWA 1998). A Bayesian performance model was developed for Texas DOT to predict longitudinal cracking on Texas roads (Park et al 2008). This model uses a sigmoidal equation with coefficients developed from prior engineering knowledge and existing longitudinal inspection data (e.g. longitudinal cracking in linear feet from inspected pavement sections), all pavement sections are inspected every year.

Another type of probabilistic pavement performance model was developed by the association of Australian and New Zealand road transportation authorities (Austroads), as a probabilistic approach to estimate the range of possible outcomes affecting the pavement life. Monte Carlo simulation of pavement age, annual traffic, moisture index, and structural numbers were used as input parameters to test all possible combinations of relevant input parameters in their deterioration models (Austroads 2013). This probabilistic approach generates the probability of occurrence of a pavement condition in the future.

Deterministic pavement prediction models predict pavement performance as a single value without taking into account the variability of pavement performance due to environmental and traffic conditions. Probabilistic models like reliability models, Markov

decision models, Markov chain models, Bayesian models, and combination of probabilistic methods models address the variability of pavement performance due to the uncertainty of future environmental conditions, traffic loads, pavement roughness, pavement structural strength.

2.4 Decision Trees

Decision trees are commonly used in decision making because of its simple graphical and analytical presentations. The analytical presentation is based on Bayes' theorem. They are constructed from a decision node, represented with a square, with branches emanating from it representing alternative decisions to be analyzed. Chance nodes, represented by a circle, have branches emanating from it, representing alternative states ending in consequences nodes, represented with a triangle, with the cost or benefit of the outcomes (Haimes 2004). An example of a decision tree is shown in Figure 2.1. In this decision tree the arterial future pavement condition can be among five possible states: very good, good non-load related, good load related, poor, or very poor. There are two alternative treatments to decide from depending upon the pavement condition.

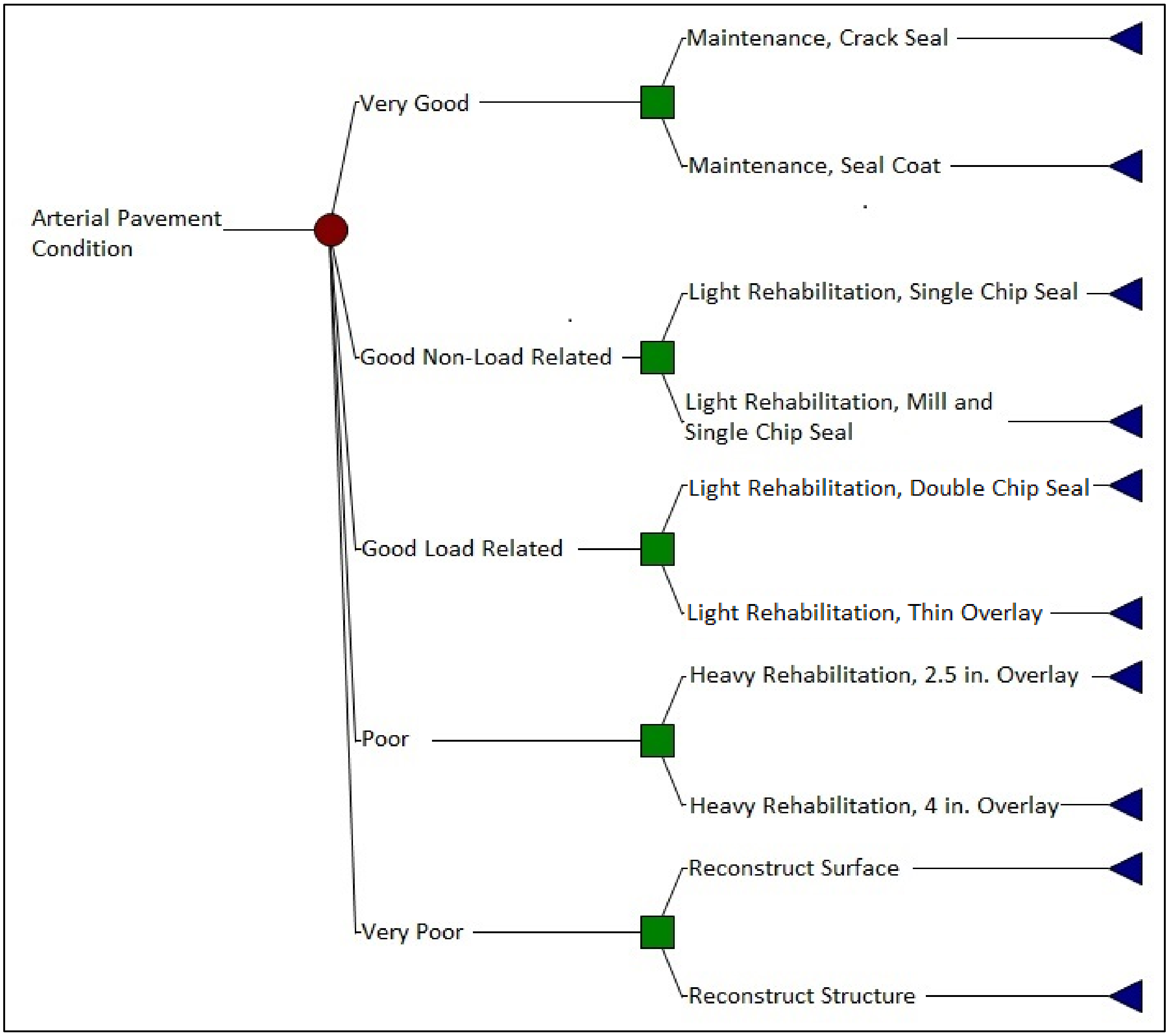

Figure 2.1 Pavement Treatment Decision Tree

Decision trees may incorporate probability distributions to calculate an expected value of cost or benefit. This approach was introduced several decades ago. Stochastic decision trees allow the use of probability estimates or frequency distributions for some or all the factors affecting the decisions. Data inputs to build a stochastic decision tree are costs or benefits of the decisions, probability of chance events, and range of values for the parameters involved in the decision-making process. Expected values of costs or benefits are calculated using the probability of chance events from the decision trees;

the alternative or branch with the highest expected value of benefit or lowest cost is the recommended alternative (Moussa et al 2006). Multi-objective decision trees may incorporate multiple, different, or even conflicting objectives. Each branch has a conditional probability; decisions are made for the first decision node from a set of Pareto-optimum alternatives in which an improvement in one objective is necessarily accompanied by a detriment in other objective, which include the multiple objectives calculated from each possible path in the decision tree (Haimes 2004).

2.5 Metropolitan Transportation Commission PMS

In 1981, the Metropolitan Transportation Commission, a metropolitan planning organization in the San Francisco, California, Bay Area developed a network level model for a pavement management system MTC-PMS. The MTC-PMS is now a software called StreetSaver® and it is used to assist cities and countries to manage their road networks. At present, a deterministic pavement performance prediction model based on the Pavement Condition Index (PCI) is used to forecast the condition of the management sections over time to identify maintenance and rehabilitation treatment needs. A management section is a pavement section or a group of sections that have similar functional classification, pavement type, weather conditions, and number of traffic loads, and the agency is responsible for maintenance, assuming the same performance in all the section length (AASHTO 2001).

Three types of analysis for the pavement network can be performed with StreetSaver®:

- Needs Analysis, based on Pavement Condition Index (PCI) projections over the period of analysis, is performed to identify the sections in need of maintenance or

rehabilitation, the treatments to apply and the budget needs to preserve the pavement network in an optimum condition.

- Target Driven Scenario Analysis that sets a target pavement condition over the period of analysis, in terms of a PCI value, to identify the sections that will be treated, and estimate the corresponding budget to maintain the network at the agency's desired PCI.
- Budget Scenario Analysis that sets a budget over the analysis period, and prioritizes the pavement sections that will receive treatment for the available budget.

In order to use StreetSaver®, the agency maintains a database with an inventory of all the management sections which are organized in four functional classes: arterial, collector, residential/local, and other; and five pavement types: asphalt concrete (AC), asphalt concrete over asphalt concrete (AC/AC), asphalt concrete over Portland cement concrete (AC/PCC), Portland cement concrete (PCC), and surface treatment (ST).

The pavement sections are classified into five PCI condition categories: category I representing pavements in very good condition with PCIs from 100 to 70; category II representing pavements in good condition with PCI loss due to non-load related causes and PCIs from 69 to 50; category III representing pavements in good condition with PCI loss due to load conditions and PCIs from 69 to 50; category IV representing pavements in poor condition and PCIs from 49 to 25; and category V representing pavements in very poor condition and PCIs below 25. The PCI range and treatments to apply are defined by the agency depending on the condition category.

2.5.1 Description of the Needs Analysis

StreetSaver® uses a deterministic PCI prediction model to forecast the pavement condition of the management sections, PCI projections are then used to identify maintenance and rehabilitation treatments and budget needs. Figure 2.2 shows a flowchart to illustrate the needs analysis process over time.

The needs analysis consists in forecasting pavement condition in PCIs over an analysis period, usually 5, 10, or 20 years, to recommend maintenance or rehabilitation treatments for each year according to PCI trigger values set by the agency, and calculate the budget needs for the selected treatments. At the end of the analysis period, the agency obtains the total budget needed to preserve the pavement network in good condition.

To begin the needs analysis, in step 1, the agency must have an inventory of the pavement network including the location of the pavement section, functional class, pavement type, date of construction, and treatment history.

In step 2, pavement surface distresses including alligator cracking, longitudinal cracking, and potholes from individual sections are collected to calculate the inspected PCI value. Each type of distress is measured in its respective unit (squared feet or linear feet for flexible pavements and number of slabs for rigid pavements), recording its severity (high, medium, low). The inspection area is also measured to calculate the distress density.

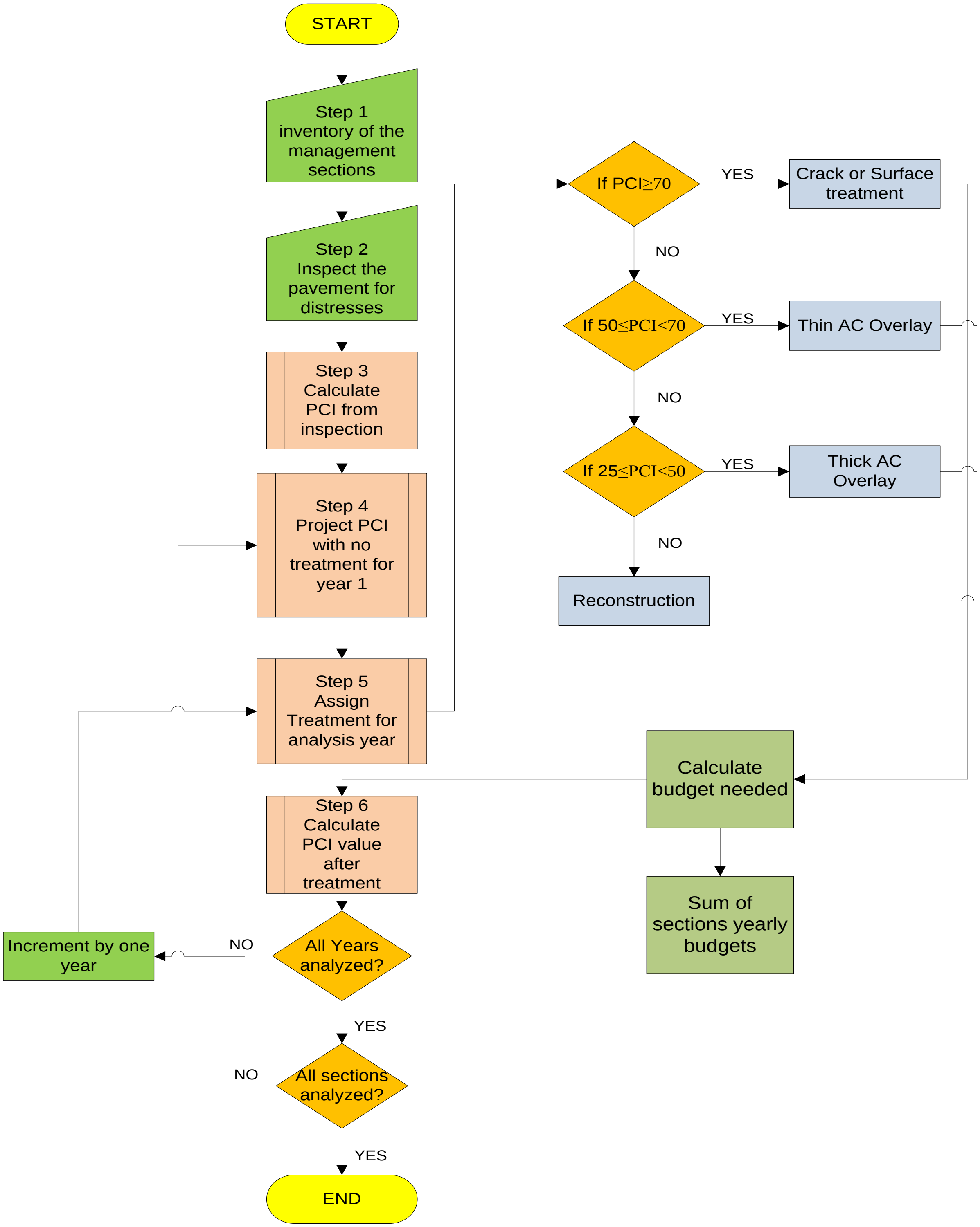

Figure 2.2 Needs Analysis Process Flowchart

After collecting distress data, deduct values for each distress type and severity combination are determined from deduct curves (MTC, 2001). The deduct value

obtained from deduct curves is subtracted from 100 to obtain the PCI inspection value in step 3.

The pavement age is needed for the needs analysis; and it can be calculated from the inspection date minus the construction date, or the inspection date minus the last overlay date. With the section's age and the PCI from inspection, the PCI value is projected for year one of the analysis in step 4.

In step 5, the model recommends treatments as needed for each year over the planning horizon. Pavement sections are selected based on the projected PCI values and the maintenance and rehabilitation strategy established by the agency. Once a treatment is selected, the PCI value increases according to the type of treatment applied; thick overlay and reconstruction treatments restore the PCI to 100, surface treatments increase the PCI value, the incremental PCI value is calculated for all functional classes and asphaltic surface types with a polynomial regression equation as a function of the PCI value before treatment. The PCI value after treatment is calculated in step 6.

Treatments are selected using deterministic decision trees with PCI categories. The decision tree used in MTC-PMS does not incorporate probabilities, decisions about pavement section selection and treatments are based on PCI trigger values. These trigger values for treatments are set by the users. Each functional class and pavement type combination has a decision tree. These decision trees are used in MTC-PMS to identify sections for treatment, the input is the pavement PCI value and the output is the recommended treatment. Table 2.1 shows MTC-PMS pavement condition categories for arterial AC streets, PCI condition category ranges, treatment category, and treatments

to apply. Figure 2.3 shows the arterial AC decision tree from MTC-PMS based on these PCI categories.

Table 2.1 Pavement Condition Categories and Treatment Selection (MTC 2001)

CATEGORY	CONDITION	PCI RANGE	TREATMENT CATEGORY	TREATMENT TO APPLY
I	Very Good	70-100	Preventing Maintenance	Seal Cracks or Surface Seals
II	Good Non-Load Related	50-69	Rehabilitation	Chip Seals
III	Good Load Related	50-69	Rehabilitation	Thin Overlays
IV	Poor	25-49	Heavy Rehabilitation	Thick Overlays
V	Very Poor	0-24	Reconstruction	Reconstruction

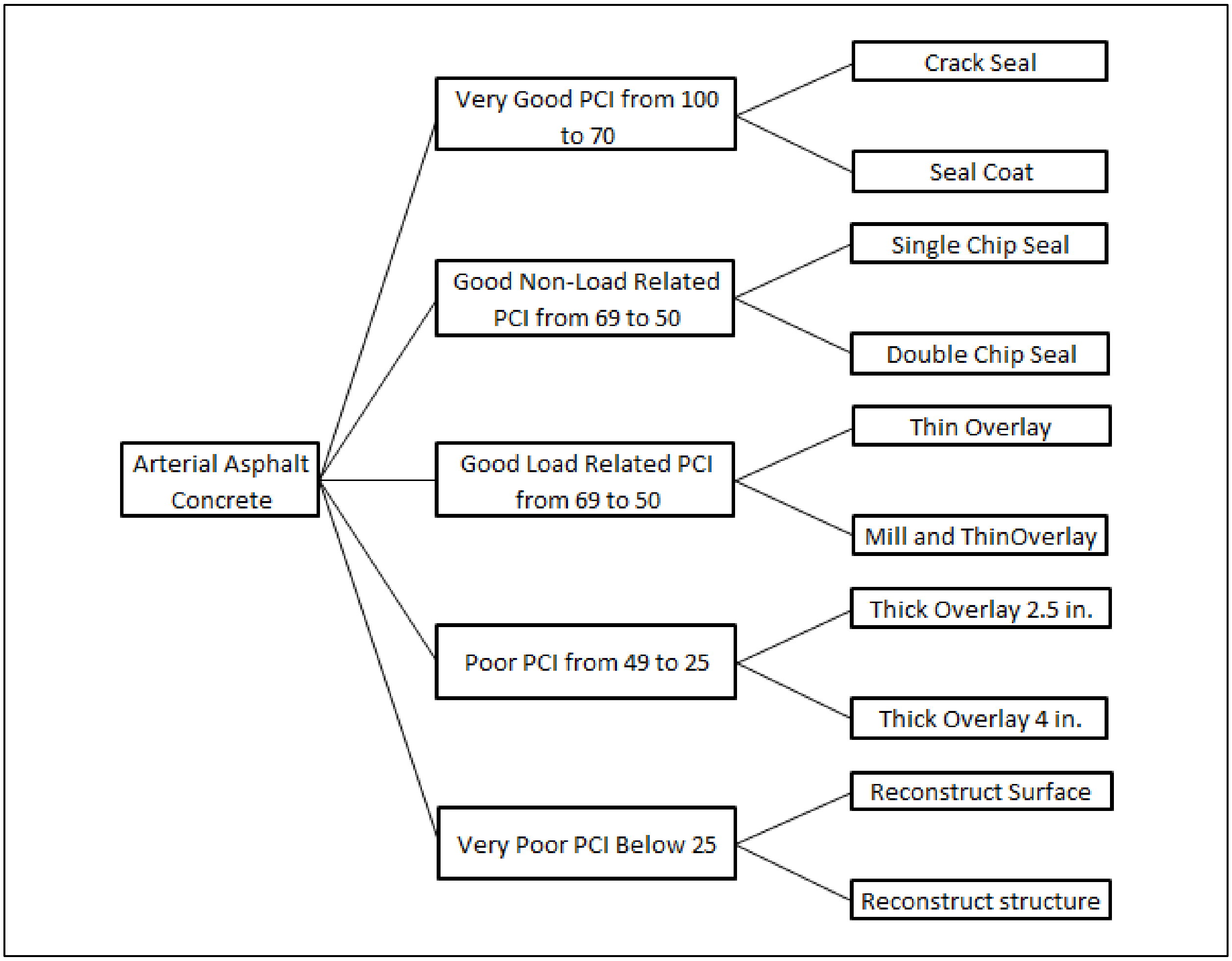

Figure 2.3 Arterial AC Treatment Decision Tree (MTC 1987)

MTC-PMS runs a deterministic model to project pavement condition and identify maintenance and rehabilitation treatments using a decision tree based on PCI condition

categories. At present, MTC-PMS generates needs analysis results showing a list of pavement sections identified for maintenance and rehabilitation with their recommended treatment. Needs analysis also estimates the budget required to preserve the pavement network in very good condition. As an output, needs analysis recommends only one maintenance and rehabilitation program.

MTC-PMS has also a target-driven scenario analysis tool, in which the agency sets future PCI target values for the pavement network, estimating the budget to reach those targets. The result is a single budget estimate as required to meet the desired pavement network condition.

2.6 Scenario Analysis

Scenario analysis is an approach to analyze problems that involve uncertainty, presenting a range of possible future events. Scenario analysis does not provide the answer to the problem; it offers a series of possible future states, offering alternative views to make better informed decisions (Wright and Cairns 2011). Scenario analysis can be incorporated into pavement management as a useful tool, analyzing different future pavement conditions to aid in the decision-making process by showing decision-makers possible future pavement condition states, helping in the development of maintenance and rehabilitation programs.

Scenario analysis considers deterministic scenario analysis (DSA) and probabilistic scenario analysis (PSA). DSA can process a huge amount of data, and it can model future alternative states for given selected performance targets, but with a limited number of scenarios, (e.g. worst case, best case, or more likely case). DSA outputs do not report the level of confidence or likelihood of occurrence. PSA has much

wider possibilities to overcome the lack of confidence in the likelihood of occurrence of events, using probabilistic methods like Monte Carlo processes with event trees to present the outcomes as probability measures. Multiple PSA scenarios can be compared by decision-makers, to have more information to make a decision on the best alternative (Yoe 2011).

MTC-PMS incorporates a deterministic scenario analysis in which a PCI target value for the pavement network is established for the analysis period; however the system's output is a single budget required to maintain the pavement network at the desired condition. This deterministic scenario analysis does not provide the decision-makers with budget alternatives to choose from.

Probabilistic scenario analysis can be adopted in pavement management systems to assist in the decision-making process for comparing multiple pavement deterioration scenarios at different probability levels to quantify the consequences of different pavement network conditions or the budget needs.

2.7 Summary and Conclusions

PMS use pavement performance prediction models to assist in the pavement management process. Deterministic pavement prediction models predict the pavement condition as a single value, and probabilistic models address the forecasting of pavement performance as a random variable with a probability distribution or likelihood of occurrence of alternative pavement condition states.

If the parameters involved in pavement performance prediction could be determined by an exact value, future pavement condition could be predicted with certainty. However, pavement deterioration caused by traffic loads and environmental

conditions appear to be random and cause uncertainty. This random process exhibits a pattern that can be modeled by probability distributions.

Probabilistic models consider the uncertainty involved in the variability of the parameters used to predict the future pavement condition; while deterministic models do not consider this variability. Table 2.2 presents a comparison between deterministic and probabilistic performance models.

Table 2.2 Comparison between Deterministic and Probabilistic Performance Models

Model Considerations	Deterministic Models	Probabilistic Models
Predict future pavement condition as a single value	Yes	No
Predict future pavement condition as a probability of a condition state	No	Yes
Considers the variability of the parameters used in the performance model	No	Yes
A mathematical function derived from observed pavement deterioration	Yes	Yes
Uncertainty about future pavement condition prediction is considered	No	Yes
Present broad information for decision-making about maintenance and rehabilitation programs	No	Yes

The stochastic models for pavement condition projections and budget needs estimates in this dissertation are based on the pavement condition index (PCI) calculated from pavement distresses and predict pavement performance using probability distributions developed from pavement history, considering the present pavement condition from inspection of the pavement sections in PCIs and section's history such as pavement past performance behavior and age, to predict future pavement condition. The advantage of the models presented in this dissertation over other probabilistic models is that they do not require structural, traffic, or neither

environmental information, nor probability transition matrixes required on Markov chain models, or prior probability distributions of pavement behavior developed from engineering knowledge as in a Bayesian framework, they require only pavement condition history data of construction dates, rehabilitation treatment dates, inspection dates, and PCI values from inspections. This pavement history data is used to develop probability distributions to construct probability-based performance curves obtaining values for parameters alpha, beta, and rho used in equation 1.1 to forecast future pavement performance. The same pavement history data is used to obtain pavement deterioration in PCI points at different pavement ages, classifying the pavement sections at different deterioration bands, forecasting future pavement condition based on annual deterioration rates instead of equation 1.1.

A disadvantage of the PBPPCs and of the PPPBSs is that when they are applied to a large pavement network, the process is time consuming and have to be used with a software like the one used in MTC-PMS. Another disadvantage is that some agencies do not have pavement history for 10 or 20 year periods of time to develop the PBPPCs or the PPPBSs.

PBPPCs and PPPBS, address the variability of the parameters involved in pavement performance prediction and model the uncertainty when forecasting pavement condition. The stochastic approach will mainly be suitable for pavement management at the network management level, although it can also be used at the project management level for individual pavement sections or groups of pavement sections. Results from multiple pavement performance scenarios can offer decision-

makers broad information about pavement performance in order to implement maintenance and rehabilitation strategies and estimate future budget needs.

Chapter 3: Stochastic Methods to Address the Uncertainty on Pavement Condition Projections and Budget Needs

Uncertainty is always present in forecasting pavement performance; a stochastic approach can model the uncertainty to provide decision-makers with more information about future pavement performance to develop maintenance and rehabilitation programs in a cost-effective manner.

The uncertainty in the prediction of pavement performance is addressed in this dissertation using two alternative stochastic methods:

- Probability-based pavement performance curves (PBPPC) to assess the prediction of pavement performance at different probability levels.
- Probabilistic pavement performance-based scenarios (PPPBS) to consider different pavement deterioration scenario trends.

The PBPPC approach consists in developing performance curves to forecast future pavement condition at different probability levels using equation 1.1 with the corresponding alpha, beta, and rho parameters calculated for each probability level. For the development of the PBPPC, PCI values from inspection of a similar pavement type and functional class at different ages of service life are fitted into probability distributions; these probability distributions are then used to compute PCI percentiles at different probability levels of pavement performance to build probability based pavement performance curves.

The probabilistic pavement performance-based scenario method consists in developing alternative scenarios at different pavement deterioration probability levels. Probability distributions are fitted to the annual cumulative pavement deterioration and

the annual cumulative deterioration is separated into three deterioration bands: low, medium, and high deterioration bands; annual deterioration is generated randomly by running Monte Carlo simulations using truncated probability distributions for each band in order to generate cumulative deterioration PCI points within each deterioration band. Maintenance and rehabilitation treatments and corresponding budgets are determined for each scenario.

Both stochastic methods can provide the agencies' decision-makers broader information about the future pavement condition in order to develop their maintenance and rehabilitation programs.

3.1 Probability-Based Pavement Performance Curves (PBPPCs)

Pavement performance can be forecasted at different deterioration rates using probability distributions to model its performance. PBPPCs are curves that forecast future pavement condition at different probability levels, the probability of pavement performance is the likelihood that a certain PCI value at year j of its service life be greater or equal to the p-percentile PCI value whereby p is the probability level. For example, for a certain pavement there is a 30% probability that in the third year after construction the PCI value will be greater or equal to 92. This is considered a 30% PBPPC (see Figure 3.1).

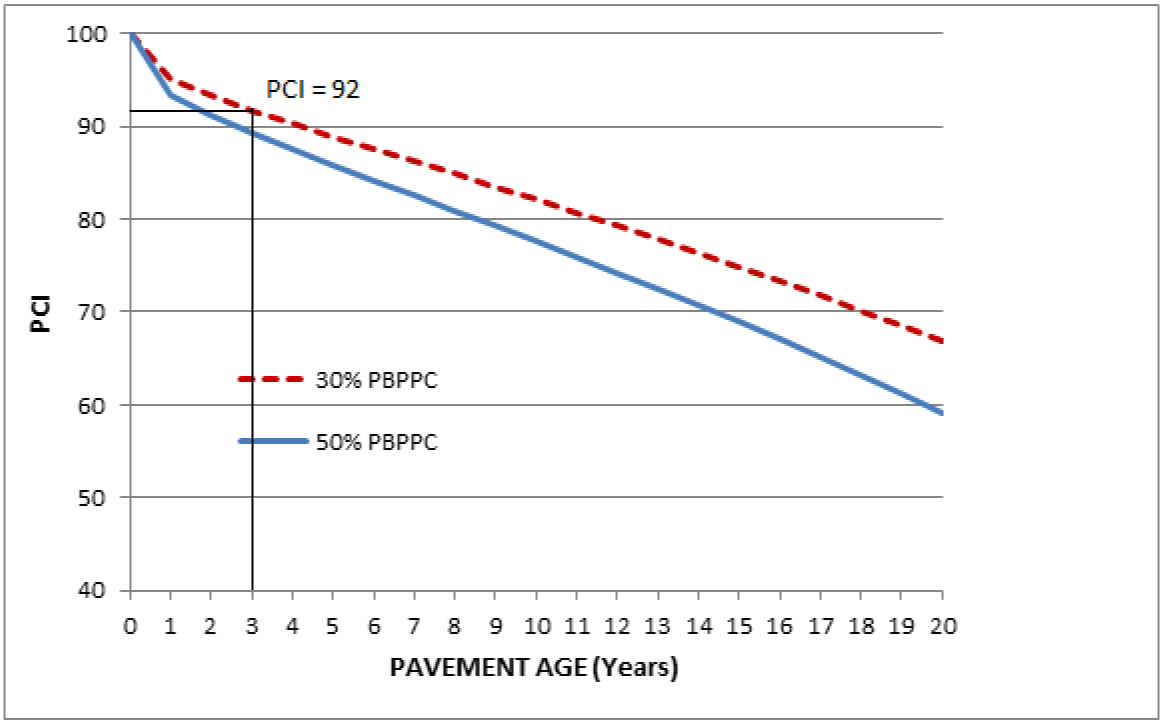

Figure 3.1 30% and 50% PBPPCs

PBPPCs are intended for use in the MTC-PMS software using values for α, β, and ρ parameters in equation 1.1 according to their corresponding probability performance level. Needs analyses can be performed using the PBPPC obtaining several pavement condition forecasts and budget needs.

To develop PBPPCs, a probability distribution is fitted to observed PCI values of similar pavement type and functional class at different ages. One of the most commonly used statistical distributions is the Normal distribution, most random variables can be modeled by a Normal distribution, numerous statistical analyses are based on the assumption of normality (Mongomery and Runger 2011). In this research the Normal distribution is used for the development of the PBPPCs. The fitted probability distributions are then used to compute PCI percentiles at each year of the analysis period. The PCI percentiles for each year are joined to build a PBPPC and by means of

a nonlinear regression for equation 1.1, parameters α, β, and ρ are found, and then used to project the pavement condition.

3.1.1 Steps for Developing the Probability-Based Pavement Performance Curves.

To construct the probability-based pavement performance curves it is necessary to collect data from pavement condition inspections including construction dates, inspection dates, and PCI values for each pavement section. The steps to develop the probability-based pavement performance curves are shown in Figure 3.2.

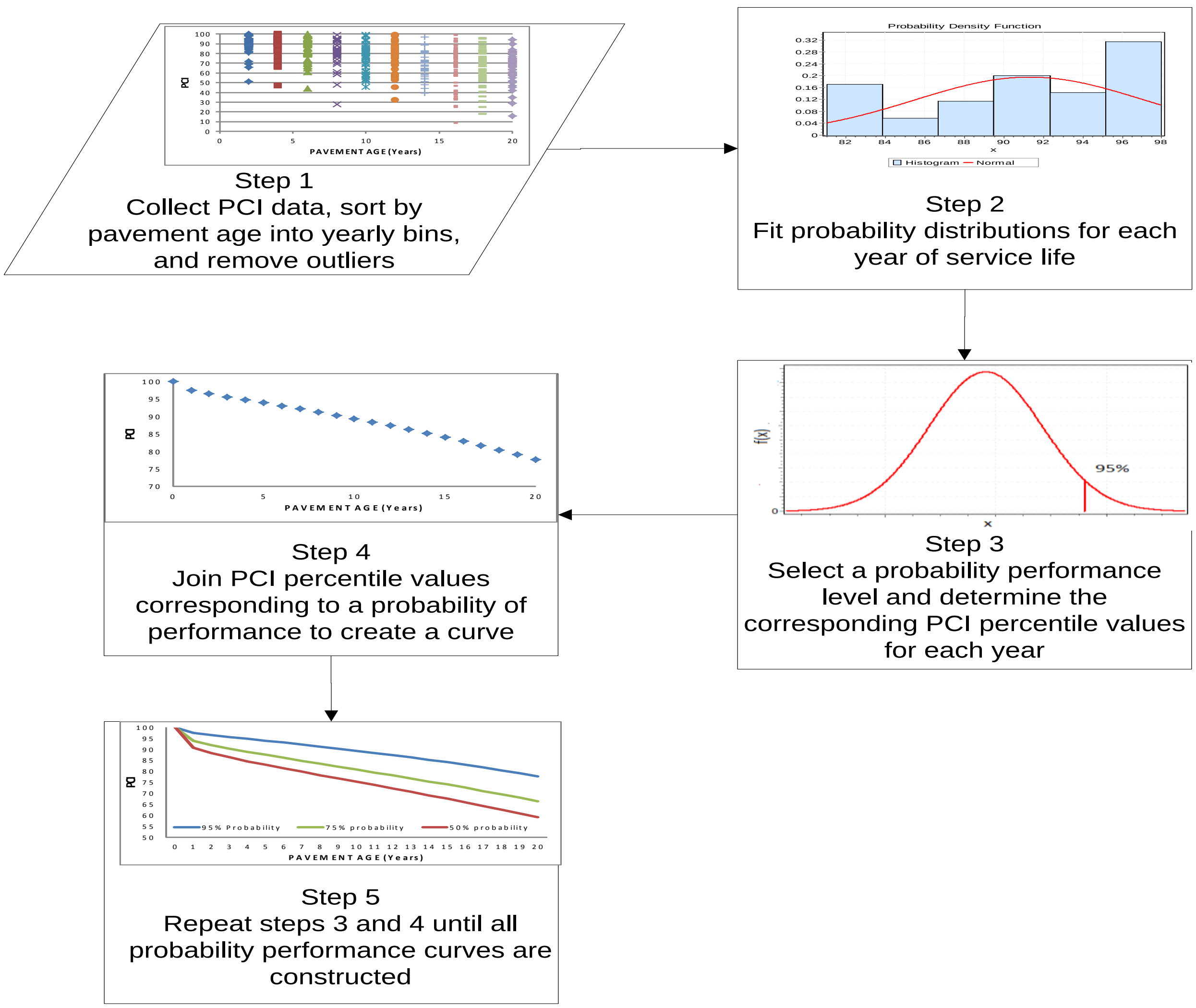

Figure 3.2 Process to Develop Probability-Based Pavement Performance Curves

Step 1. Collect PCI data, sort PCI values by pavement age into yearly bins, and remove outliers.

Collect Inspection data and then sort PCI values into yearly bins. Very low PCI values at early ages and very high PCI values at the end of the service life are treated as outliers. These outliers are removed by establishing lower and upper limits based on expert knowledge from the practitioners, as shown in figure 3.3. Upper limit line starts at a PCI value of 100 at year 0 keeping this value until year 2, then descends with a constant slope of -0.5 down to year 5, changes slope in this point to -1 and descends with this slope until year 20 to end at a PCI value of 79. Lower limit line starts at a PCI value of 92 at year 0 descending with a constant slope of -4 down to year 4, changes slope at this point down to year 10, and changes again slope down to year 20 to end in a PCI value of 18.

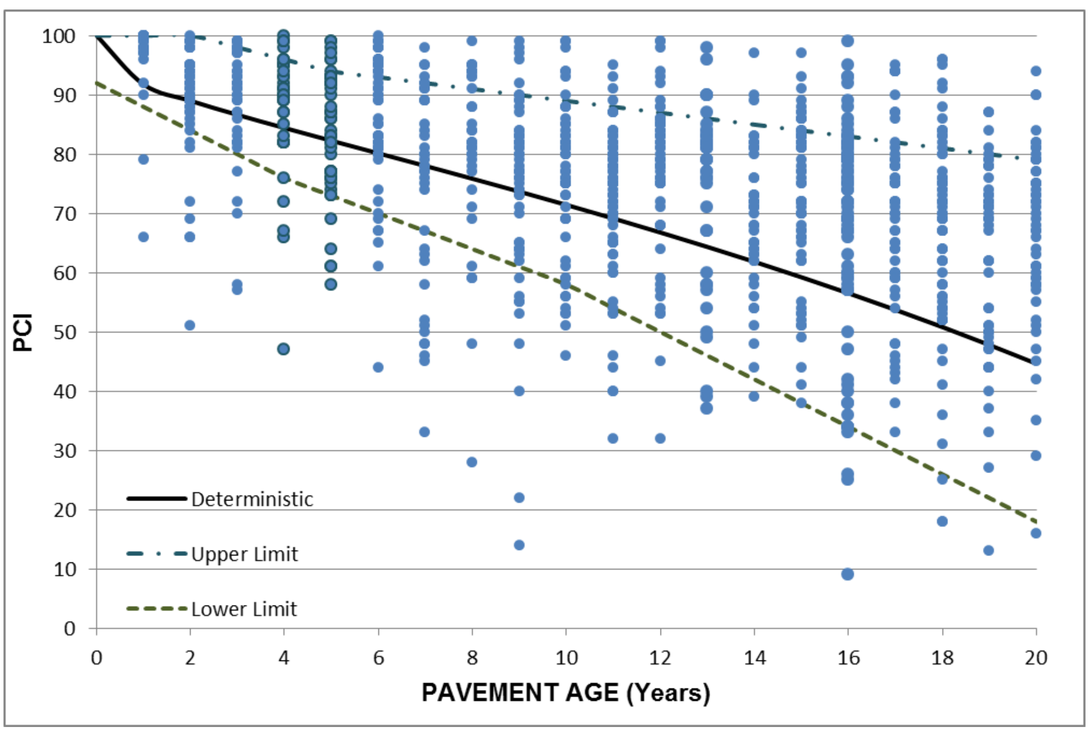

Figure 3.3 PCI Inspections at Different Pavement Ages and Limits for Outliers

Step 2. Fit probability distributions for each year of the pavement service life

Probability distributions are fitted for the PCI values with outliers removed. In this research, Kolmogorov-Smirnov, Anderson-Darling, and Chi-Squared goodness of fit tests were used to check if the data sets follow a Normal distribution. The null hypothesis that the data set is Normal distributed is rejected, if the test statistic is greater than the critical value obtained from a table and, or if α is greater than the P-value calculated based on the test statistic.

An α = 0.01 significance level was used for the goodness of fit test. Goodness of fit tests were done using EasyFit software for Kolmogorov-Smirnov, Anderson-Darling, and Chi-Squared goodness of fit tests. All data sets passed Kolmogorov-Smirnov goodness of fit test for Normal distribution with statistic values less than the critical values and P-values higher than 0.01. All data sets passed Anderson-Darling goodness of fit test for Normal distribution with statistic values less than the critical values. All data sets except data set from year 6, passed Chi-Squared goodness of fit test for Normal distribution with statistic values less than the critical values and P-values higher than 0.01. Data set from year 6 was rejected as a Normal distribution because the statistic value was higher than the critical value and the P-value was less than 0.01. Data set from year 6 is considered to have a Normal distribution because it passed Kolmogorv-Smirnov and Anderson-Darling goodness of fit tests for Normal distribution. Results from the goodness of fit tests are shown in Table 3.1.

Table 3.1 PCI Goodness of Fit for Normal Distribution Arterial AC

Year	Kolmogorov-Smirnov			Anderson-Darling		Chi-Squared		
	Statistic	Cr. Value	P-Value	Statistic	Cr. Value	Statistic	Cr. Value	P-Value
1	0.2592	0.2899	0.0289	3.2092	3.9074	1.5933	9.2103	0.4508
2	0.1231	0.2306	0.4272	0.6795	3.9074	4.3459	15.0860	0.5008
3	0.1506	0.2690	0.3681	1.0803	3.9074	1.1355	11.3450	0.7685
4	0.1615	0.2899	0.3738	0.8313	3.9074	0.0956	9.2103	0.9533
5	0.1852	0.2461	0.0982	1.7314	3.9074	2.9821	11.3450	0.3944
6	0.1689	0.2768	0.2716	0.9370	3.9074	17.5720	9.2103	<0.001
7	0.1547	0.3295	0.5872	0.5795	3.9074	1.1230	9.2103	0.5704
8	0.1377	0.3524	0.7941	0.3751	3.9074	5.6577	9.2103	0.0591
9	0.1177	0.2406	0.5372	0.8164	3.9074	2.8749	13.2770	0.5790
10	0.1529	0.2461	0.2531	0.9154	3.9074	2.5469	13.2770	0.6363
11	0.1129	0.2051	0.3899	0.5454	3.9074	3.6164	15.0860	0.6059
12	0.2055	0.2177	0.0178	2.9752	3.9074	11.7540	13.2770	0.0193
13	0.2342	0.2768	0.0448	2.6482	3.9074	6.3400	9.2103	0.0420
14	0.0988	0.2490	0.7824	0.4192	3.9074	0.4856	15.0860	0.9926
15	0.1346	0.2157	0.2485	1.7503	3.9074	7.1272	13.2770	0.1293
16	0.1755	0.1930	0.0249	3.1112	3.9074	6.8808	15.0860	0.2297
17	0.1194	0.2330	0.4782	1.0117	3.9074	2.6456	13.2770	0.6188
18	0.1327	0.2084	0.2291	1.0545	3.9074	6.5243	15.0860	0.2585
19	0.1696	0.2380	0.1336	1.2957	3.9074	7.7979	13.2770	0.0993
20	0.1010	0.2433	0.7227	0.7491	3.9074	2.7664	11.3450	0.4291

Step 3. Determine PCI percentile values for a probability pavement performance level.

The p-percentile PCI value is computed as follows:

Let PCI_j be the random PCI at year j defined by a Normal probability function with mean μ_j and standard deviation σ_j. Thus

$$PCI_j = N(\mu_j, \sigma_j) \quad (3.1)$$

Where $N(\mu_j, \sigma_j)$ defines a Normal distribution function

Let PCI_p be the p-percentile of PCI_j where p is the probability performance level

$$p \quad = (PCI_j \geq PCI_p) = 1 - \Phi\left(\frac{PCI_p - \mu_j}{\sigma_j}\right) \quad (3.2)$$

Where $\Phi(.)$ Is the standard cumulative Normal distribution.

For a given probability value p, PCI_p is thus obtained as,

$$PCI_p = \Phi^{-1}(1-p)\sigma_j + \mu_j \qquad (3.3)$$

Where $\Phi^{-1}(.)$ is the inverse standard Normal distribution.

This computation process is conducted for each year over the time span of the analysis period and at different probability levels (p). As an example, Figure 3.4 shows the cumulative distribution function for year 2 and the fitted normal curve.

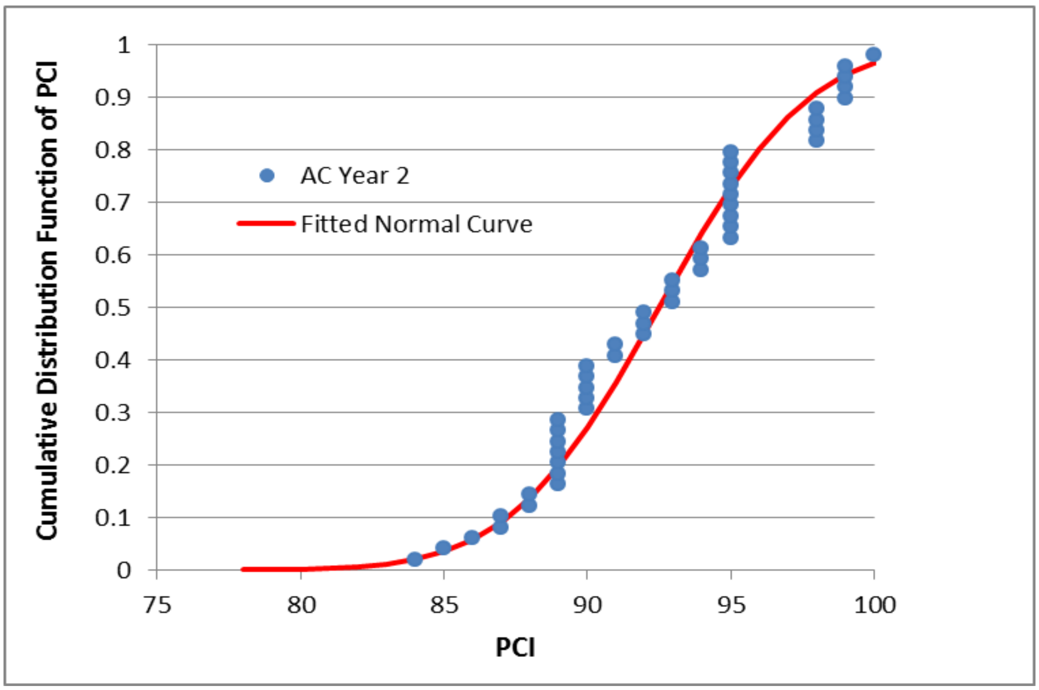

Figure 3.4 Cumulative Distribution Function for Arterial Asphalt Concrete Pavements at Year 2

Step 4. Join the PCI percentile values to create a probability-based curve

For a specific pavement performance probability level, PCI_p values calculated for each year of the analysis period using equation 3.3 are joined to build the PBPPC.

Step 5. Repeat steps 3 and 4 for selected probability performance levels

Steps 3 and 4 are repeated to develop PBPPC at selected probability levels. Figure 3.5 shows probability-based performance curves for 90%, 70%, 50%, and 30% probability of performance levels. Smoothing the probability-based performance curves, values for parameters α, β, and ρ are obtained through a nonlinear regression for equation 1.1, smoothed curves for 90%, 70%, 50%, and 30% are shown in Figure 3.6.

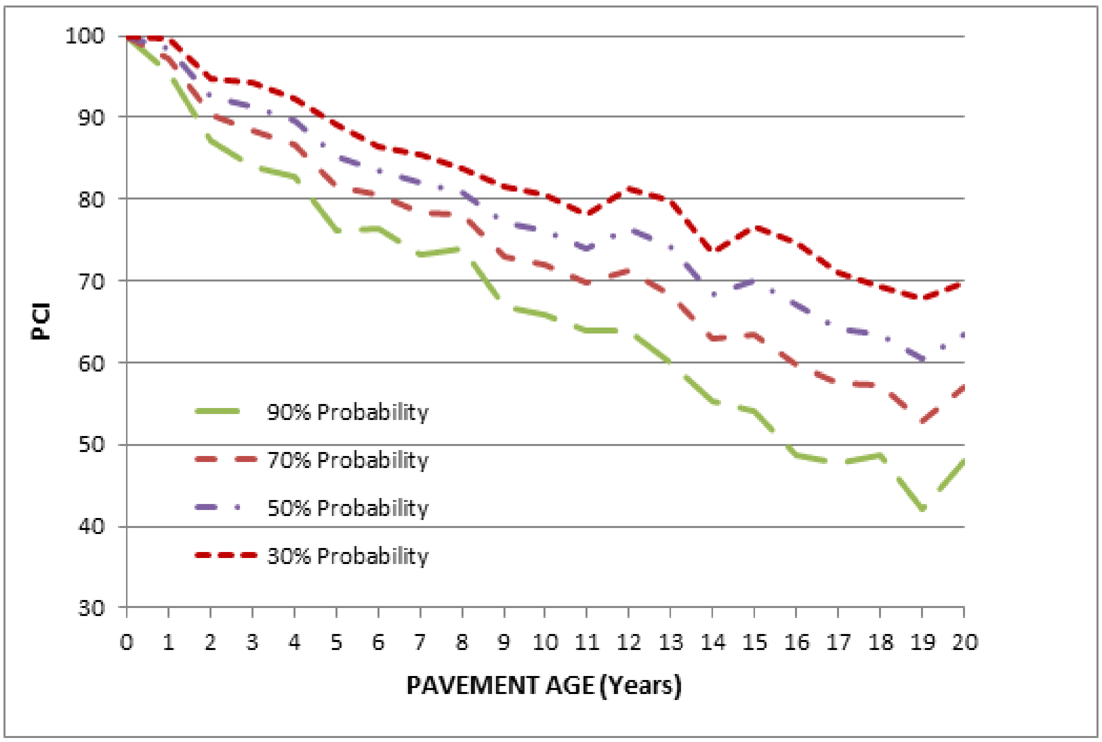

Figure 3.5 Probability-Based Pavement Performance Curves

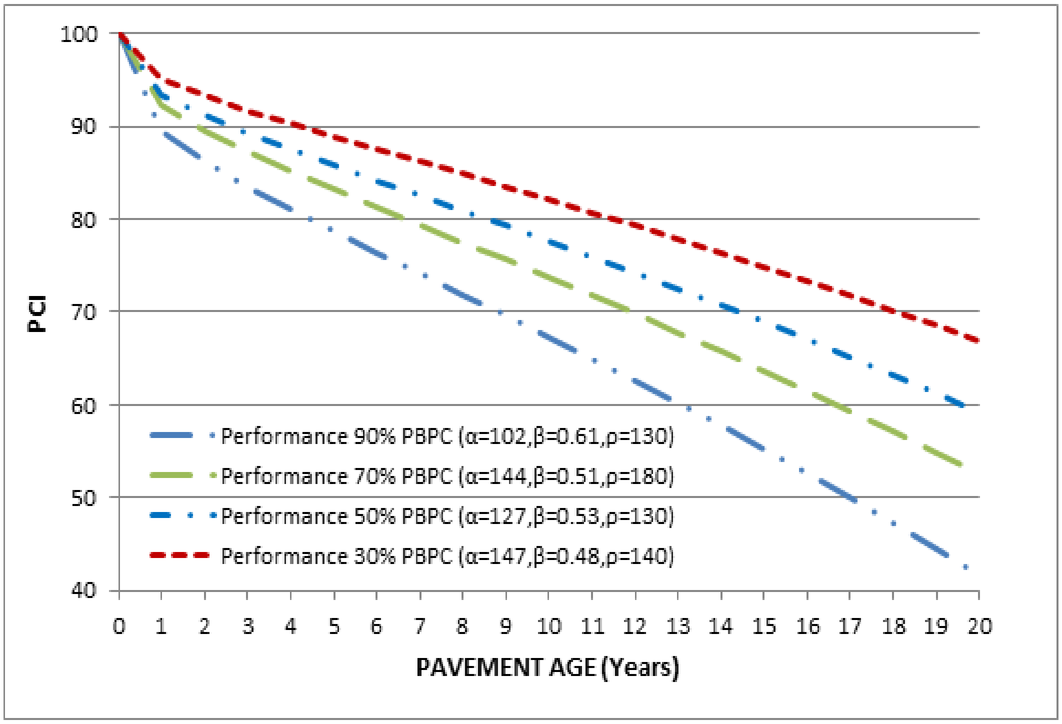

Figure 3.6 Smoothed Probability-Based Pavement Performance Curves

3.1.2 Use of the Probability-Based Pavement Performance Curves to Project Pavement Condition

At network level, needs analysis can be performed using PBPPCs at different probability performance levels, using the corresponding set of values for α, β, and ρ parameters in equation 1.1. For each probability performance level, the output of the analysis is the projected PCIs over the analysis period.

The procedure to project the PCI over an analysis period, using α, β, and ρ parameters for a given probability performance level, is shown in Figure 3.7. The steps are described as follows:

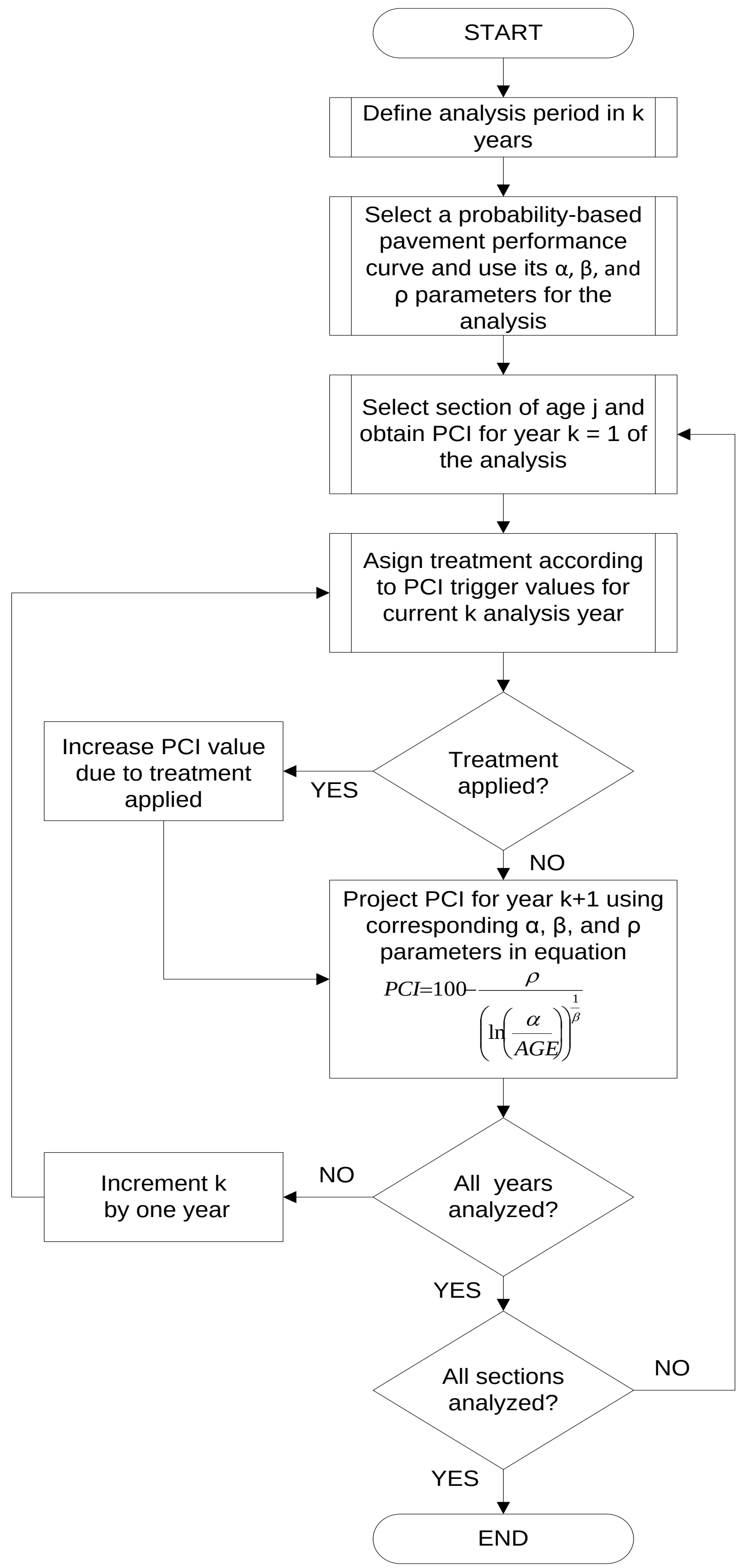

Figure 3.7 Procedure to Project PCI Using the Probability-Based Pavement Performance Curves

- Select the analysis period in k years.
- Select the probability level and the corresponding α, β, and ρ parameters for the PBPPC.
- Select a section and calculate its age j at year k=1 of the analysis, age j is calculated as the year of analysis minus the year of construction, or year of analysis minus the year of the latest overlay treatment applied. An initial PCI value for year k=1 of the analysis period can be: the inspected PCI of the section, or if there is not an inspected PCI, an initial PCI can be projected with equation 1.1 for age j.
- PCI is compared with the PCI trigger values to evaluate if a treatment is needed in the first year of analysis. PCI trigger values are set by the agencies to trigger the application of a specified treatment.
- Project the PCI for year k+1 using equation 1.1 with α, β, and ρ parameters and age j+1.
- If a treatment is applied at year k, then PCI increases due to treatment and this value is used to project the PCI for the next year.
- After all years are analyzed for one section, the procedure is repeated for the other pavement sections in the network.

If a history of treatments and inspections for a pavement section is available, the section's deterioration past performance can be used to identify the corresponding probability-based performance curve for future pavement condition projections based on the section's deterioration trend. In this approach, a specific set of α, β, and ρ parameters will be assigned to individual sections instead of analyzing the whole

pavement network with the same PBPPC family curves. This approach models the pavement performance level of those sections in a more accurate manner by selecting the PBPPC that better fits the section's history. However, this methodology can be a time-consuming procedure for a large pavement network.

The performance prediction process for individual pavement sections based on their deterioration trend is more suitable for small pavement networks or for a project management level analysis because the sections are analyzed individually or in groups of sections with a PBPPC level according to the history of the individual or group of sections. The pavement performance analysis using the PBPPC at the network and project management levels is a great decision-making tool to study pavement performance.

3.2 Probabilistic Pavement Performance-Based Scenarios (PPPBS)

The probabilistic pavement performance-based scenarios (PPPBS) approach consists in developing alternative scenarios at different pavement deterioration probability levels. Pavement deterioration is a loss in pavement quality; it is a normal process mainly due to traffic loads and environmental effects that can be stated as the cumulative deterioration of the pavement condition in PCI points (CDPCI) at a certain age j. CDPCI is calculated as 100 minus the PCI value at age j. The PCI value decreases and the cumulative deterioration increases as the pavement age increases as shown in Figure 3.8.

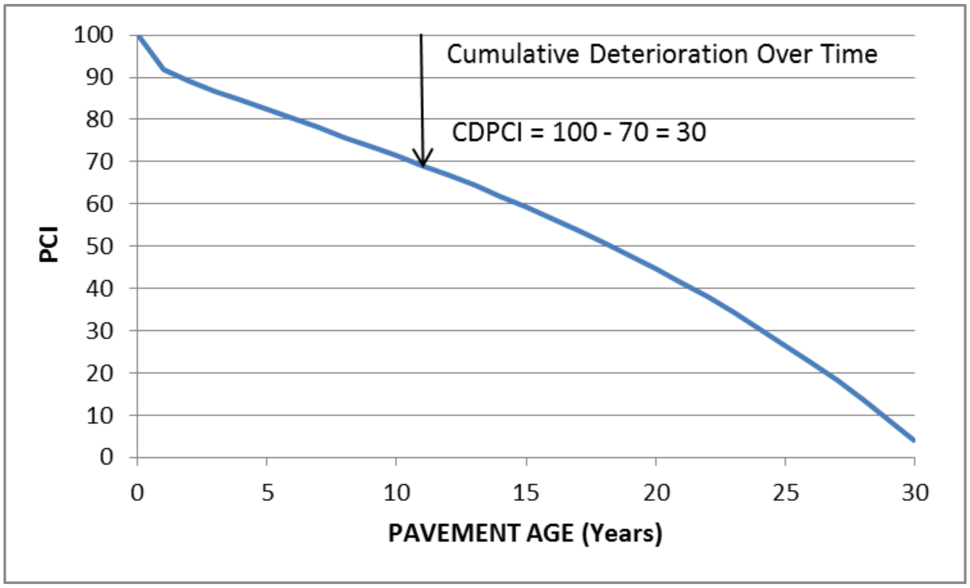

Figure 3.8 PCI and Cumulative Deterioration of Pavement Condition over Time

Uncertainty in traffic loads and environmental effects need to be considered when predicting pavement performance (Hong 2001). The uncertainty in pavement performance prediction can be addressed using a probabilistic pavement performance scenario approach. PPPBS are based on probability distributions of the yearly pavement cumulative deterioration in PCI points (CDPCI) to forecast pavement performance, simulating annual CDPCIs at different ages to establish an annual deterioration rate (ADR) that can be used to classify the pavement sections in low, medium, and high deterioration bands creating pavement performance scenarios.

The steps to develop probabilistic pavement performance-based scenarios from PCI inspection data and treatment history are outlined in Figure 3.9.

3.2.1 Steps for the Probabilistic Pavement Performance-Based Scenario Approach.

- Step 1 Collect PCI data and sort PCI values by pavement age j.

- Step 2 Calculate the cumulative pavement deterioration for each year from the sorted PCI data, subtracting 100 from the PCI inspection values at each year.

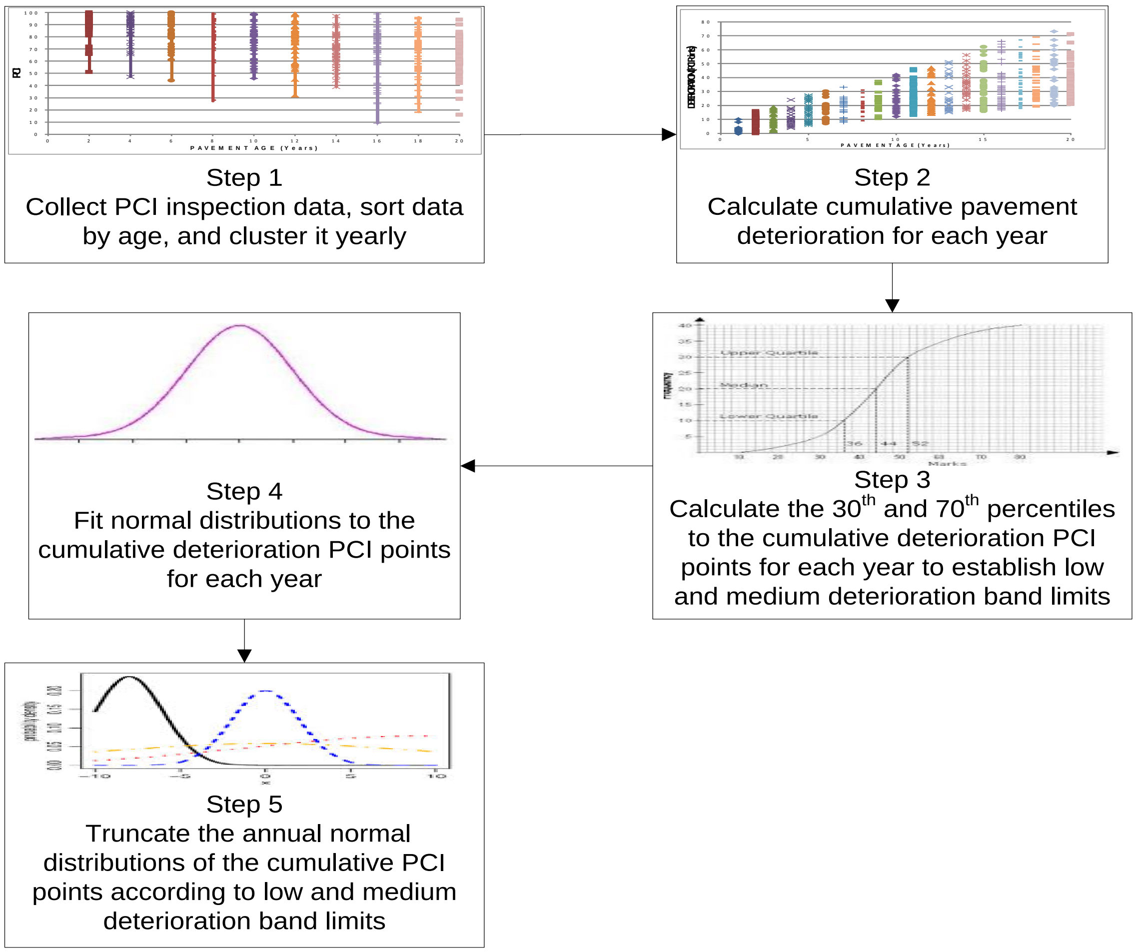

Figure 3.9 Steps for Developing the Probabilistic Pavement Performance-Based Scenarios

- Step 3 Calculate the 30th and 70th percentiles of the cumulative deterioration PCI points for each age j over the service life in order to establish low and medium deterioration band limits.
- Step 4 Fit normal distributions to the annual cumulative deterioration PCI points at age j.

- Step 5 Truncate the annual normal distributions of the cumulative deterioration PCI points at each age j over the service life, using the limits for low and medium deterioration bands established in step 3, to obtain PCI cumulative deterioration points with values within the limits of each deterioration band. The truncated annual normal distribution has its range (-∞ to +∞) but is constrained to assume values only in (k_1, k_2), being k_1 and k_2 in this research, the limits of the deterioration band. The objective of truncating the annual normal distribution within the limits of a deterioration band is to obtain, using Monte Carlo simulation, cumulative deterioration PCI points for each year with values within these limits. Monte Carlo simulation is a technique that uses random numbers from a probability distribution, in this case from the probability distribution of the CDPCI yearly values. Monte Carlo simulation of the annual CDPCI points displays the possible cumulative pavement deteriorations for the number of simulations performed.

Step 1. Collect PCI data and sort PCI values by pavement age

Collect inspected PCI data and sort PCI values into yearly bins corresponding to pavement age. Filtered inspection data used for the development of the probability-based performance curves are also used in the probabilistic pavement performance-based scenarios.

Step 2. Calculate the cumulative pavement deterioration in each year

Using the filtered inspection data clustered by age j, the cumulative pavement deterioration in PCI points (CDPCI) is calculated for each inspected pavement section

by subtracting the PCI value from 100 at the corresponding age bin as shown in Figure 3.10.

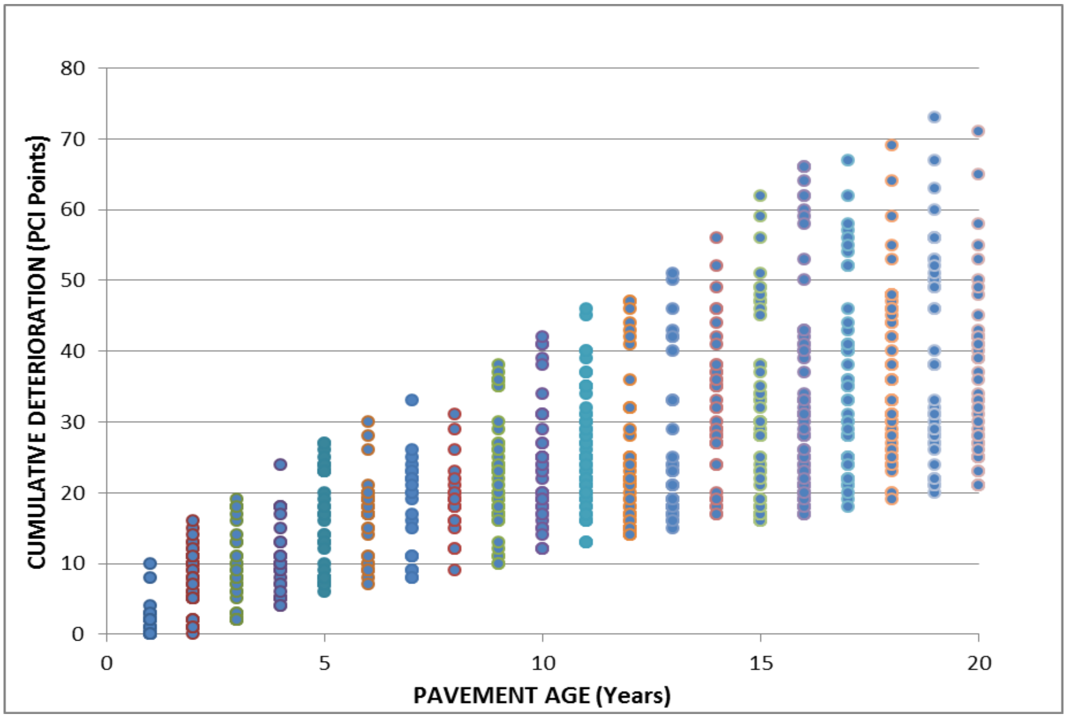

Figure 3.10 Cumulative Pavement Deterioration in PCI Points

Pavement cumulative deterioration is measured in PCI points at age j of the service life. Pavement cumulative deterioration is calculated at age j as 100 – PCI. Pavement deterioration in terms of PCI values can be clustered by age, Figure 3.10 shows cumulative pavement deterioration in terms of PCI points for each year of age j, for a period of 20 years after the outliers were removed. The annual deterioration ratio (ADR_j) is the number of PCI points a pavement loses in a certain year of age j. ADR is calculated as the cumulative deterioration in terms of PCI (CDPCI) points divided by j as shown in equation (3.4).

$$ADR_j = \frac{CDPCI_j}{j} \qquad (3.4)$$

where,

$CDPCI_j$ = Cumulative Deterioration in PCI points at year j

j = 1….20 years

Step 3. Calculate the 30th and 70th percentiles of the cumulative deterioration PCI points for each year.

PCI points of pavement cumulative deterioration are clustered in low, medium, and high deterioration bands. The MTC-PMS criteria for classifying pavement condition in PCI values is considered to establish limits for low, medium, and high deterioration bands. According to the MTC-PMS criteria, a pavement in very good condition has a PCI value from 100 to 70, a pavement in good condition has PCI values between 69 to 50, a pavement in poor condition has PCI values between 49 to 25, and a pavement in very poor condition or a failed pavement has PCI values below 25.

Upper limits for medium and low deterioration bands were set ± 20 percentile points respectively from the median of each CDPCI points age bin. The 30th percentile is set as the upper limit for the low deterioration band, in which the cumulative deterioration PCI points correspond to pavements in very good condition according to their age, with PCI values from 100 to 70. The 70th percentile is set as upper limit for the medium deterioration band that corresponds to pavements in good condition also based on their age, with PCI values between 50 and 69. The high deterioration band includes the upper 30% of the cumulative deterioration PCI values that corresponds to pavements having deteriorations above the medium considering their age, with PCI values between 25 and 49. Lowest and highest cumulative deterioration PCI points at each year are set as minimum values for the low deterioration band, and maximum

values for the high deterioration band. The deterioration band limits for cumulative PCI deterioration points are shown in Table 3.2, and plotted in Figure 3.11.

Table 3.2 Pavement Deterioration Band Limits in PCI Point

Pavement Age j	Low Deterioation Band Limits CDPCI Points		Medium Deterioration Band Limits CDPCI Points		High Deterioration Band Limits CDPCI Points	
	Lower, Lowest Value	Upper, 30th Percentile	Lower, 30th Percentile	Upper, 70th Percentile	Lower, 70th Percentile	Upper, Highest Value
1	0	0	0	2	2	10
2	0	5	5	10	10	16
3	2	3	3	11	11	19
4	4	7	7	12	12	24
5	6	8	8	19	19	27
6	7	15	15	19	19	30
7	8	13	13	22	22	33
8	9	17	17	20	20	31
9	10	18	18	26	26	38
10	12	19	19	25	25	42
11	13	21	21	30	30	46
12	14	17	17	25	25	47
13	15	18	18	27	27	51
14	17	27	27	36	36	56
15	16	19	19	33	33	59
16	17	22	22	36	36	66
17	18	27	27	41	41	67
18	19	28	28	44	44	69
19	20	29	29	50	50	73
20	21	28	28	42	42	71

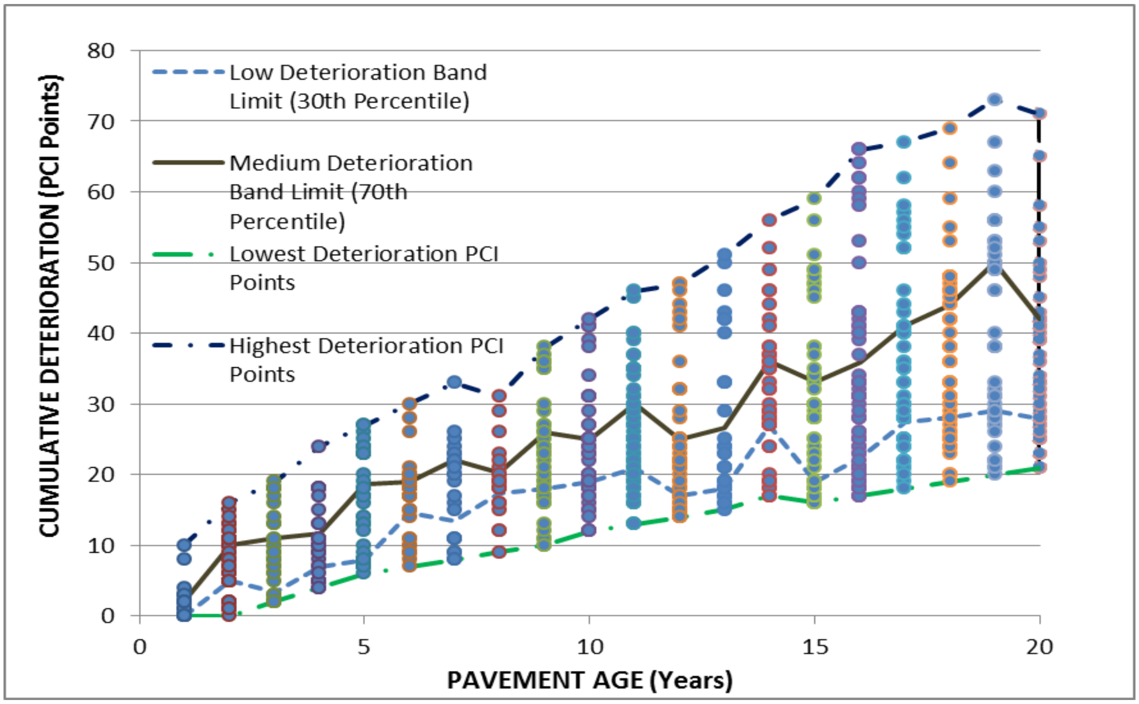

Figure 3.11 Low, Medium, and High Pavement Deterioration Bands

Step 4. Fit normal distributions to the cumulative deterioration PCI points.

Normal distributions for the PCI inspected values are also normal distributions for the cumulative deterioration PCI points because the cumulative deterioration PCI points are a linear function of PCI. The CDPCI points mean is calculated as:

$\mu_{CDPCI} = 100 - \mu_{PCI}$

where,

μ_{CDPCI} = CDPCI points mean

μ_{PCI} = PCI mean

The standard deviation for the CDPCI points is the same standard deviation as the PCI annual inspected values, because the standard deviation measures the amount of variation from the average. Normal distributions for each year of age and deterioration band are truncated at each deterioration band limits; the truncated Normal distributions are used because the range to generate CDPCI values is finite at both

ends of the interval for the limits of each deterioration band; hence the CDPCI generated values will be within the limits of the deterioration band. CDPCI means and standard deviations are used to build the truncated normal distributions.

Table 3.3 presents the means and standard deviations for the annual CDPCI in PCI points. Figure 3.12 shows a plot of the cumulative deterioration PCI points and fitted normal distributions.

Table 3.3 Cumulative Pavement Deterioration Statistics

Pavement Age j	Inspected PCI Mean	CDPCI Points Mean	PCI and CDPCI Standard Deviation
1	98.467	1.533	2.374
2	92.500	7.500	4.136
3	91.314	8.686	5.805
4	89.500	10.500	5.178
5	85.286	14.714	7.093
6	83.455	16.545	5.574
7	81.957	18.043	6.786
8	80.850	19.150	5.422
9	77.205	22.795	8.025
10	76.262	23.738	8.166
11	73.902	26.098	7.873
12	76.296	23.704	9.593
13	74.121	25.879	11.042
14	68.195	31.805	9.953
15	70.055	29.945	12.516
16	67.203	32.797	14.328
17	64.255	35.745	12.851
18	63.390	36.610	11.408
19	60.422	39.578	14.339
20	63.523	36.477	12.130

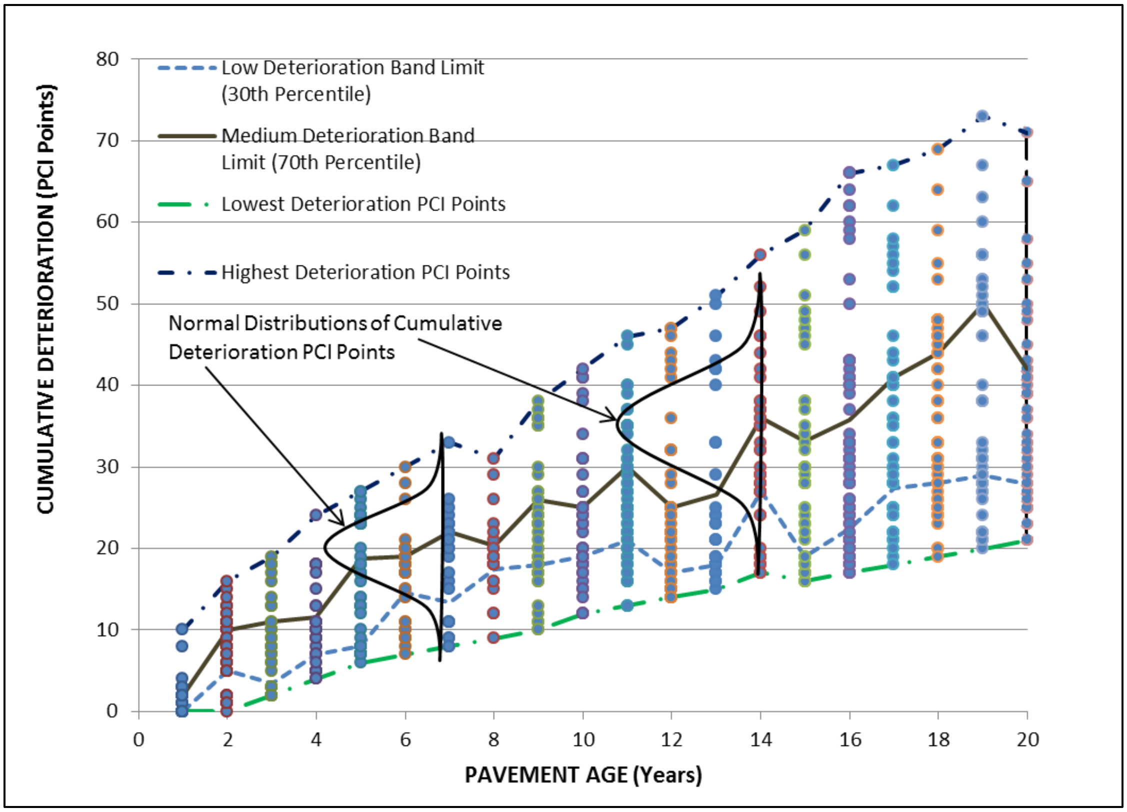

Figure 3.12 Cumulative Deterioration PCI Points and fitted Normal Distributions

Step 5. Truncate the annual normal distributions of the CDPCI points for each deterioration band.

To obtain the ADR that will be used in a needs analysis for each deterioration band, yearly cumulative deterioration points within each deterioration band limits have to be obtained, this is done truncating the annual normal distribution of the CDPCI points as explained before (step 5 page 54).

Truncate the normal distribution of cumulative deterioration PCI points for each year of age and deterioration band to obtain PCI cumulative deterioration points with values within the limits of each deterioration band (Greene 2008).

The truncated probability density function is stated as:

$$f(x;\ \mu,\sigma,a,b) = \frac{\frac{1}{\sigma}\varphi\left(\frac{x-\mu}{\sigma}\right)}{\emptyset\left(\frac{b-\mu}{\sigma}\right) - \emptyset\left(\frac{a-\mu}{\sigma}\right)} \tag{3.5}$$

$$F(x;\ \mu,\sigma,a,b) = \frac{\emptyset\left(\frac{x-\mu}{\sigma}\right) - \emptyset\left(\frac{a-\mu}{\sigma}\right)}{\emptyset\left(\frac{b-\mu}{\sigma}\right) - \emptyset\left(\frac{a-\mu}{\sigma}\right)} \tag{3.6}$$

A Monte Carlo simulation is used to generate random cumulative deterioration PCI points for each age j using equation 3.7 within the limits of a deterioration band, the random $CDPCI_j$ values are used to calculate random ADR_j values with equation 3.4, to project PCI values over the analysis period, instead of using PCIs projected with equation 1.1. With the use of Monte Carlo simulation, a set of random PCIs over the analysis period is obtained to build an end of period PCI histogram. Percentiles chosen from the set of PCIs used to build the histogram generate a probabilistic performance-based scenario of pavement performance.

A random value for CDPCI is calculated with the following equation:

$$CDPCI_j = \emptyset^{-1}\left(\emptyset\left(\frac{a-\mu}{\sigma}\right) + U\left(\emptyset\left(\frac{b-\mu}{\sigma}\right) - \emptyset\left(\frac{a-\mu}{\sigma}\right)\right)\right)\sigma + \mu \tag{3.7}$$

where

$CDPCI_j$ = random CDPCI value at age j within the band limits

μ = mean of the normal distribution of cumulative deterioration PCI points at age j

σ = standard deviation of the normal distribution of cumulative deterioration PCI points at age j

a = lower limit of the deterioration band at age j

b = upper limit of the deterioration band at age j

$\varphi(.)$ = probability density function of (.)

$\emptyset(.)$ = cumulative distribution function of (.)

$\emptyset^{-1}(.)$ = inverse cumulative distribution function of (.)

U = a random number (0, 1)

Figure 3.12 shows a plot of the probability density function of the cumulative deterioration PCI points for year 2. Figure 3.13 shows the truncated probability density function of the CDPCI points for year 2 over 0 to 5 CDPCI points in the low deterioration band and Figure 3.14 shows the truncated cumulative distribution function of the CDPCI points for year 2 in the low deterioration band for CDPCI points from 0 to 5.

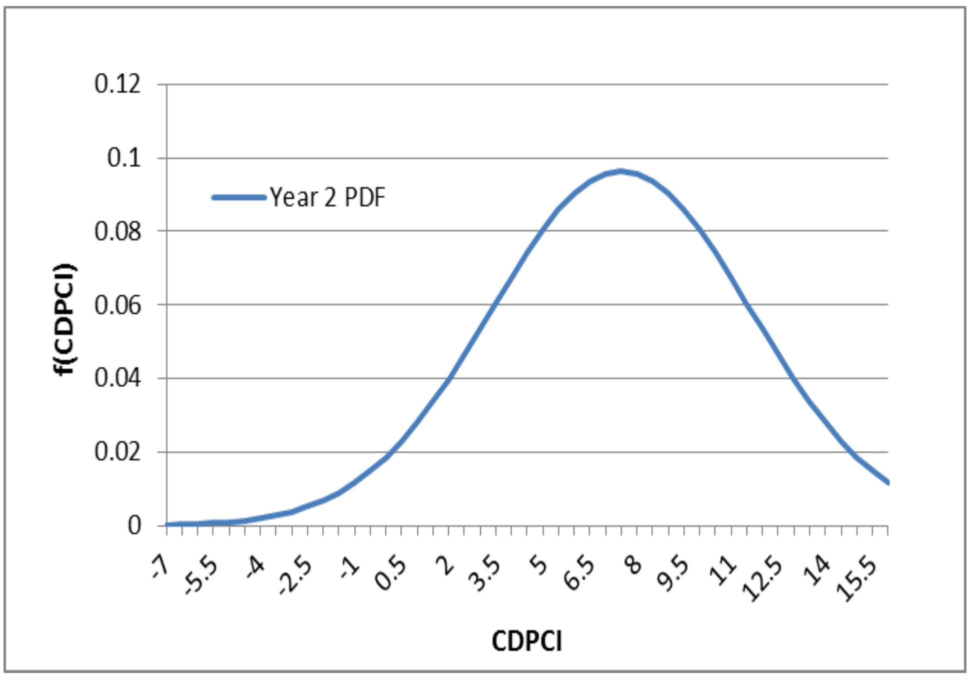

Figure 3.12 Probability Density Function of the Cumulative Deterioration PCI Points for Year 2

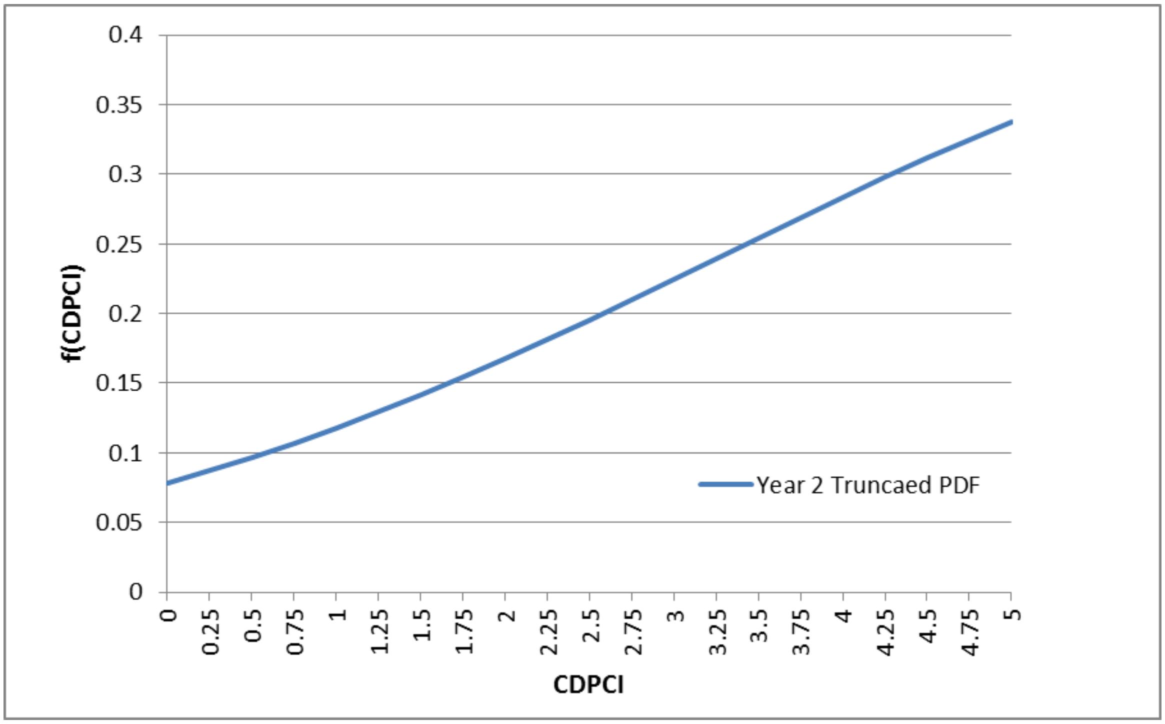

Figure 3.13 Truncated PDF of the Cumulative Deterioration PCI Points for the Low Deterioration Band at Year 2

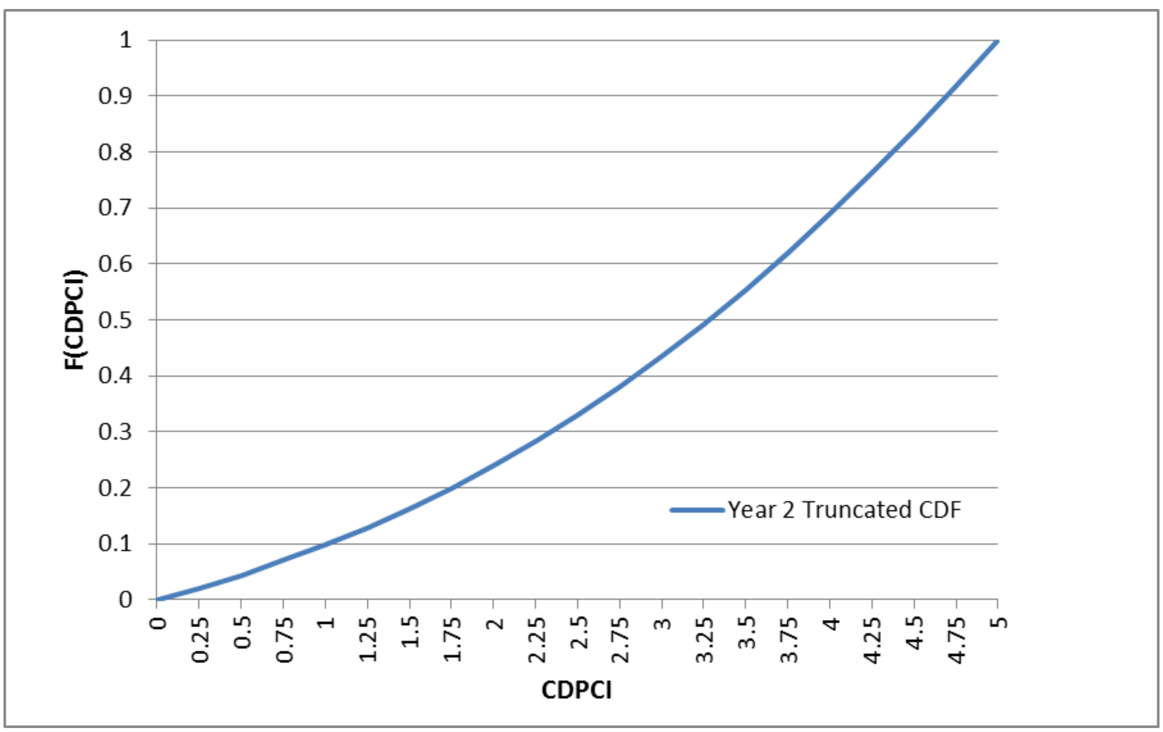

Figure 3.14 Truncated CDF of the Cumulative Deterioration PCI Points for the Low Deterioration Band at Year 2

3.2.2 Use of the Probabilistic Performance-Based Scenarios to Project Pavement Condition

The needs analysis using the PPPBS generates annual CDPCI points within a deterioration band using Monte Carlo simulation that will be used to project pavement performance instead of using equation 1.1, presenting possible pavement performance scenarios.

The year at which the PCI projection period begins is year k=1 of the analysis period, which can be 5, 10, or 20 years. Pavement sections analyzed can have different ages j. Based on the PCI of the section at age j, the section is located in the low, medium, or high deterioration band. CDPCI values for the section are calculated for ages j, j+1 until j=20, which are used for year k=1, k=2, until k= last year of the analysis period. Figure 3.15 shows a flowchart with the procedure to project PCIs in a probability performance-based scenario.

The procedure for the PCI projection analysis for a pavement deterioration scenario is as follows.

- Define analysis period in k years
- Select a low, medium, or high pavement deterioration band to conduct a section's PCI projection analysis
- Select a section and calculate the age j at year k=1 of the analysis, as follows:

$AGE_{j,\ k=1}$ = ANAL_YR – CONST_YR

Or if an overlay treatment was applied to the section

$AGE_{j,\ k=1}$ = ANAL_YR – OVERLAY_YR

OVERLAY_YR = Date of the latest overlay treatment

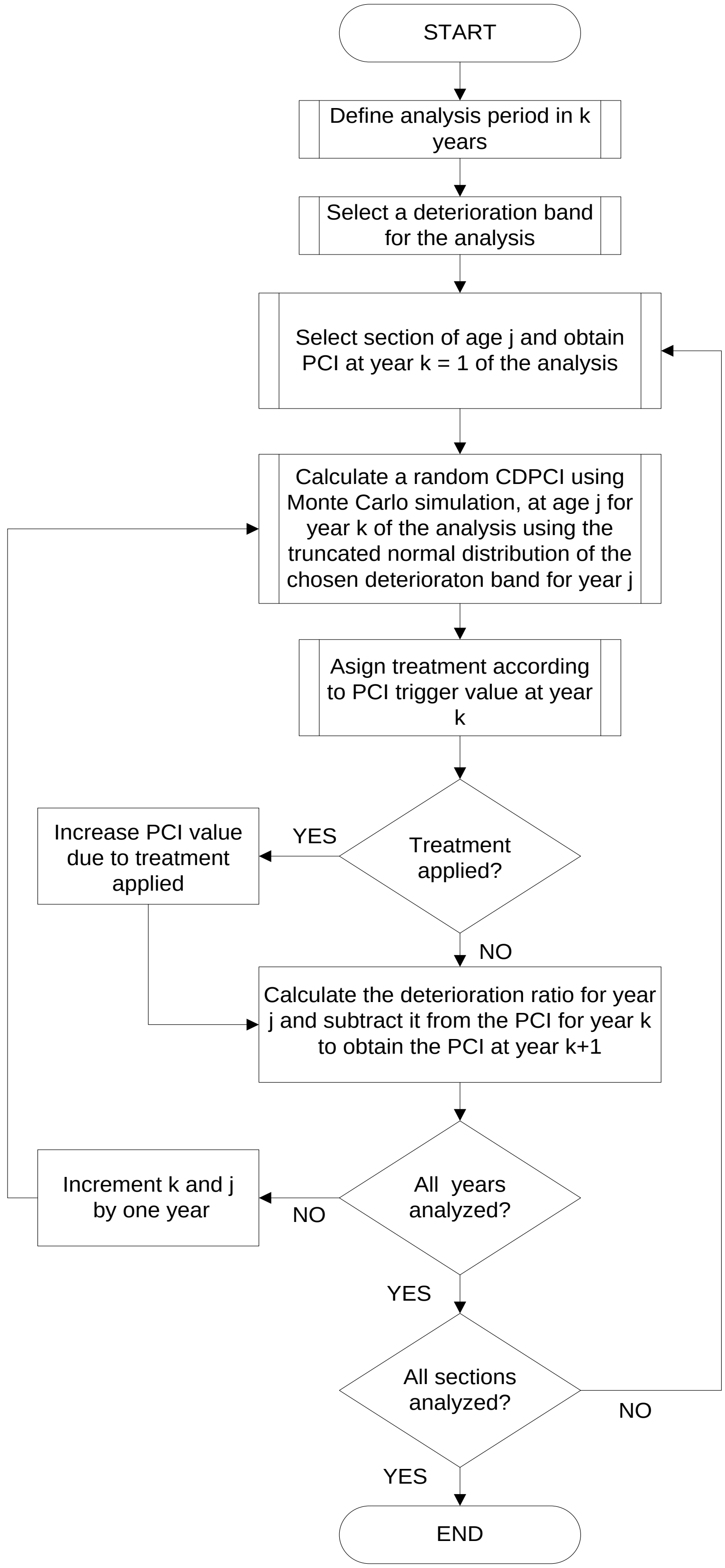

Figure 3.15 Procedure for PCI Projections for a Probabilistic Pavement Deterioration-Based Scenario

where

ANAL_YR = Date at the beginning of the analysis

CONST_YR = Construction date

- Obtain the PCI of a section at the beginning of the analysis period as:

$PCI_{k=1}$ = PCI_INSP

If there is not an inspected PCI then project the PCI at age j as:

PCI_{PROj} = 100 - $CDPCI_j$

$PCI_{k=1}$ = PCI_{PROj}

where

$PCI_{k=1}$ = PCI at the beginning of the analysis period

PCI_INSP = Inspected PCI value of the section

PCI_{PROj} = Projected PCI at age j

- Calculate a random $CDPCI_j$ using Monte Carlo simulation for age j with equation 3.7 from the truncated probability distribution for that band. Random $CDPCI_j$ values for age j are used to calculate an ADR_j using equation 3.4, to obtain a PCI value.

- Calculate the PCI value for year k+1as:

$$PCI_{j,\,k+1} = PCI_{j,\,k} - ADR_j \qquad (3.8)$$

where

j: 1….20 year of the pavement age

k: 1….m year of the analysis period

ADR_j = Annual deterioration rate for age j

- If a treatment is applied in year k based on PCI trigger values, the PCI value at year k increases as shown in Figure 3.15. The PCI before treatment increases its value due to the treatment applied, to obtain the PCI after treatment. The PCI value for year k+1 is calculated from the PCI after treatment for year k.

$$PCI_{ATk} = PCI_{BTk} + INC$$

$$PCI_{j,\,k+1} = PCI_{ATk} - ADR_j \qquad (3.9)$$

where

PCI_{BTk} = PCI before treatment at year k

PCI_{ATk} = PCI after treatment at year k

INC = PCI points increase due to treatment applied

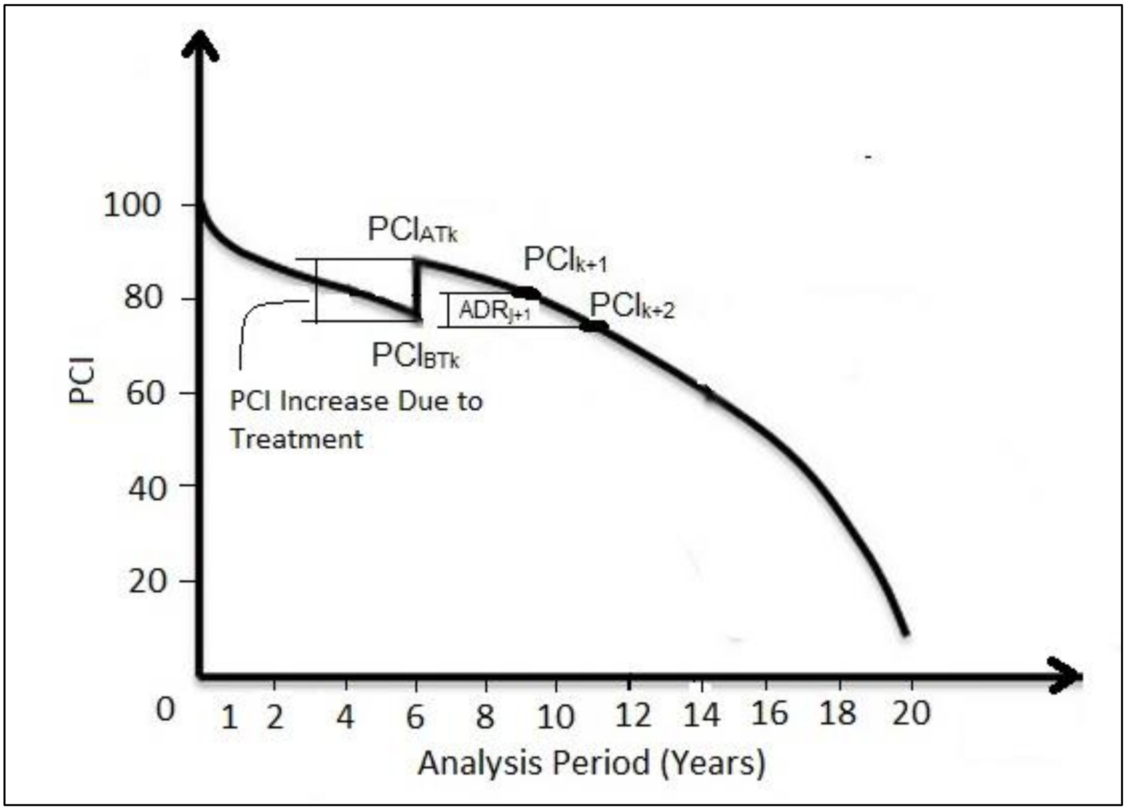

Figure 3.15 Cumulative Deterioration Calculation process

- Calculate PCI value at year k+2 as:

$$PCI_{k+2} = PCI_{k+1} - ADR_{j+1}$$

ADR_{j+1} is calculated with equation 3.4 for age j+1as:

$$ADR_{j+1} = \frac{CDPCI_{j+1}}{j+1}$$

PCI values are calculated for each year over the analysis period with equation 3.8. This process is repeated until the end of the analysis period.

- Once the PCI has been projected for all years of analysis for one section, the same calculation process is repeated for all the other sections in the pavement network.

When the PCI projection analysis is finished, there will be as many projected PCIs at the end of the analysis period as the number of Monte Carlo simulations. The number of projected PCIs in the deterioration band is shown in a histogram. PCI values can be obtained for different percentiles representing a pavement performance-based scenario. Figures 3.16a and 3.16b show as an example the histogram for a group of five pavement sections in a low deterioration band at year 5 showing frequency and density of the PCIs respectively.

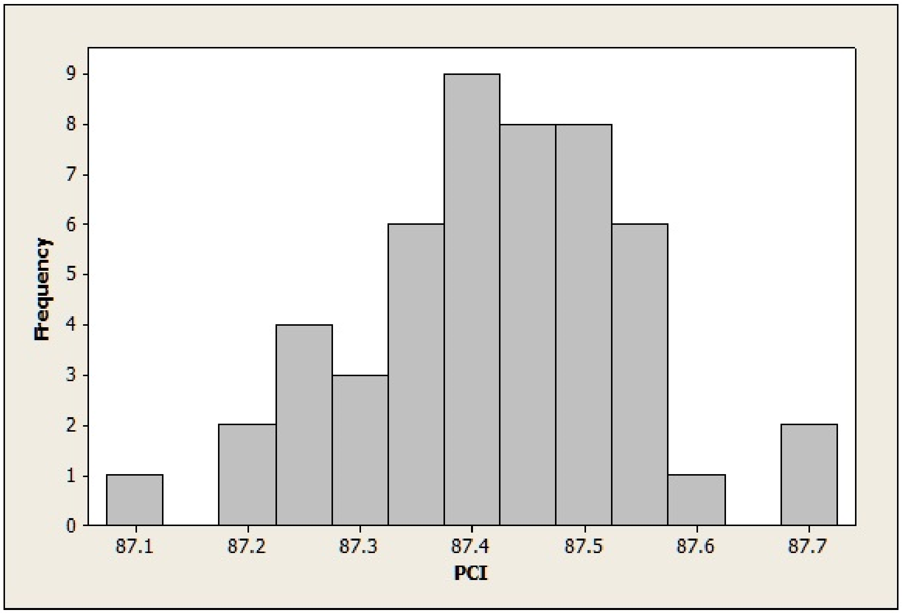

Figure 3.16a Histogram of PCIs at Year 5 for a Low Deterioration Band Showing PCI Frequency

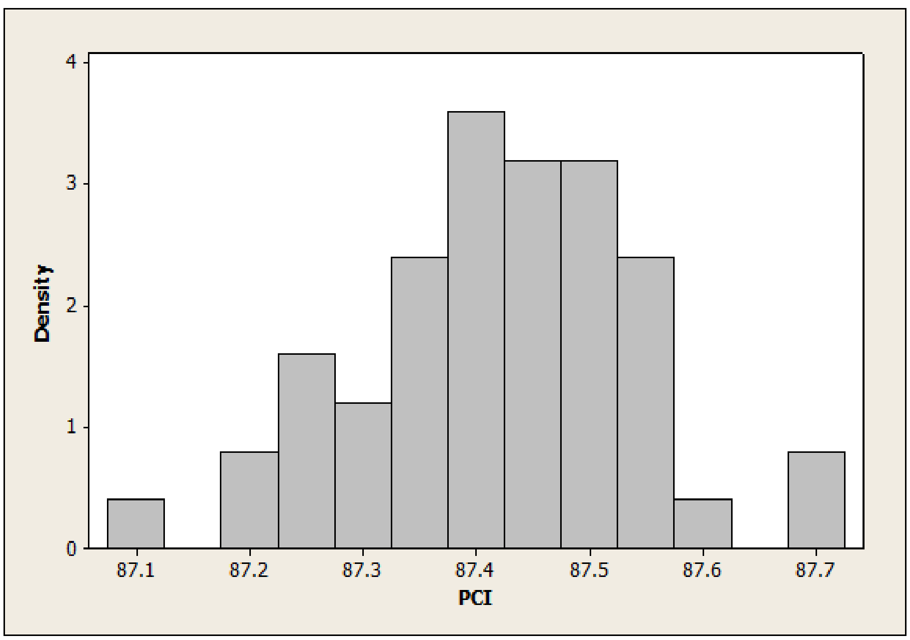

Figure 3.16b Histogram of PCIs at Year 5 for a Low Deterioration Band Showing PCI Density

3.3 Concluding Remarks

The probabilistic pavement performance prediction models developed in this dissertation address the uncertainty in the prediction of future pavement condition.

Probability-based pavement performance curves predict future pavement condition starting from the pavement present condition state providing alternatives of future pavement condition according to chosen probability of performance levels. Probabilistic pavement performance-based scenarios predict pavement condition based on a Monte Carlo simulation of the CDPCI, also starting from the pavement present condition state, obtaining scenarios of future pavement condition according to different pavement deterioration bands. End of period PCI values can be plotted in a histogram, to show diverse pavement performance scenarios according to different percentiles.

As an advantage to the traditional models, both stochastic approaches described in this Chapter, provide broad information about future pavement condition scenarios to develop maintenance and rehabilitation programs. These models can be applied at the network management level for the entire pavement network, or at the project management level for individual pavement sections. The models are easier to apply when compared to Markovian or Bayesian models, because there is no need to construct probability transition matrices or establish prior probabilities. The future pavement condition is predicted using PBPPCs setting the probability of performance level based on low, medium, or high past pavement performance; or using PPPBS generating random CDPCI values using Monte Carlo simulation to calculate ADR values and project PCIs for each year of the analysis period within the selected deterioration band.

PBPPC and PPPBS are an aid for decision making for section selection and budget allocation. At the network management level, needs analyses can be performed for the entire pavement network to simulate different pavement performance trends and

obtain corresponding budget needs scenarios. At the project management level Individual sections or groups of sections can be analyzed with a PBPPC or within a PPPBS deterioration band selected based on the section's past performance.

In Chapter 4, the PBPPC approach is applied in a case study to a needs and a target driven analysis for a pavement network, to estimate budget needs at different pavement performance levels comparing results to an average pavement performance. In Chapter 5, the PPPBS approach is applied in a case study to a needs analysis for a pavement network, to estimate budget needs for different pavement deterioration trends, obtaining alternate pavement deterioration scenarios, comparing results to an average pavement deterioration trend.

Chapter 4: Applicability of Probability-Based Pavement Performance Curves in Pavement Management Case Studies

4.1 Probabilistic Pavement Performance and Budget Needs

The stochastic methods presented in Chapter 3 use PCI probability distributions for the prediction of pavement performance. The approach recognizes the uncertainty in pavement deterioration and recommends PBPPC to assess the uncertainty and variability in pavement future condition predictions.

Databases from the Cities of Belmont, San Carlos, Milpitas, San Ramon, San Anselmo, and Santa Rosa in the San Francisco California Bay Area are used to develop PBPCs for arterial streets, paved with asphalt concrete (AC) and with asphalt concrete over asphalt concrete (AC/AC). The model selected to illustrate the application of the PBPCs is from the MTC-PMS. The pavement network of Milpitas, California is used to run the analyses for case studies applying the PBPPCs on arterial streets paved with AC and with AC/AC to estimate budget needs at different pavement performance levels, comparing results to an average pavement performance level.

Database from Marion County, Oregon is used to develop PBPPCs for residential streets paved with surface treatment (ST); the model selected to illustrate the application of PBPPCs is also from the MTC-PMS. Marion County, Oregon pavement network is used to run the analyses for case studies applying the PBPPCs on residential streets paved with ST, also to estimate budget needs at different pavement performance levels comparing results to an average pavement performance level.

Two case studies are presented in this chapter to demonstrate the applicability of the PBPC for pavement condition projections and budget needs.

- Case 1 consists of three different independent needs analyses using the probability-based pavement performance curves applied to:

  1.a. Arterial streets paved with asphalt concrete from the Milpitas, California pavement network.

  1.b. Arterial streets paved with asphalt concrete over asphalt concrete from the Milpitas, California pavement network.

  1.c. Residential streets paved with surface treatments from the Marion County, Oregon pavement network.

- Case 2 consists of three different independent target driven PCI analyses using the probability-based pavement performance curves applied to:

  2.a. Arterial streets paved with asphalt concrete from the Milpitas, California pavement network.

  2.b. Arterial streets paved with asphalt concrete over asphalt concrete from the Milpitas, California pavement network.

  2.c. Residential streets paved with surface treatments from the Marion County, Oregon pavement network.

4.2 Case study 1. Needs Analysis using the Probability-Based Pavement Performance Curves

Probability-based pavement performance curves are applied in independent needs analyses using the pavement network of the City of Milpitas, California and the pavement network of Marion County, Oregon.

The City of Milpitas has 291.5 lane miles with a pavement area of 1 square miles, 15.01 lane miles correspond to arterial streets paved with asphalt concrete. 74% of the

pavement network is asphalt concrete with 99 sections, and the remaining 26% is asphalt concrete over asphalt concrete with 87 sections. The current average pavement network condition is a PCI of 63 that is considered good condition. Arterial streets have an average PCI of 65 that is considered a good condition.

Marion County, Oregon has 2223.7 lane miles with a pavement area of 4.1 square miles. The pavement network is mainly composed of residential and local streets.16% of the pavement network is surface treatment with 151 sections, 49% is asphalt concrete over asphalt concrete, 22% is asphalt concrete, and the remaining 13% is gravel. The current pavement network condition average is a PCI of 73, which is considered in very good condition. Residential streets have an average PCI of 72 that is considered a very good condition.

The needs analysis consists in identifying pavement sections in need of maintenance or rehabilitation based on PCI projected values and PCI trigger values set in the treatment selection decision three. The needs analysis recommends the maintenance and rehabilitation treatment for each pavement section over the planning period, to preserve the entire pavement network in good condition. This analysis assumes unlimited budget.

The data consist of PCI values from field inspections, date of inspections, and construction dates for each management section. With the inspection and construction dates, a pavement age associated to the PCI value is established for each inspected section. Data from each surface type is processed separately. When the PCI on an asphalt concrete pavement drops below 50, the treatment recommended to apply is an overlay with AC or a reconstruction of the surface using a thick AC overlay, changing the

surface type to AC/AC, the analysis continues from this point considering the section's surface type as AC/AC. Residential ST sections are used in the case study because of the study conducted for MTC in the Marion County, Oregon residential ST pavement sections.

The steps to construct the PBPPCs as stated in Chapter 3 are followed in the next section.

4.2.1 Collect PCI Data, Sort PCI Values by Pavement Age into Yearly Bins and Remove Outliers

Data sets spanning no further than 20 years were selected because many agencies do not have reliable entries in their databases for events older than 20 years. Many times the treatments applied to the pavements more than 20 years ago are not recorded in the databases, and PCI inspected values from more than 20 years ago are sometimes not recorded in the databases.

Data from arterial sections was sorted from 0 to 20 years of age and separated in yearly bins. Upon inspection of the raw data, it was observed that there were very low PCI values for early ages, and very high PCI values for late ages, probably due to rehabilitation treatments that were applied but not registered, or inspection dates that were not entered correctly in the database. These outliers are removed by setting lower and upper limits by expert knowledge.

For arterial sections paved with asphalt concrete, the cutting line starts at a PCI value of 100 at year 0 keeping this value until year 2, then descends with a constant slope of -0.5 down to year 5, changes slope in this point to -1 and descends with this slope until year 20 to end at a PCI value of 79. Points with very low PCI value are

filtered by removing data points below a line that starts at a PCI value of 92 at year 0 descending with a constant slope of -4 down to year 4, changes slope at this point down to year 10, and changes again slope down to year 20 to end in a PCI value of 18, these limits are shown in Figure 4.1.

For arterial sections paved with asphalt concrete over asphalt concrete, the cutting line starts at a PCI value of 100 at year 0 keeping this value until year 3, then descends with a constant slope of -1.6 down to year 7, changes slope in this point and descends with slope until year 20 to end at a PCI value of 79. Points with very low PCI value are filtered by removing data points below a line that starts at a PCI value of 92 at year 0 and descends with a constant slope of -3.5 until year 3, changes slope at this point down to year 7, changes slope again down to year 20 to end in a PCI value of 33, these limits are shown in Figure 4.2.

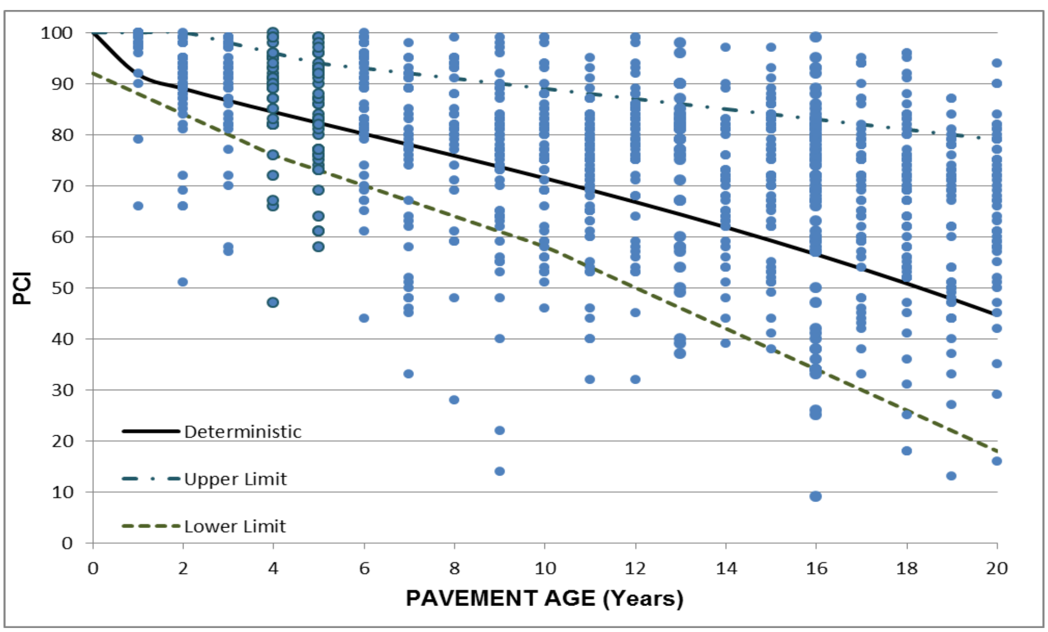

Figure 4.1 AC PCI Values from Inspection at Different Ages and Limits for Outliers

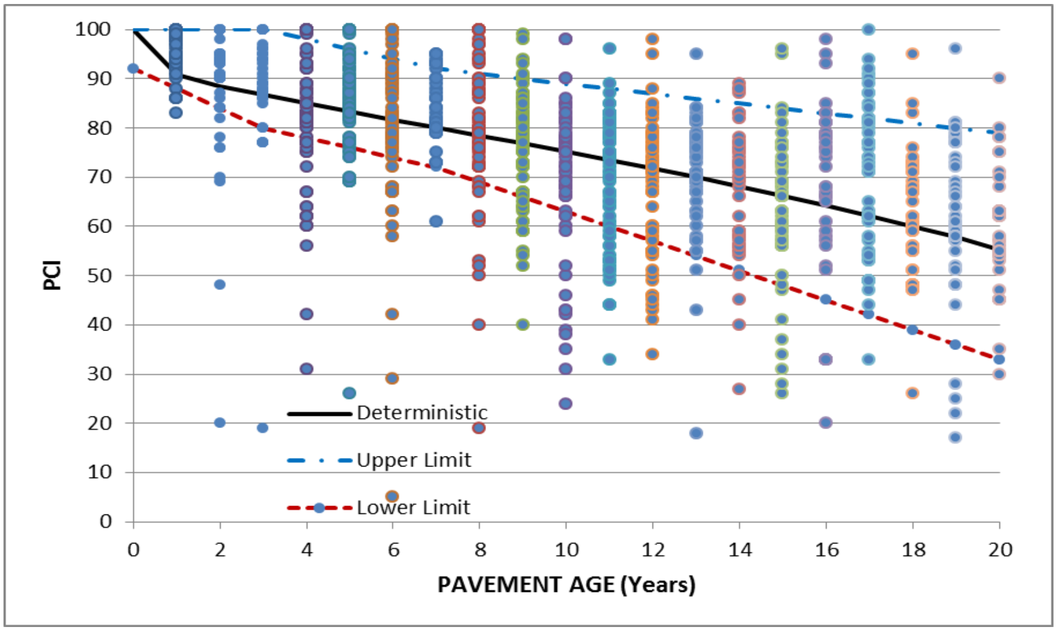

Figure 4.2 AC/AC PCI Values from Inspection at Different Ages and Limits for Outliers

For residential sections with a surface treatment the cutting line starts at a PCI value of 100 at year 0 and descends with a constant slope of -1 down to year 5, changes slope in this point to -2, down to year 10, changes slope to -3 down to year 15, and changes slope to -4 to end in a PCI value of 50 at year 20. Sections with very low PCI values for their age are filtered by eliminating sections with PCI values below a straight line that starts at a PCI value of 90 at year 0, and ends in year 18 with a PCI value of 0. The limits for the outliers are set this way, by expert knowledge, so the drop in PCI value in the first years will not be so sharp because a new pavement is not likely to lose more than 20 PCI points in the first year of its service life. The limits are shown in Figure 4.3.

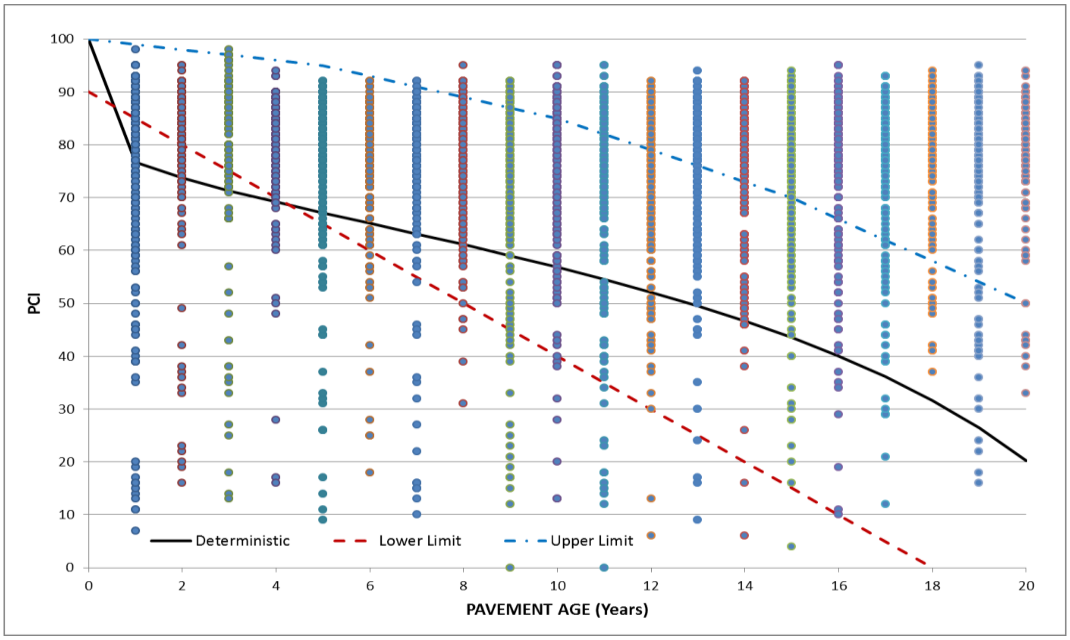

Figure 4.3 ST PCI Values from Inspection at Different Ages and Limits for Outliers

Only values falling within these bounds are used in the analysis. Figures 4.1, 4.2, and 4.3 show all the observed PCI data, the limits for PCI outliers, and the projected pavement condition family curve plotted with the α, β, and ρ default values.

4.2.2 Fit Probability Distributions for each Year of the Pavement Service Life.

Using the reduced data sets, for the inspected PCI values over the expected service life; probability distributions for the inspected PCI values were fitted for each year. Inspected arterial AC PCI values without outliers are shown in Appendix A, Tables A.1a and A.1b; Inspected arterial AC/AC PCI values without outliers are shown in Appendix A, Tables A.2a and A.2b; Inspected residential ST PCI values are shown in Appendix A, Tables A.3a through A.3d. In this work, the Normal distribution was chosen for fitting PCI values because it fitted all data sets according to goodness of fit tests with a 0.01 significance level (see Appendix A, Tables A.4, A.5, and A.6).

Mean (μ_j) and standard deviation (σ_j) for each year j of the service life were computed for arterial AC, arterial AC/AC, and residential ST sections and are shown in Table 4.1. These statistics are used to construct the PBPPCs utilized for cases 1 and 2. Figures 4.4, 4.5, and 4.6 show, as an example, the cumulative distributions fits to the PCIs for year 3 and the fitted normal cumulative distribution functions for arterial AC, arterial AC/AC, and residential ST sections (see also Appendix A, Figures A.1 through A.6 for arterial AC; Appendix A, Figures A.7 through A.12 for arterial AC/AC and Appendix A, Figures A.13 through A.18 for residential ST).

Table 4.1 PCI Statistics for Years 1 to 20

Year j	Arterial AC Sections			Arterial AC/AC Sections			Residential ST Sections		
	PCI Mean μj	PCI Standard Deviation σj	PCI Coefficient of Variation %	PCI Mean μj	PCI Standard Deviation σj	PCI Coefficient of Variation %	PCI Mean μj	PCI Standard Deviation σj	PCI Coefficient of Variation %
1	98.47	2.37	2.41	97.19	3.20	3.30	89.39	2.82	3.16
2	92.50	4.14	4.47	93.84	4.61	4.91	86.18	3.63	4.22
3	91.31	5.81	6.36	91.82	5.60	6.10	86.37	5.61	6.49
4	89.50	5.18	5.79	85.28	4.68	5.49	82.66	5.38	6.51
5	85.29	7.09	8.32	86.44	5.14	5.95	80.93	6.17	7.62
6	83.46	5.57	6.68	83.30	5.34	6.41	80.15	6.95	8.67
7	81.96	6.79	8.28	81.85	4.79	5.85	79.83	6.83	8.55
8	80.85	5.42	6.71	79.70	5.59	7.02	77.47	8.81	11.37
9	77.21	8.03	10.39	79.37	6.33	7.98	74.38	10.30	13.85
10	76.26	8.17	10.71	75.14	5.64	7.51	73.22	11.18	15.27
11	73.90	7.87	10.65	75.10	7.01	9.33	69.31	12.03	17.36
12	76.30	9.59	12.57	72.68	7.21	9.92	65.04	12.51	19.23
13	74.12	11.04	14.90	71.58	7.88	11.00	63.59	10.24	16.10
14	68.20	9.95	14.59	67.12	9.34	13.92	59.00	10.71	18.15
15	70.06	12.52	17.87	65.08	8.52	13.10	53.72	14.93	27.80
16	67.20	14.33	21.32	71.52	9.90	13.85	50.98	14.18	27.82
17	64.26	12.85	20.00	63.83	11.57	18.13	48.00	13.02	27.13
18	63.39	11.41	18.00	61.08	9.36	15.33	47.06	5.88	12.49
19	60.42	14.34	23.73	63.29	10.25	16.19	38.54	10.12	26.26
20	63.52	12.13	19.10	59.39	10.30	17.35	42.56	5.39	12.66

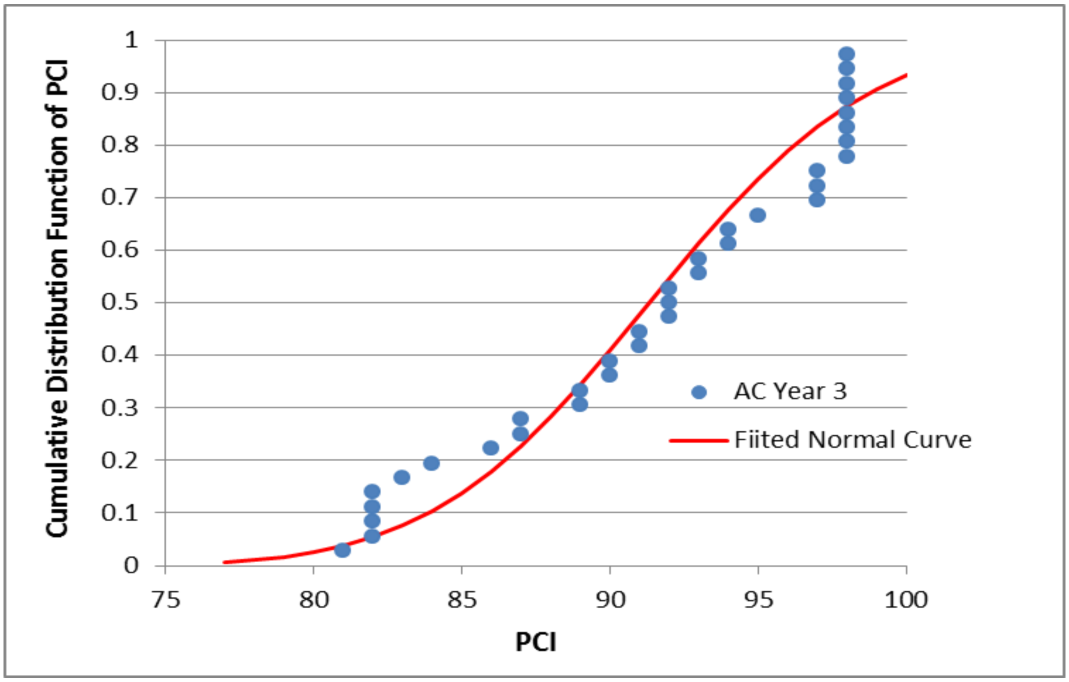

Figure 4.4 PCI Cumulative Distribution Function Year 3 for Arterial AC Sections

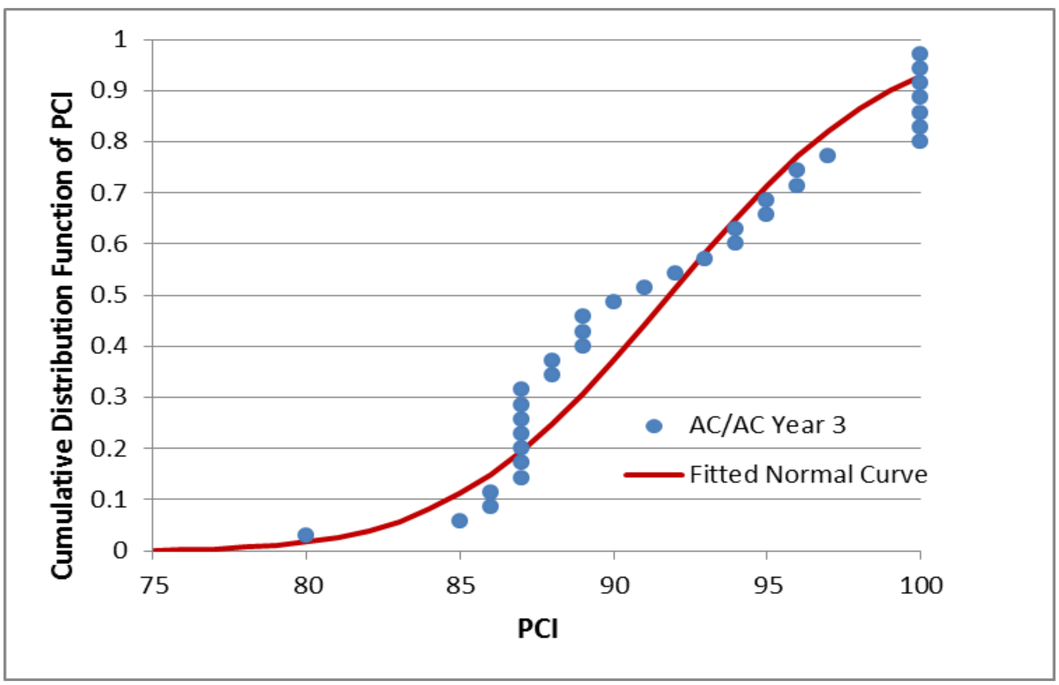

Figure 4.5 PCI Cumulative Distribution Function Year 3 for Arterial AC/AC Sections

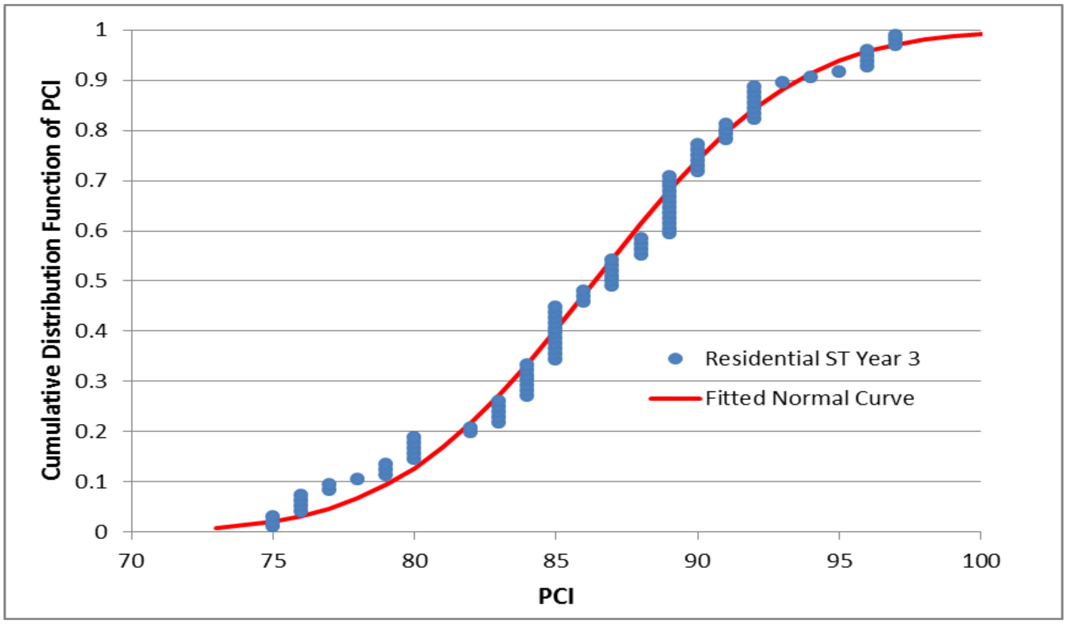

Figure 4.6 PCI Cumulative Distribution Function Year 3 for Residential ST Sections

4.2.3 Determine PCI Percentile Values for a Probability of Performance Level and Join the PCI Percentile Values to Create a Probability-Based Pavement Performance Curve.

The probability of performance is the likelihood that a certain PCI value at year j will be greater or equal to the p-percentile PCI value, being p the probability level, this level can be any value set by the decision-makers.

Since probability distributions are already determined for every year in the 20 year range, probability pavement performance curves for 90%, 70%, 50%, and 30% probability levels are calculated for each year in the 20 year range, as stated in Chapter 3.

The projected PCI value decreases as the age increases; this means a pavement deteriorates due to traffic loads and environmental effects as the pavement gets older. A 30% probability of pavement performance means that a pavement has a

30% probability that at a certain year the PCI will be greater or equal to the p-percentile PCI value.

Projected PCI values obtained using the current deterministic α, β, and ρ parameters as well as projected PCI values obtained using the α, β, and ρ parameters for the 90%, 70%, 50%, and 30% PBPCs for arterial AC, arterial AC/AC, and residential ST at each year of the twenty-year analysis period are shown in Tables 4.2, 4.3, and 4.4 respectively, and plotted in Figures 4.7, 4.8, and 4.9. The average pavement performance is considered a medium pavement deterioration rate that is represented by a 50% probability level curve. Low, medium, and high deterioration rates ranges are set considering the MTC-PMS criteria for classifying pavement condition in PCI values as follows.

- The low deterioration rate range is set for probability levels of 30% or below, corresponding to pavements in very good condition with PCIs from 100 to 70.
- The medium deterioration range is set from above 30% to below 70% probability levels, considering in this range the average pavement performance, including pavements in good condition with PCIs from 69 to 50.
- The high deterioration rate range is set for probability levels of 70% and above, corresponding to pavements in poor condition with PCIs below 50.

The deterministic PCI curves in Figures 4.7, 4.8, and 4.9 show a uniform deterioration trend from years 1 to 20 because were plotted using α, β, and ρ default values. However, the probability-based performance curves do not show a uniform deterioration rate because the points in each year for each performance probability were developed with equation (3.4) from Chapter 3 using means and standard

deviations calculated from inspection data, and show the variability in the PCI from year to year as reported in Table 4.1.

Table 4.2 Arterial AC Projected PCI Values for Each Probability Level

Age	Current Deterministic PCI	Arterial AC Probability-Based Pavement Performance Curves			
		90%	70%	50%	30%
0	100	100	100	100	100
1	91.78	95.42	97.22	98.47	99.71
2	89.01	87.20	90.33	92.50	94.67
3	86.64	83.87	88.27	91.31	94.36
4	84.43	82.86	86.78	89.50	92.22
5	82.28	76.20	81.57	85.29	89.01
6	80.15	76.31	80.53	83.46	86.38
7	78.02	73.26	78.40	81.96	85.52
8	75.87	73.90	78.01	80.85	83.69
9	73.68	66.92	73.00	77.21	81.41
10	71.44	65.80	71.98	76.26	80.54
11	69.15	63.81	69.77	73.90	78.03
12	66.79	64.00	71.27	76.30	81.33
13	64.36	59.97	68.33	74.12	79.91
14	61.85	55.44	62.98	68.20	73.41
15	59.24	54.02	63.49	70.06	76.62
16	56.55	48.84	59.69	67.20	74.72
17	53.75	47.79	57.52	64.26	70.99
18	50.84	48.77	57.41	63.39	69.37
19	47.81	42.05	52.90	60.42	67.94
20	44.66	47.98	57.16	63.52	69.88

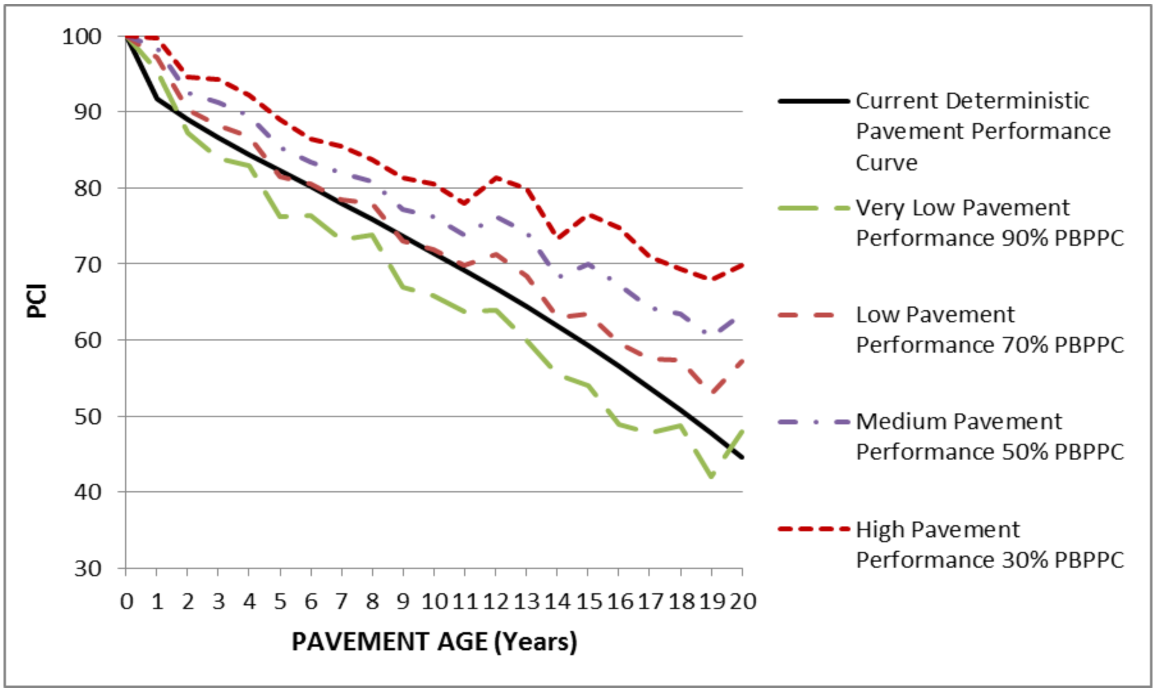

Figure 4.7 Arterial AC Probability-Based Pavement Performance Curves for a Twenty-Year Period

Table 4.3 Arterial AC/AC Projected PCI Values for Each Probability Level

Age	Current Deterministic PCI	Arterial AC/AC Probability-Based Pavement Performance Curves			
		90%	70%	50%	30%
0	100	100	100	100	100
1	90.85	93.08	95.51	97.19	98.87
2	88.56	87.94	91.43	93.84	96.26
3	86.67	84.65	88.89	91.82	94.76
4	84.94	79.28	82.83	85.28	87.74
5	83.30	79.85	83.74	86.44	89.13
6	81.70	76.46	80.50	83.30	86.10
7	80.10	75.72	79.34	81.85	84.36
8	78.50	72.53	76.77	79.70	82.63
9	76.88	71.26	76.05	79.37	82.69
10	75.24	67.91	72.18	75.14	78.10
11	73.55	66.12	71.42	75.10	78.77
12	71.82	63.44	68.90	72.68	76.46
13	70.03	61.49	67.45	71.58	75.71
14	68.18	55.15	62.22	67.12	72.02
15	66.27	54.15	60.61	65.08	69.55
16	64.27	58.82	66.32	71.52	76.71
17	62.19	54.00	62.77	68.83	74.90
18	60.02	49.08	56.17	61.08	65.99
19	57.74	50.15	57.91	63.29	68.66
20	55.36	46.19	53.99	59.39	64.79

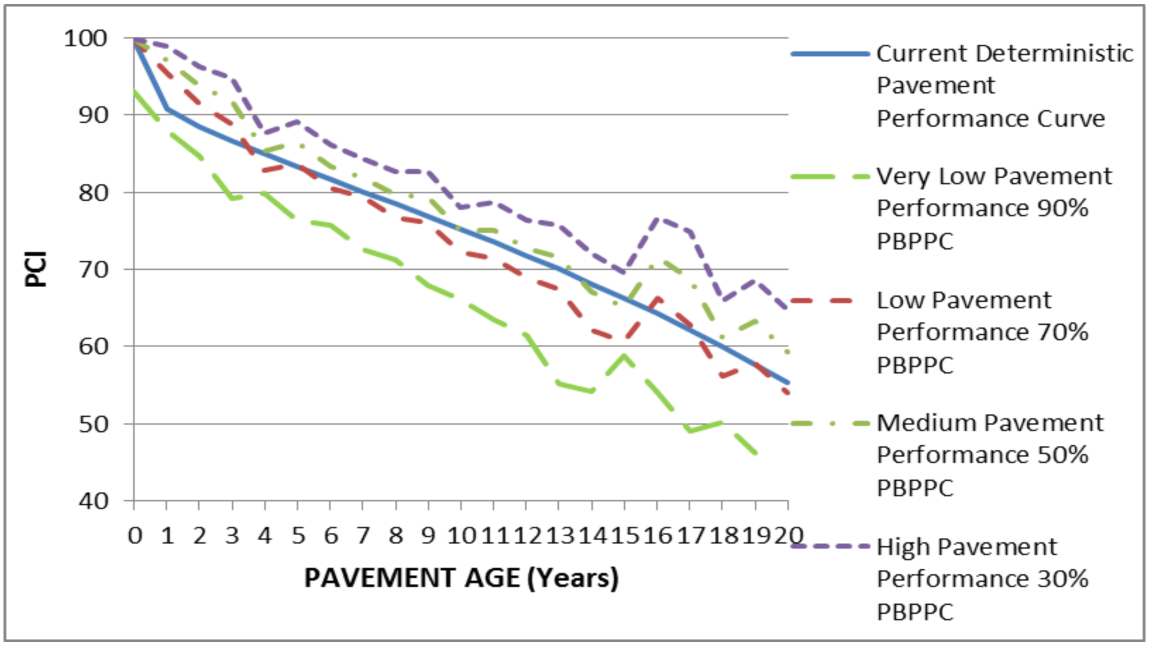

Figure 4.8 Arterial AC/AC Probability-Based Pavement Performance Curves for a Twenty-Year Period

Table 4.4 Residential ST Projected PCI Values for Each Probability Level

Age	Current Deterministic PCI	Residential ST Probability-Based Pavement Performance Curves			
		90%	70%	50%	30%
0	100	100	100	100	100
1	76.67	85.78	87.91	89.39	90.87
2	73.67	81.52	84.28	86.18	88.09
3	71.28	79.18	83.43	86.37	89.31
4	69.14	75.77	79.84	82.66	85.48
5	67.11	73.02	77.69	80.93	84.16
6	65.12	71.24	76.51	80.15	83.80
7	63.13	71.08	76.25	79.83	83.41
8	61.11	66.18	72.85	77.47	82.09
9	59.02	61.17	68.98	74.38	79.78
10	56.85	58.89	67.36	73.22	79.09
11	54.56	53.88	63.00	69.31	75.62
12	52.12	49.01	58.48	65.04	71.60
13	49.50	50.47	58.22	63.59	68.96
14	46.65	45.28	53.38	59.00	64.62
15	43.53	34.58	45.89	53.72	61.55
16	40.06	32.80	43.54	50.98	58.41
17	36.15	31.31	41.17	48.00	54.83
18	31.68	39.52	43.98	47.06	50.14
19	26.48	25.57	33.23	38.54	43.85
20	20.29	35.65	39.73	42.56	45.38

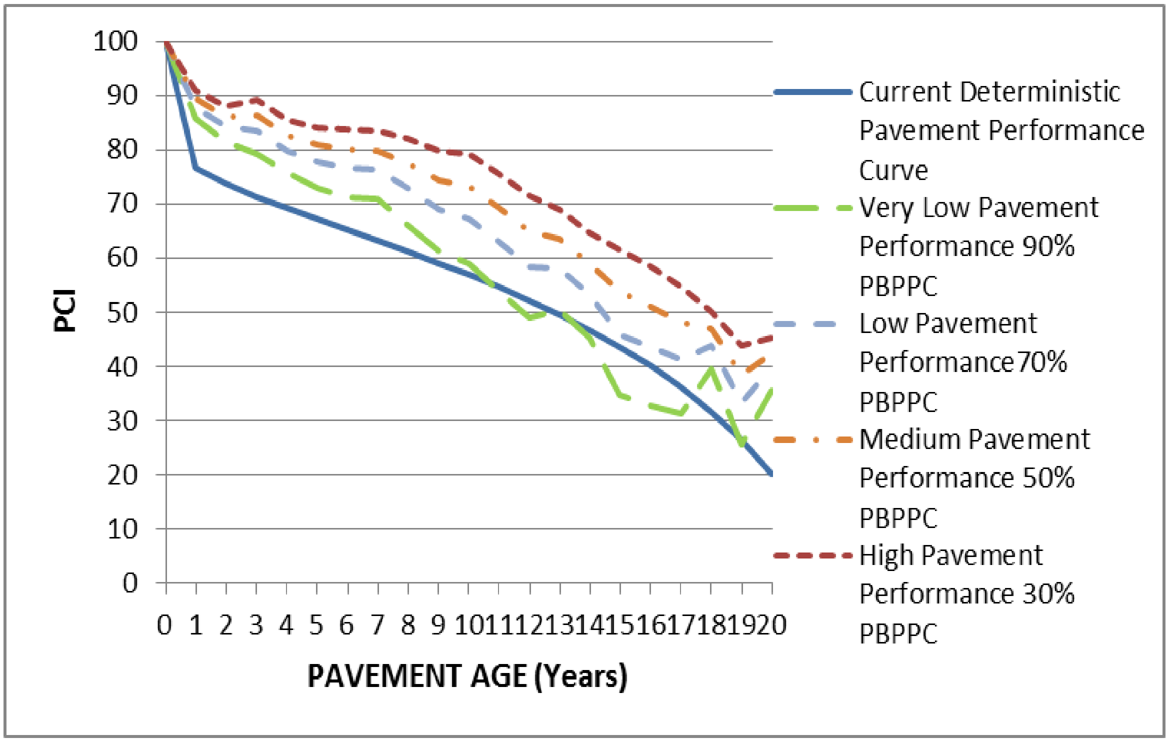

Figure 4.9 Residential ST Probability-Based Pavement Performance Curves for a Twenty-Year Period

From year 12 to year 13, there is a high increase in PCI value in the arterial AC performance curves due to a higher value of the coefficient of variation at year 13 with respect to year 12 that reflects a great variation of the data sets from years 12 and 13. There is also a similar increase in PCI value from year 15 to year 16 due to the same reasons. The coefficient of variation increases in value due to the increase of the standard deviation as the mean decreases in these periods. From year 16 to year 17, there is a high increase in PCI value in arterial AC/AC performance curves also due to a great variation of the data sets from years 16 to 17. Residential ST curves present a similar behavior in years 14 to 15, and 18 to 19.

To smooth the probability-based pavement performance curves, PCI values for parameters α, β, and ρ are obtained through a nonlinear regression for equation (1.1) for each probability level. These parameters are used to predict pavement performance

with the probability level chosen by the decision-makers. Figures 4.10, 4.11, and 4.12 show the probability pavement performance smoothed curves for arterial AC, arterial AC/AC, and residential ST pavements respectively at different probability levels, and the default PCI curve.

PCI values for arterial AC, arterial AC/AC, and residential ST pavements at different probability levels for a 20 year period are shown in Tables 4.5, 4.6, and 4.7.

Table 4.5 Arterial AC Smoothed PCI Values for Each Probability-Based Pavement Performance Curve Level

Age	Current Deterministic PCI	Arterial AC Smoothed Probability-Based Pavement Performance Curves			
		90%	70%	50%	30%
0	100	100	100	100	100
1	91.78	89.44	92.24	93.38	95.08
2	89.01	86.22	89.58	91.14	93.29
3	86.64	83.53	87.33	89.24	91.75
4	84.43	81.06	85.26	87.49	90.31
5	82.28	78.71	83.28	85.81	88.93
6	80.15	76.42	81.35	84.17	87.58
7	78.02	74.16	79.44	82.54	86.23
8	75.87	71.90	77.54	80.92	84.89
9	73.68	69.63	75.63	79.28	83.53
10	71.44	67.34	73.71	77.63	82.15
11	69.15	65.01	71.76	75.96	80.76
12	66.79	62.65	69.79	74.26	79.34
13	64.36	60.24	67.79	72.53	77.90
14	61.85	57.78	65.75	70.76	76.42
15	59.24	55.26	63.67	68.95	74.91
16	56.55	52.68	61.55	67.10	73.37
17	53.75	50.03	59.38	65.21	71.78
18	50.84	47.30	57.16	63.26	70.16
19	47.81	44.49	54.89	61.27	68.49
20	44.66	41.60	52.56	59.21	66.78

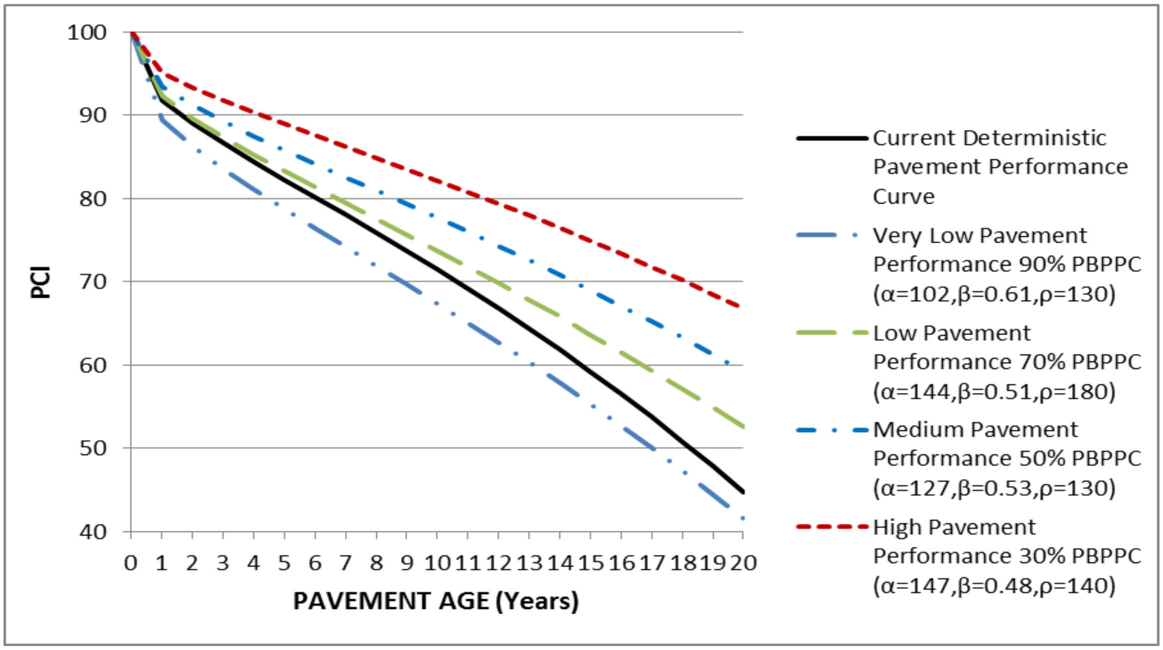

Figure 4.10 Smoothed Probability-Based Pavement Performance Curves for Arterial AC Pavements

Table 4.6 Arterial AC/AC Smoothed PCI Values for Each Probability-Based Pavement Performance Curve Level

Age	Current Deterministic PCI	Arterial AC/AC Smoothed Probability-Based Pavement Performance Curves			
		90%	70%	50%	30%
0	100	100	100	100	100
1	90.85	89.53	91.77	93.09	94.90
2	88.56	86.32	89.08	90.77	93.01
3	86.67	83.65	86.82	88.81	91.40
4	84.94	81.23	84.76	87.02	89.90
5	83.30	78.94	82.80	85.30	88.45
6	81.70	76.72	80.89	83.63	87.04
7	80.10	74.55	79.02	81.98	85.63
8	78.50	72.40	77.16	80.34	84.22
9	76.88	70.25	75.30	78.69	82.80
10	75.24	68.10	73.43	77.03	81.37
11	73.55	65.93	71.54	75.36	79.91
12	71.82	63.75	69.64	73.66	78.44
13	70.03	61.54	67.71	71.94	76.93
14	68.18	59.30	65.75	70.19	75.40
15	66.27	57.02	63.76	68.40	73.83
16	64.27	54.71	61.73	66.58	72.22
17	62.19	52.35	59.67	64.72	70.58
18	60.02	49.94	57.55	62.82	68.90
19	57.74	47.48	55.40	60.88	67.18
20	55.36	44.97	53.20	58.88	65.41

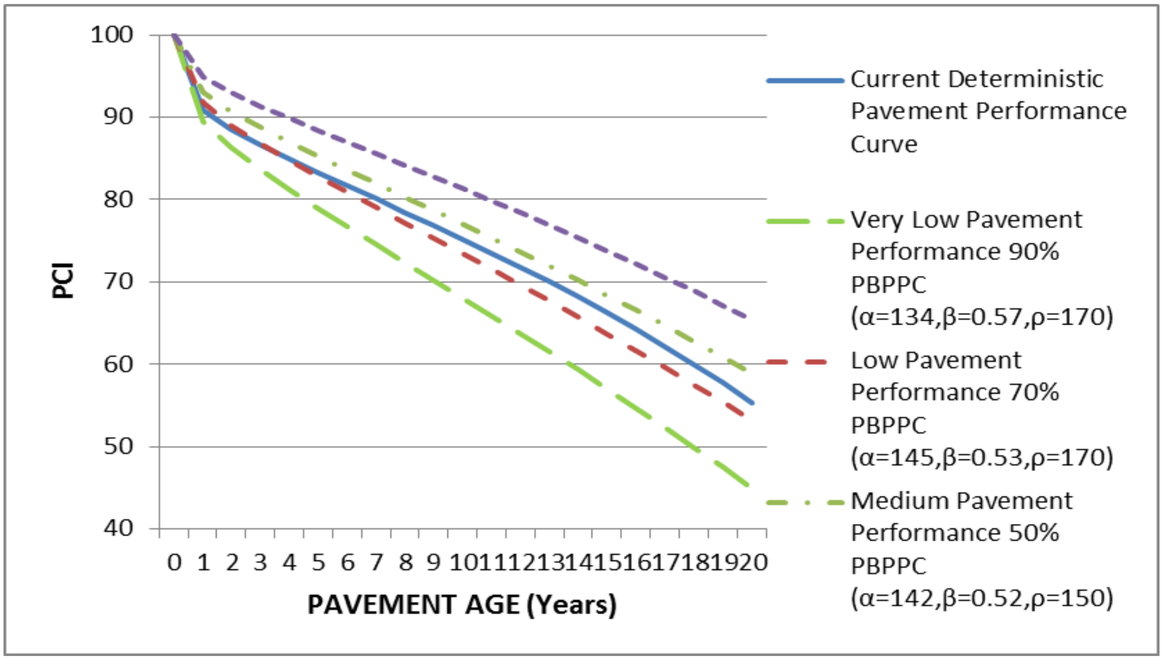

Figure 4.11 Smoothed Probability-Based Pavement Performance Curves for Arterial AC/AC Pavements

Table 4.7 Residential ST Smoothed PCI Values for Each Probability-Based Pavement Performance Curve

Age	Current Deterministic PCI	Residential ST Smoothed Probability-Based Pavement Performance Curves			
		90%	70%	50%	30%
0	100	100	100	100	100
1	76.67	85.52	89.17	91.18	93.59
2	73.67	81.50	85.90	88.50	91.66
3	71.28	78.16	83.12	86.20	89.97
4	69.14	75.12	80.54	84.02	88.34
5	67.11	72.22	78.05	81.89	86.71
6	65.12	69.40	75.58	79.76	85.04
7	63.13	66.61	73.11	77.59	83.31
8	61.11	63.83	70.60	75.36	81.49
9	59.02	61.02	68.05	73.05	79.57
10	56.85	58.19	65.43	70.65	77.51
11	54.56	55.31	62.74	68.14	75.31
12	52.12	52.37	59.96	65.51	72.92
13	49.50	49.37	57.08	62.74	70.33
14	46.65	46.29	54.09	59.80	67.51
15	43.53	43.12	50.97	56.69	64.40
16	40.06	39.86	47.72	53.39	60.98
17	36.15	36.50	44.33	49.86	57.17
18	31.68	33.02	40.77	46.10	52.92
19	26.48	29.42	37.04	42.05	48.13
20	20.29	25.70	33.12	37.71	42.72

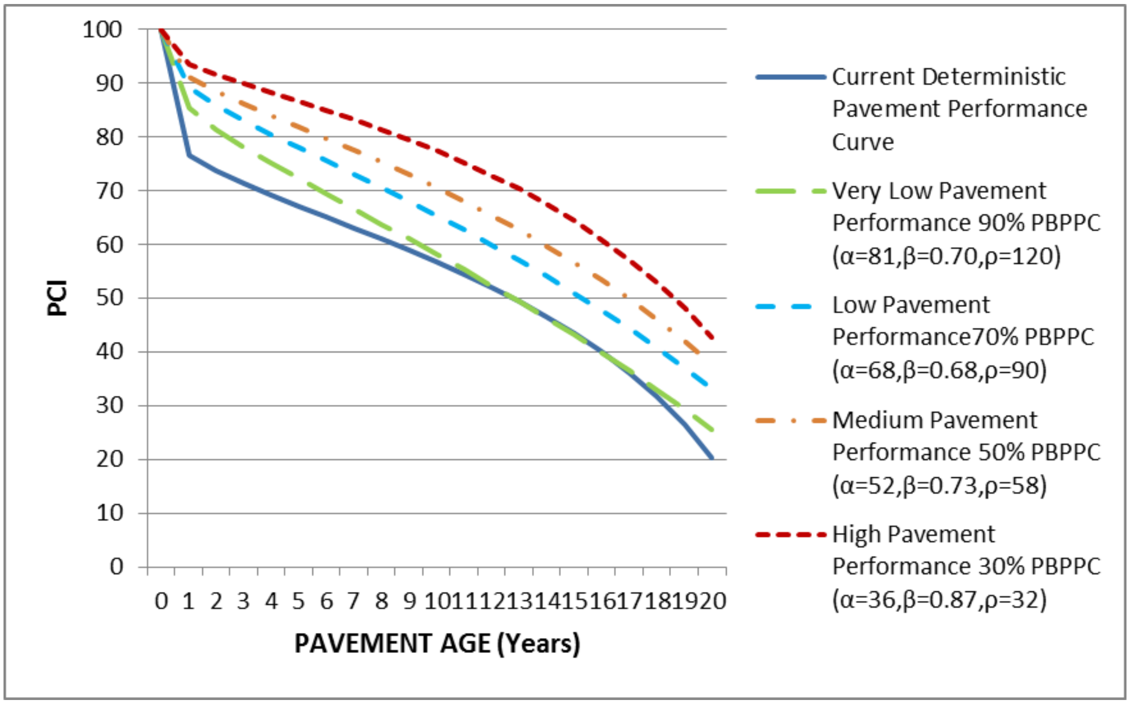

Figure 4.12 Smoothed Probability Pavement Performance Curves for Residential ST Pavements

4.3 Needs Analysis for Pavement Deterioration over Time using the Probability-Based Pavement Performance Curves

Needs analysis is conducted on the Milpitas, California and in the Marion County, Oregon pavement networks over a period of 20 years by selecting different PBPPCs for the analysis. The PCI for year k=1 is the inspected PCI, if there is not an inspected PCI then PCI for year k=1 is a projected PCI with equation 1.1 for age j. The analysis projects PCIs over the analysis period, selects sections for treatment, treatments to apply, and calculates the corresponding budget. Projection of PCI process is explained in Chapter 3. Figure 4.13 shows the needs analysis process.

Reports from the needs analyses performed for arterial streets paved with AC and with AC/AC and for residential streets paved with ST are in the Appendix B, Tables B.1 through B.12. The needs analysis reports include network pavement condition and maintenance and rehabilitation budgets for each year of the analysis period.

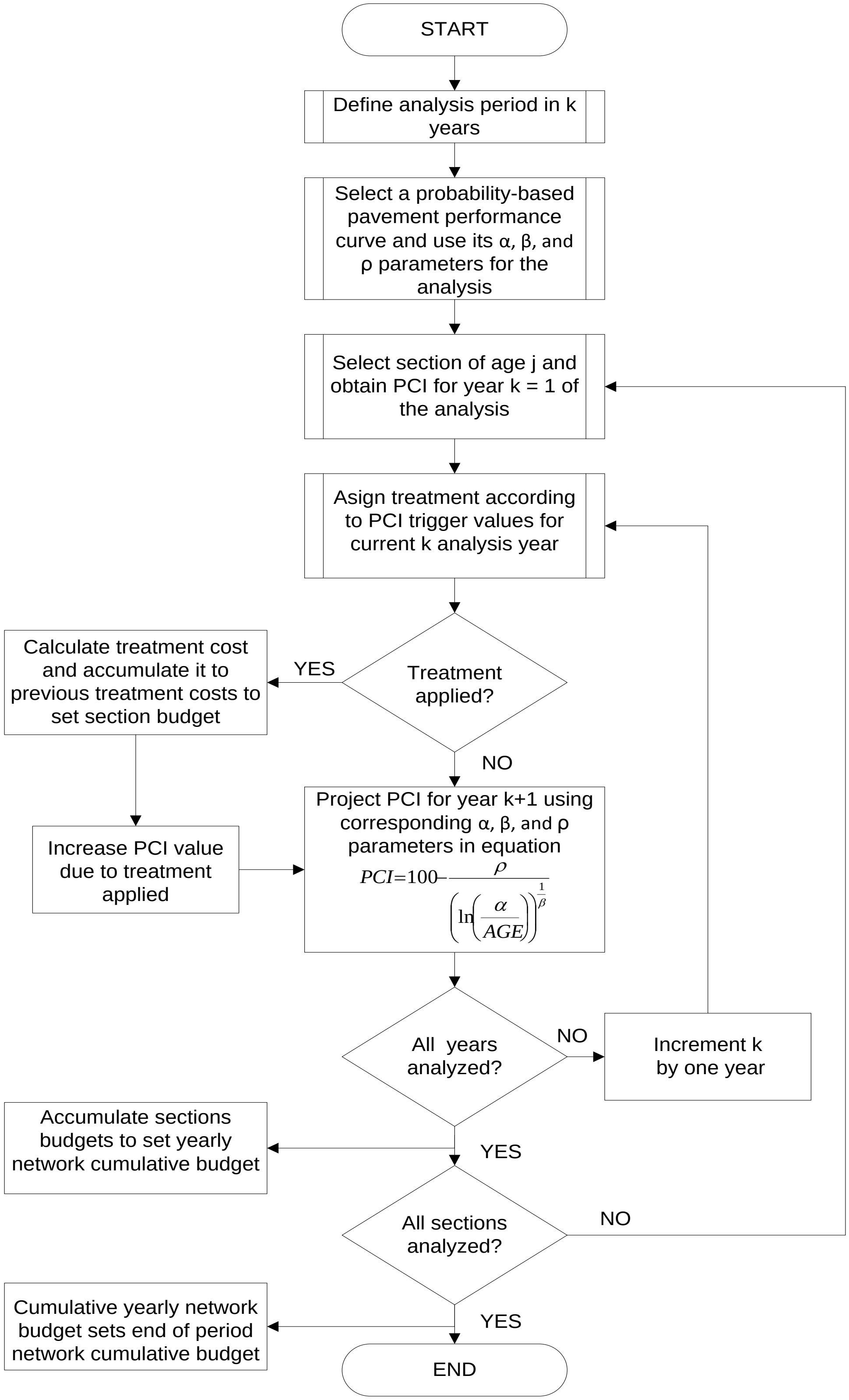

Figure 4.13 Needs Analysis process with Pavement Condition Projection and Budget Needs

Case 1.a Needs analysis for arterial AC streets

Needs analyses are run using the pavement network of Milpitas, California in StreetSaver®, with the default α, β, and ρ parameters for arterial streets paved with AC and run with the α, β, and ρ parameters for 90%, 70%, 50%, and 30% PBPPCs for arterial streets paved with AC.

Results for Case 1.a of the needs analysis at the end of period for arterial streets paved with AC are shown in Table 4.8. The cumulative budget needed in a 20 years period at the 30% probability of performance level is 19% lower than the cumulative budget needed at the 50% probability level that corresponds to a medium or average pavement performance. Maintenance and rehabilitation treatments are recommended for the first 4 years and thereafter only maintenance treatments are recommended because of the high pavement performance trend with a low deterioration rate (see Table B.4 Appendix B). The cumulative budget needed for 5 and 10 year periods are 30% lower than the cumulative budget needed at the 50% probability level.

At the 70% probability of performance level the cumulative budget needed is higher by 27% in a 5 years period, 37% higher in a 10 years period, and 11% higher in a 20 years period than the cumulative budget needed for the 50% PBPPC. Maintenance and rehabilitation treatments are recommended in the first 6 years of the analysis, and from the 7th to the 20th year only maintenance treatments are recommended (see Table B.2 Appendix B).

At the 90% PBPPC the cumulative budget needed is higher by 176% in a 5 years period than the cumulative budget for the 50% PBPPC because heavy rehabilitation treatments are recommended for the first 5 years. Cumulative budget is higher by 102%

in a 10 years period than the cumulative budget for the 50% PBPPC because rehabilitation treatments are recommended up to year 6. Cumulative budget is higher by 35% in a 20 years period than the cumulative budget for the 50% PBPPC because after year 6 only maintenance treatments are recommended (see Table B.1 Appendix B).

70% and 90% PBPPCs represent low pavement performance trends or high deterioration rates. Cumulative budgets for 90%, 70%, 50%, and 30% over the analysis periods are shown in Figure 4.14.

Table 4.8 Needs Analysis for Arterial Streets Paved with AC at the End of the Analysis Period, Case 1.a

Analysis Period	Current Deterministic Pavement Performance Curve		Arterial AC Probability-Based Pavement Performance Curves Parameters							
			Very Low Pavement Performance 90% PBPC		Low Pavement Performance 70% PBPC		Medium Pavement Performance 50% PBPC		High Pavement Performance 30% PBPC	
	PCI at End of Period	Cumulative Budget	PCI at End of Period	Cumulative Budget	PCI at End of Period	Cumulative Budget	PCI at End of Period	Cumulative Budget	PCI at End of Period	Cumulative Budget
5 Years	84	$ 7,872,345	82	$10,217,459	82	$ 4,690,407	84	$ 3,696,459	86	$ 2,622,360
10 Years	85	$11,655,931	83	$13,695,000	84	$ 9,308,892	85	$ 6,751,578	85	$ 4,549,827
20 Years	83	$20,517,218	84	$22,589,602	82	$18,655,153	84	$16,732,006	84	$13,541,519

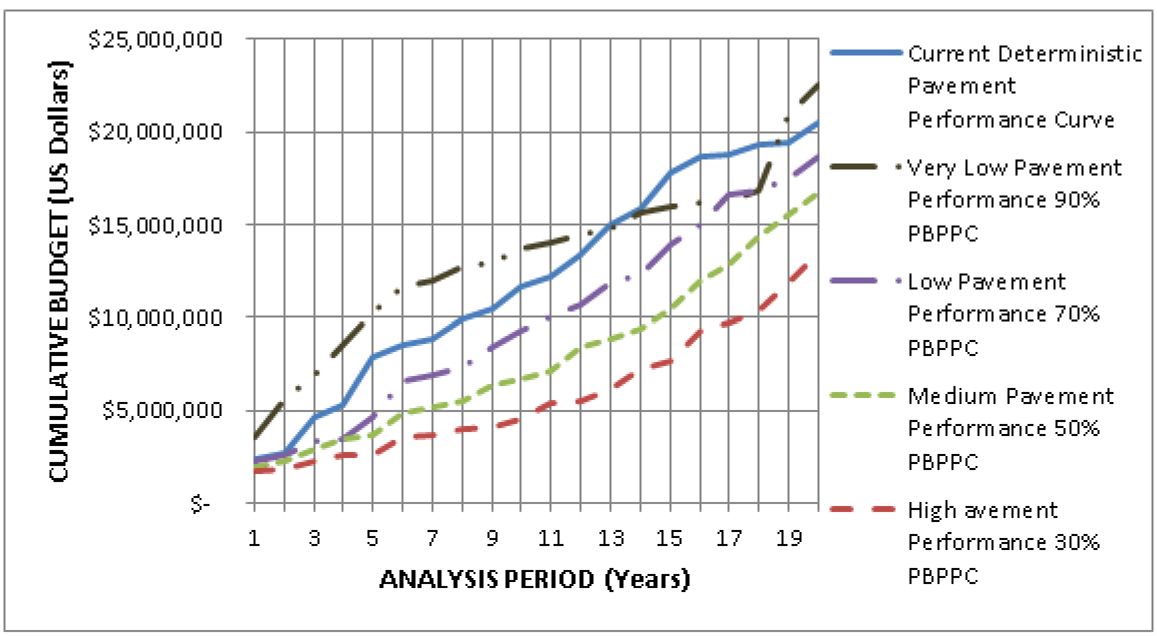

Figure 4.14 Projected Cumulative Budget Network Needs for 90%, 70%, 50%, and 30% PBPPCs for Arterial AC in a 20 Years Period Case 1.a

From Figure 4.14 the current deterministic cumulative budget results are around the 80% PBPPC that corresponds to a low pavement performance.

For the 30% PBPPC the PCIs are the same for 10 and 20 year periods than the PCIs for the 50% PBPPC, and two points higher in a 5 years period than the 50% probability level (see Table 4.8).

For the 70% PBPPC the PCIs are lower by two PCI points for the 5 and 20 year periods than the PCI for the 50% PBPPC and only one PCI point lower for the 10 years period than the 50% probability level (see Table 4.8).

For the 90% PBPPC the PCIs are lower by two PCI points for the 5 and 10 year periods than the PCI for the 50% PBPPC; the PCI is the same PCI for the 20 years period than the PCI for the 50% PBPPC (see Table 4.8).

Variations of the PCI curves over the analysis period for 90%, 70%, 50%, and 30% PBPC are shown in Figure 4.15.

PCI variations of a maximum of four points obtained with different PBPPCs, in the analysis periods are due to the fact that needs analysis preserves the pavement network in a very good condition using an unconstrained budget and the PCIs are above 80 as shown in Table 4.8 and Figure 4.15.

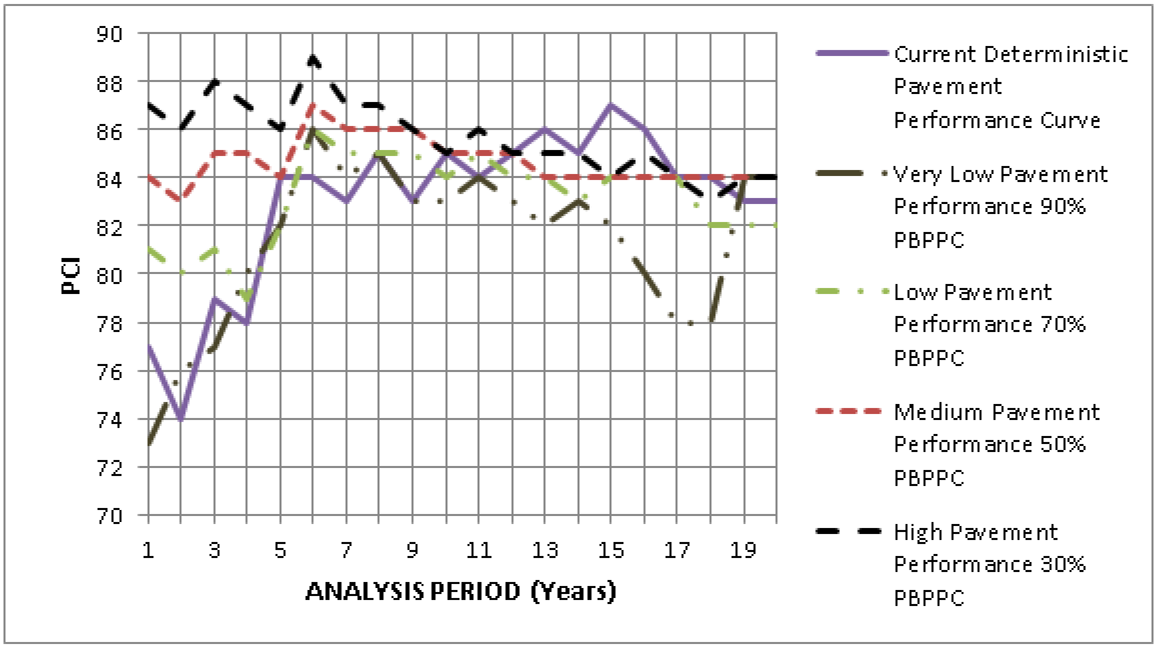

Figure 4.15 Projected Network PCI Average at 90%, 70%, 50%, and 30% PBPPCs for Arterial AC in a 20 Years Period, Case 1.a

Case 1.b Needs analysis for arterial AC/AC streets

Needs analyses are run using the pavement network of Milpitas, California in StreetSaver®, with the default α, β, and ρ parameters for arterial streets paved with AC/AC and run with the α, β, and ρ parameters for 90%, 70%, 50%, and 30% PBPPCs for arterial streets paved with AC/AC.

Results for Case 1.b of the needs analysis at the end of period for arterial streets paved with AC/AC are shown in Table 4.9. The cumulative budget needed for a 20 years period for the 30% PBPPC is 54% lower than the cumulative budget needed for the 50% PBPC; the cumulative budget needed for the 10 years period is 11% lower than the cumulative budget needed for the 50% PBPPC, these differences are due to a higher performance trend or low deterioration rate needing less rehabilitation and more maintenance treatments. The cumulative budget needed for the 5 years period is 3%

higher than the cumulative budget needed for the 50% PBPPC due to heavier rehabilitation treatments in the first years (see Table B.8 from Appendix B).

For the 70% PBPPC the cumulative budget needed is 30% higher for the 20 and 10 year periods than the cumulative budget needed for the 50% PBPPC. The cumulative budget needed for the 5 years period is 36% higher than the cumulative budget needed for the 50% PBPPC. For the 70% PBPPC maintenance and rehabilitation treatments are recommended in the first 4 years and in the 7th year, the rest of the analysis period only maintenance treatments are recommended (see Table B.6 from Appendix B).

For the 90% PBPPC the cumulative budget needed is 137% higher for the 5 years period than the cumulative budget needed for the 50% PBPPC level, cumulative budget needed was higher 95% in the 10 years period than the cumulative budget needed for the 50% PBPPC level; cumulative budget needed is 29% higher for the 20 years period than the cumulative budget needed for the 50% PBPPC. Maintenance and rehabilitation treatments are recommended for the first 6 years and for the 16th year, the rest of the analysis period only maintenance treatments are recommended (see Table B.5 from Appendix B), that is why more money is needed in the first five years. 70% and 90% PBPPCs represent low pavement performance trends or a high deterioration rate. Cumulative budgets for the four probability levels are shown in Figure 4.16 presenting alternatives of pavement performance related to different performance trends.

From Figure 4.16 and Table 4.9 the current deterministic cumulative budget results are around the 60% PBPPC that corresponds to a medium pavement performance.

Table 4.9 Needs Analysis for Arterial Streets Paved with AC/AC at the End of the Analysis Period, Case 1.b

Analysis Period	Current Deterministic Pavement Performance Curve		Arterial AC/AC Probability-Based Pavement Performance Curves							
			Very Low Pavement Performance 90% PBPC		Low Pavement Performance 70% PBPC		Medium Pavement Performance 50% PBPC		High Pavement Performance 30% PBPC	
	PCI at End of Period	Cumulative Budget	PCI at End of Period	Cumulative Budget	PCI at End of Period	Cumulative Budget	PCI at End of Period	Cumulative Budget	PCI at End of Period	Cumulative Budget
5 Years	87	$ 3,447,219	79	$ 4,436,028	83	$ 2,542,308	85	$ 1,869,673	89	$ 1,927,213
10 Years	85	$ 4,472,312	81	$ 7,049,890	84	$ 4,666,082	86	$ 3,606,383	89	$ 3,193,306
20 Years	82	$12,611,503	85	$15,438,522	85	$15,690,769	84	$11,920,314	80	$ 5,493,150

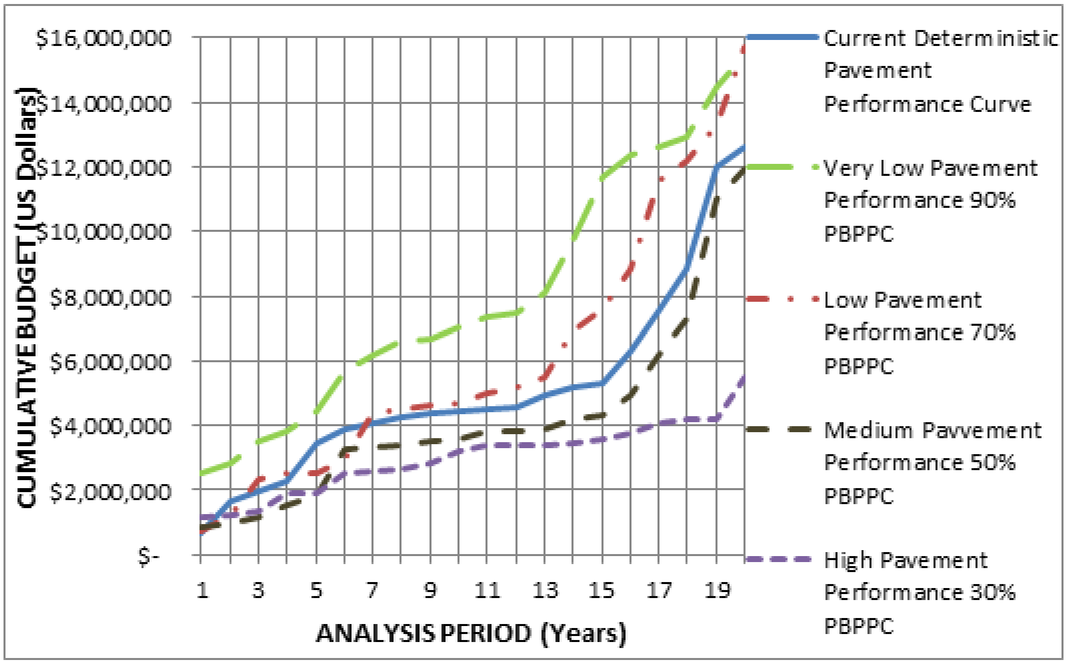

Figure 4.16 Projected Cumulative Budget Network Needs for 90%, 70%, 50%, and 30% PBPPCs for Arterial AC/AC in a 20 Years Period, Case 1.b

For the 30% PBPPC PCI values are higher by 4 PCI points for the 5 years period and 3 PCI points higher for the 10 years period than the PCIs for 50% PBPPC, but the PCI is lower by 4 points for the 20 years period than the PCI for the 50% PBPPC level (see Table 4.9).

For the 70% PBPPC the PCI is lower by 2 points for 5 and 10 year periods than the PCIs for a 50% PBPPC, but for the 20 years period the PCI is higher by one PCI point than the 50% PBPPC level (see Table 4.9).

For the 90% PBPPC, PCI values are lower by 6 PCI points for the 5 years period and lower by 5 PCI points for the 10 years period than the PCIs for the 50% PBPPC level, but for the 20 years period the PCI is higher by one point than the PCI for the 50% PBPPC (see Table 4.9).

In Figure 4.17 there is a drop of 5 points in the PCI value from years 8 to 13 due to only light maintenance treatments recommended to be applied in these years for the four probability levels. A low cumulative budget increase in these years can be seen in Figure 4.16 and in Tables B.5 through B.8 from Appendix B.

Needs analysis preserves the pavement network in very good condition with an unconstrained budget, that is the reason for a one to five PCI points variation in the analysis periods for different PBPPCs as shown in Figure 4.17.

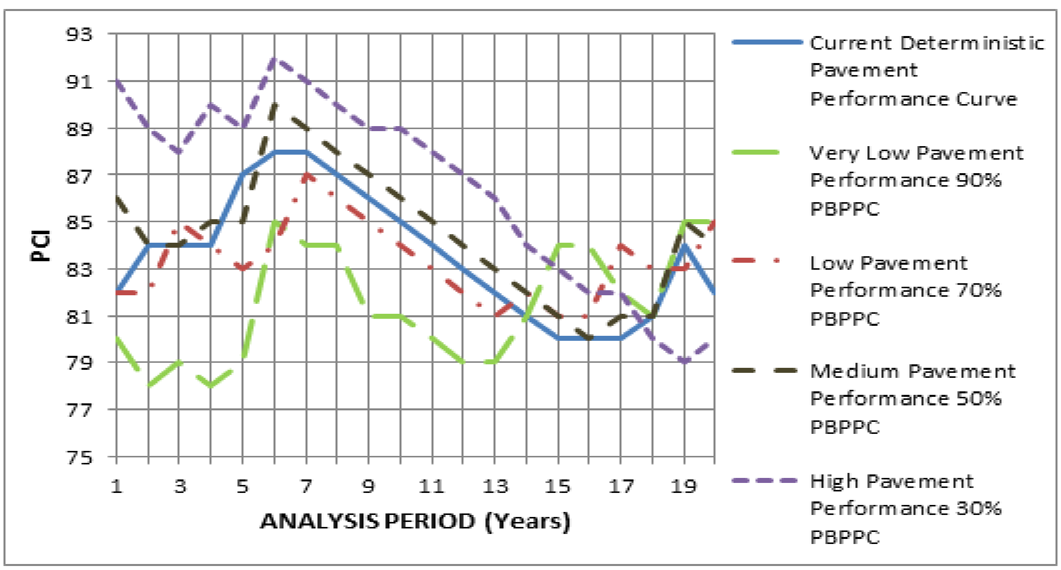

Figure 4.17 Projected Network PCI Average at 90%, 70%, 50%, and 30% PBPPCs for Arterial AC/AC in a 20 Years Period, Case 1.b

Case 1.c Needs analysis for residential ST streets

Needs analyses are performed using the pavement network of Marion County, Oregon in StreetSaver® with the default α, β, and ρ parameters for residential streets

paved with ST, and run with the α, β, and ρ parameters for 90%, 70%, 50%, and 30% PBPPCs for residential streets paved with ST.

Results for Case 1.c of the needs analysis at the end of period for residential streets paved with ST are shown in Table 4.10. The cumulative budget needed for a 20 years period for the 30% PBPPC is 3% lower than the cumulative budget needed for the 50% PBPC; the cumulative budget needed for a 10 years period is 14% lower than the cumulative budget needed for the 50% PBPPC. For the 5 years period, the cumulative budget needed is 10 % lower than the budget needed for the 50% PBPC. Both PBPPC recommend more rehabilitation than maintenance treatments (see Figure 4.18 and Tables B.11 and B.12 from Appendix B).

For the 70% PBPPC the cumulative budget needed is 25% higher for 20 and 10 years periods than the 50% PBPPC. The cumulative budget needed is 20% higher for the 5 years period than the cumulative budget for the 50% PBPPC. 50% PBPPC and 70% PBPPC recommend maintenance and rehabilitation treatments in the whole analysis period (see Figure 4.18 and Tables B.10 and B.11 from Appendix B).

For the 90% PBPPC the cumulative budget needed is 74% higher for the 20 years period than the cumulative budget needed for the 50% PBPPC. For the 10 years period, the cumulative budget needed is 81% higher than the budget obtained with the 50% PBPPC. The cumulative budget needed is 77% higher for the 5 years period than the cumulative budget needed for the 50% PBPPC. The 90% PBPPC represents a very low pavement performance or a high deterioration rate, the recommendation is more rehabilitation treatments ($15,750,700) than maintenance treatments ($33,682), this is due to a PCI of 60 in the first year of the analysis before treatments are applied (see

Table B.9 from Appendix B). Cumulative budgets for the four probability levels are shown in Figure 4.18.

From Figure 4.18 and Table 4.10 the current deterministic cumulative budget results are above the budget obtained with the 90% PBPPC that corresponds to a very low pavement performance. The analysis made with the current deterministic pavement performance curve considers a very low pavement performance or a very high deterioration trend, needing a higher budget to preserve the pavement network in good condition.

Table 4.10 Needs Analysis for Residential/Other Streets Paved with ST at the End of the Analysis Period Case 1.c

Analysis Period	Current Deterministic Pavement Performance Curve		Residential ST Probability-Based Pavement Performance Curves							
			Very Low Pavement Performance 90% PBPC		Low Pavement Performance 70% PBPC		Medium Pavement Performance 50% PBPC		High Pavement Performance 30% PBPC	
	PCI at End of Period	Cumulative Budget	PCI at End of Period	Cumulative Budget	PCI at End of Period	Cumulative Budget	PCI at End of Period	Cumulative Budget	PCI at End of Period	Cumulative Budget
5 Years	83	$19,150,363	83	$15,784,382	83	$10,789,835	84	$ 8,898,649	86	$ 8,026,761
10 Years	87	$26,576,694	86	$22,349,480	86	$15,479,817	85	$12,371,637	84	$10,598,761
20 Years	83	$37,397,675	85	$36,753,737	83	$26,334,060	83	$21,093,881	85	$20,507,441

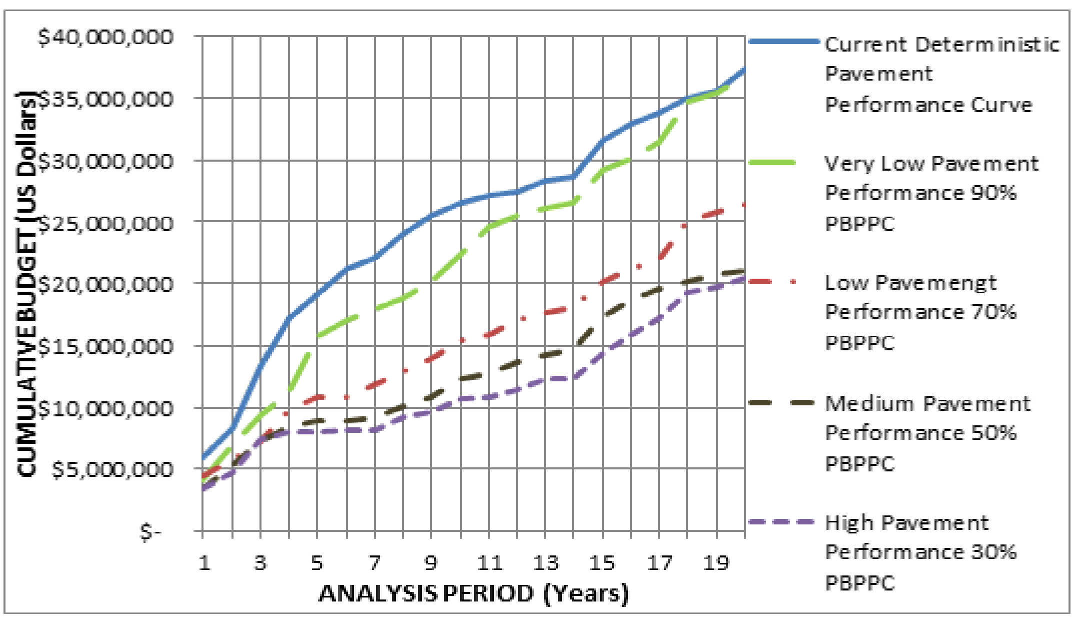

Figure 4.18 Projected Cumulative Budget Network Needs for 90%, 70%, 50%, and 30% PBPPCs for Residential ST in a 20 Years Period, Case 1.c

PCI values for 30% PBPPC for 5 and 20 year periods are two points higher than the PCI for the 50% PBPPC, in the 10 years period the PCI value is one point lower. PCI values for 90% and 70% PBPPCs for 5 years period are one point lower than the PCI value for the 50% PBPPC. PCI values for 70% and 90% PBPPCs for 10 years period are a point higher than the PCI value for the 50% PBPPC. PCI value for 70% PBPPC in the 20 years period is the same as the PCI value for the 50% PBPPC, for the 90% PBPPC in the 20 years period, PCI value is two points higher than the PCI for the 50% PBPPC (see Table 4.10).

Pavement network is preserved in very good condition in the needs analysis using an unconstrained budget, that is the reason for a one to two PCI points variation in the analysis periods for different PBPPCs as shown in Figure 4.19.

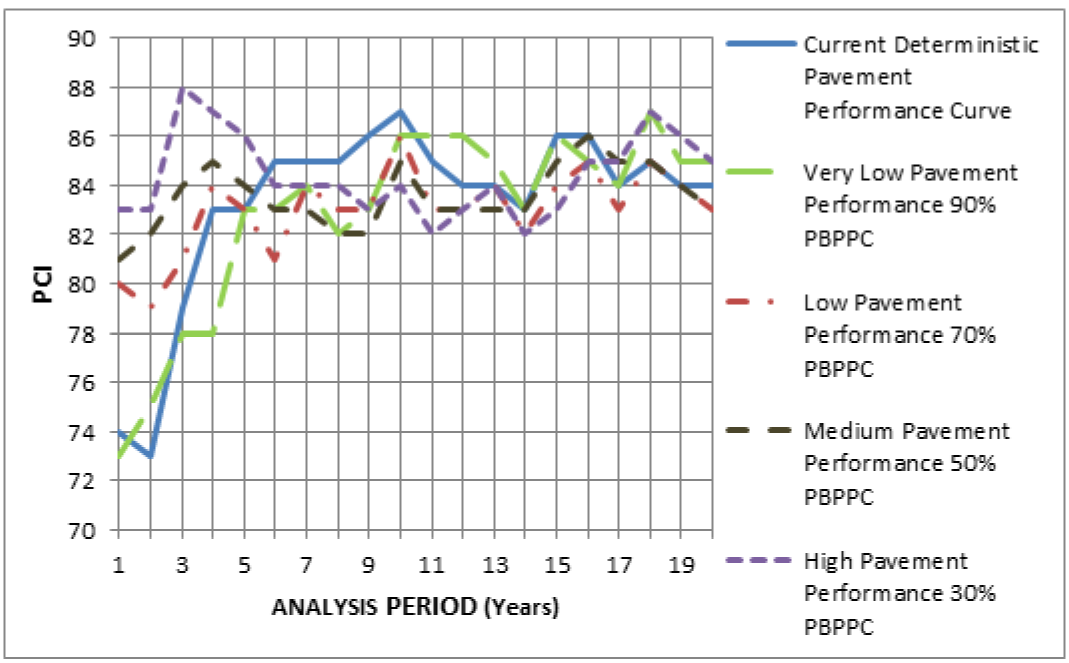

Figure 4.19 Projected Network PCI Average at 90%, 70%, 50%, and 30% PBPPCs for Residential ST in a 20 Years Period, Case 1.c

The 50% PBPPC represents the average pavement performance trend, the 70% PBPPC represents a conservative pavement performance trend and the 30% PBPPC represents a low performance trend. The deterministic pavement performance curves are plotted with the default parameters obtained from different databases, these curves are used only as an example of a deterministic analysis that provides a single pavement condition and budget needs projection curve, making a difference with the probability-based pavement performance curves that present information about pavement condition and budget needs for several possible pavement performance trends. Using different probability performance levels, the PBPPC can present diverse performance scenarios for the agencies' decision-makers.

4.4 Case Study 2. Target Driven PCI Analysis using the Probability-Based Pavement Performance Curves

PBPPC were used in three independent target driven PCI analyses: Case 2.a. for the arterial AC, Case 2.b for the arterial AC/AC from the pavement network of the City of Milpitas, California, and Case 2.c for the residential ST streets from the pavement network of Marion County, Oregon. The target PCI was set at 75 for the three pavement types. The output of the analysis is the cumulative budget needed to preserve the network at the target PCI over 5, 10, and 20 years.

Figure 4.20 shows a flowchart of the process to calculate a PCI target driven budget scenario. Reports from the PCI target driven analyses performed are in Appendix B, Tables B.13 through B.24.

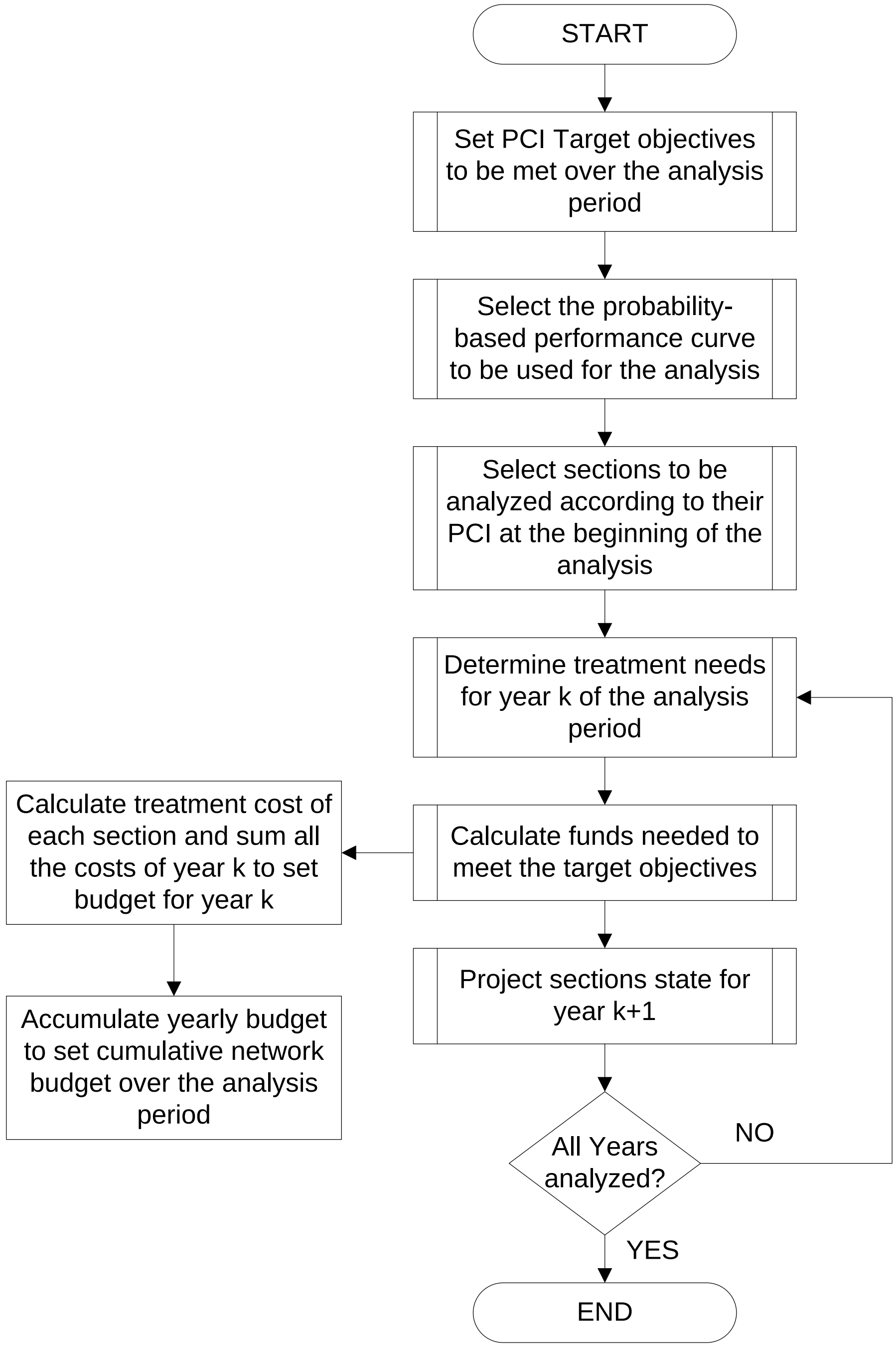

Figure 4.20 Process for a Target Driven Budget Scenario

Case 2.a Target-driven analysis for arterial AC streets

Target-driven analyses are run using the pavement network of Milpitas, California in StreetSaver®, with the default α, β, and ρ parameters for arterial streets paved with

AC and run with the α, β, and ρ parameters for 90%, 70%, 50%, and 30% PBPPCs for arterial streets paved with AC.

Case 2.a results of the target driven analysis at the end of period for arterial streets paved with AC are shown in Table 4.11. Considering a 30% PBPPC corresponding to a high performance, for a 5 years period there is no need to do maintenance or rehabilitation during the first three years because the pavement network has an average PCI in the first three years of the analysis above the target PCI of 75 (see Figure 4.21 and Table B.16 from appendix B).

Table 4.11 Target Driven Scenarios Cumulative Budget for 90%, 70%, 50%, and 30% PBPPCs Arterial AC, Case 2.a

Analysis Period	Current Deterministic Pavement Performance Curve	Arterial AC Probability-Based Pavement Performance Curves Parameters			
		Very Low Pavement Performance 90% PBPC	Low Pavement Performance 70% PBPC	Medium Pavement Performance 50% PBPC	High Pavement Performance 30% PBPC
	Cumulative Budget	Cumulative Budget	Cumulative Budget	Cumulative Budget	Cumulative Budget
5 Years	$ 4,580,968	$ 7,530,308	$ 2,733,927	$ 1,442,389	$ 561,546
10 Years	$ 7,744,144	$ 9,685,866	$ 5,774,158	$ 3,565,632	$ 1,990,626
20 Years	$ 15,145,100	$ 15,288,494	$ 13,226,354	$ 9,787,415	$ 6,938,635

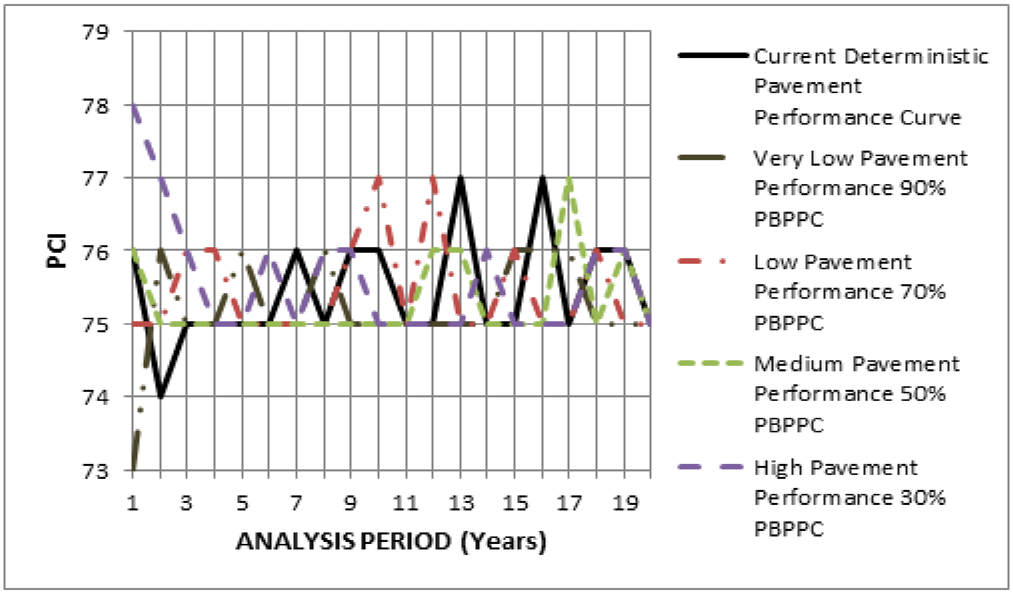

Figure 4.21 Projected Network PCI Average at 90%, 70%, 50%, and 30% PBPPCs Arterial AC, Case 2.a

In the fourth and fifth years there are sections selected for treatments, the cumulative budget needed is 61% lower than the cumulative budget needed for the 50% PBPPC in the 5 years period. In the 10 years period, the cumulative budget needed is 44% lower than the cumulative budget needed for the 50% PBPPC. In the 20 years period, the cumulative budget is 29% lower than the cumulative budget needed for the 50% PBPPC, as shown in Figure 4.22. The 30% PBPPC has a high performance or a low deterioration associated to it; pavements deteriorate slower than average in this case, that is why the budgets needed for this pavement performance level are lower than the budgets needed for the 50% PBPPC that represents a medium performance average deterioration rate.

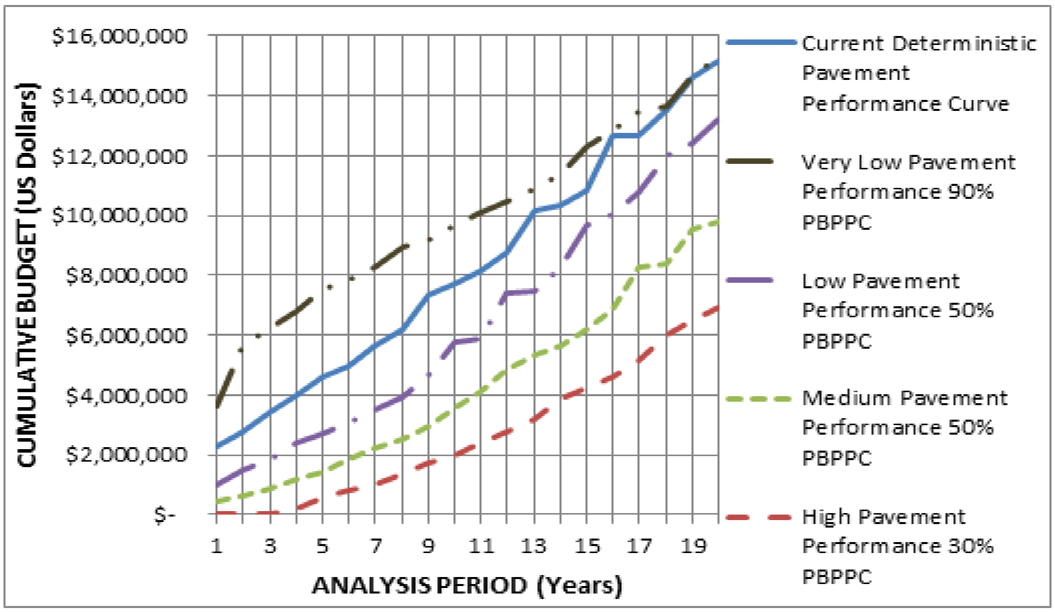

Figure 4.22 Projected Cumulative Budget Network Needs for 90%, 70%, 50%, and 30% PBPPCs Arterial AC Case 2.a

For the 70% PBPPC the cumulative budgets needed are 89%, 62%, and 35% higher respectively for 5, 10, and 20 year periods than the cumulative budgets needed for the 50% PBPPC.

For the 90% PBPPC level the budget for a 5 year period is 422% higher than the cumulative budget needed for the 50% PBPPC, this is a high deterioration trend, and the PCI at year 1 is 73. 70% and 90% PBPPCs represent low pavement performance trends or high deterioration rates, that is why budgets needed are higher than the budgets for a medium pavement performance. The deterministic pavement performance curve lies between the 70% and the 90% PBPPCs, this curve is plotted with the default parameters (see Figure 4.22).

Case 2.b Target-driven analysis for arterial AC/AC streets

Target-driven analyses are run using the pavement network of Milpitas, California in StreetSaver®, with the default α, β, and ρ parameters for arterial streets paved with AC/AC and run with the α, β, and ρ parameters for 90%, 70%, 50%, and 30% PBPPCs for arterial streets paved with AC/AC.

Case 2.b results of the target driven analysis at the end of period for arterial streets paved with AC/AC are shown in Table 4.12. Considering a 30% PBPPC, that corresponds to a high pavement performance or a low deterioration rate, in the 5 year period there is no need to do maintenance or rehabilitation because the pavement network has a PCI above 75 in the first 7 years (see Figure 4.23 and Table B.20 from Appendix B).

Table 4.12 Target Driven Scenarios Cumulative Budget for 90%, 70%, 50%, and 30% PBPPCs Arterial AC/AC, Case 2b

Analysis Period	Current Deterministic Pavement Performance Curve	Arterial AC/AC Probability-Based Pavement Performance Curves			
		Very Low Pavement Performance 90% PBPC	Low Pavement Performance 70% PBPC	Medium Pavement Performance 50% PBPC	High Pavement Performance 30% PBPC
	Cumulative Budget	Cumulative Budget	Cumulative Budget	Cumulative Budget	Cumulative Budget
5 Years	$ 590,986	$ 3,636,904	$ 919,176	$ 263,666	$ -
10 Years	$ 2,070,741	$ 5,601,157	$ 2,439,463	$ 1,942,468	$ 684,534
20 Years	$ 7,485,465	$ 10,041,464	$ 8,768,762	$ 6,704,704	$ 4,479,833

In the 10 years period the budget needed is 65% lower than the budget needed for the 50% PBPPC, and in the 20 years period the budget needed is 33% lower than the budget needed for the 50% PBPPC level. The 50% PBPPC has PCI values above 75 for the first 4 years, sections are selected for treatment from year 4 to year 20. In the 5 years period there are no treatments in the first 3 years (see Figures 4.23, 4.24, and Table B.19 from Appendix B).

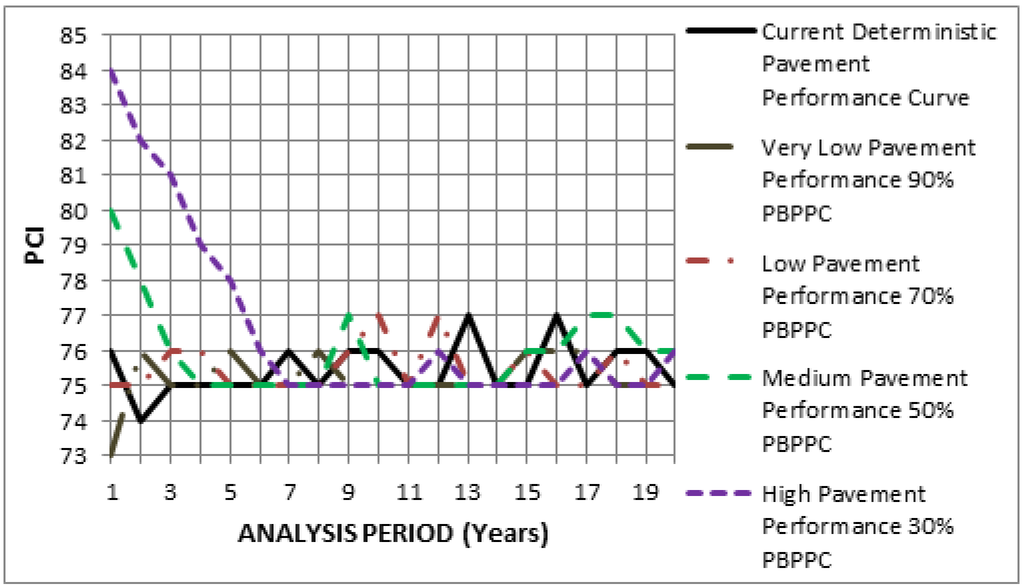

Figure 4.23 Projected Network PCI Average at 90%, 70%, 50%, and 30% PBPPCs Arterial AC/AC, Case 2.b

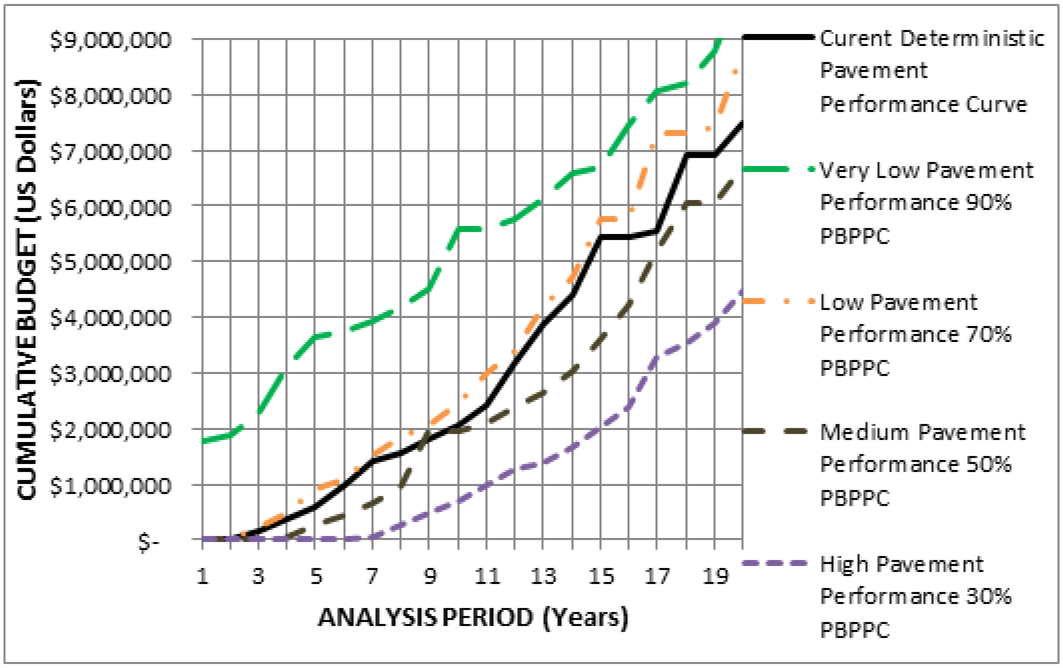

Figure 4.24 Projected Cumulative Budget Network Needs for 90%, 70%, 50%, and 30% PBPPCs Arterial AC/AC, Case 2.b

For 70% PBPPC, the pavement network has a PCI of 75 at year 1, the budget needed for a 5 year period is 248% higher than the budget needed for the 50% PBPPC level, for 10 years period the budget is 25% higher and for 20 years period the budget needed is 30% higher than the budgets needed for the 50% PBPPC.

For the 90% PBPPC, that represents a high deterioration trend, the budget needed for a 5 years period is 12 times higher than the budget needed for the 50% PBPPC, because the PCI at year 1 is 73 and rehabilitation treatments are applied in the first five years; for the 50% PBPPC there are no treatments applied in the first three years because the PCI is above 75 (see Figure 4.23 and Tables B.17 and B.19 from Appendix B). For the 10 years period, the budget needed is 188% higher than the budget needed for the 50% PBPPC, and for the 20 years period the budget is 50% higher than the budget needed for the 50% PBPPC. The PBPPCs of 70% and 90%

represent a low pavement performance or high deterioration rate that is why a higher budget is needed. The deterministic pavement performance curve lies between the 50% and the 70% PBPPCs (see Figure 4.24).

Case 2.c Target-driven analysis for residential ST streets

Target-driven analyses are performed using the pavement network of Marion County, Oregon in StreetSaver® with the default α, β, and ρ parameters for residential streets paved with ST, and run with the α, β, and ρ parameters for 90%, 70%, 50%, and 30% PBPPCs for residential streets paved with ST.

Case 2.c results for the residential ST pavement network are shown in Table 4.13, to preserve a PCI of 75 during the analysis periods. Considering a 30% PBPPC level for the 5 years period the budget needed is 11% lower than the budget needed for the 50% probability level, for 10 years period the budget needed is 1% higher than the budget needed for the 50% PBPPC level, and for the 20 years period the budget needed is 10% lower than the budget needed for the 50% PBPPC level as shown in Figure 4.25. PBPPC of 30% represents a high performance or a low deterioration rate.

Table 4.13.Target Driven Scenarios Cumulative Budget for 90%, 70%, 50%, and 30% PBPPCs Residential ST, Case 2.c

Analysis Period	Current Deterministic Pavement Performance Curve	Residential ST Probability-Based Pavement Performance Curves			
		Very Low Pavemet Performance 90% PBPC	Low Pavement Performance 70% PBPC	Medium Pavement Performance 50% PBPC	High Pavement Performance 30% PBPC
	Cumulative Budget	Cumulative Budget	Cumulative Budget	Cumulative Budget	Cumulative Budget
5 Years	$ 13,799,059	$ 10,543,859	$ 6,328,453	$ 4,959,734	$ 4,366,223
10 Years	$ 18,858,185	$ 16,866,218	$ 10,079,021	$ 9,731,255	$ 9,832,598
20 Years	$ 29,290,131	$ 28,115,476	$ 21,491,367	$ 19,201,433	$ 17,202,341

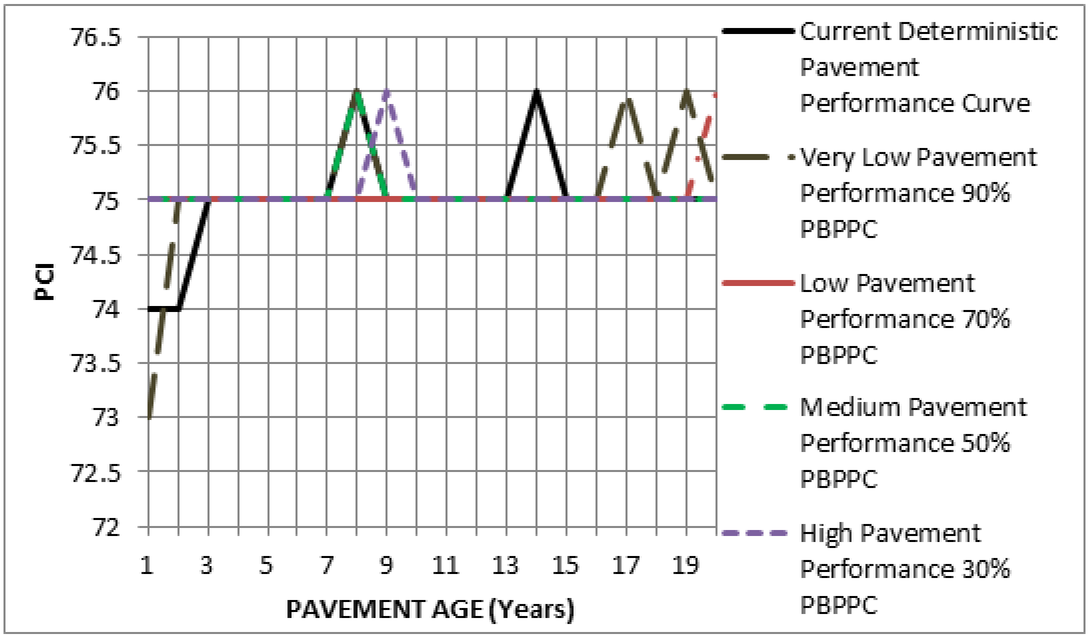

Figure 4.25 Projected Network PCI Average at 90%, 70%, 50%, and 30% PBPPCs Residential ST, Case 2.c

For the 70% PBPPC the budget needed for the 5 years period is 27% higher than the budget for the 50% PBPPC level, for the 10 years period the budget needed is 4% higher than the budget needed for the 50% PBPPC, and for the 20 years period the budget needed is 12% higher than the budget needed for the 50% PBPPC (see Figure 4.26).

For the 90% PBPPC, the budget needed for the 5 years period is 112% higher than the budget needed for the 50% PBPPC; the PCI is 73 at year 1 as shown in Figure 4.26. For the 10 years period the budget is 73% higher, and for the 20 years period the budget is 46% higher than the budget needed for the 50% PBPPC. 70% and 90% PBPPCs represent low and very low performance with a high and very high deterioration trends respectively that is the reason for higher budgets at these deterioration trends. The deterministic pavement performance curve is above the 90% PBPPC that corresponds to a very low pavement performance.

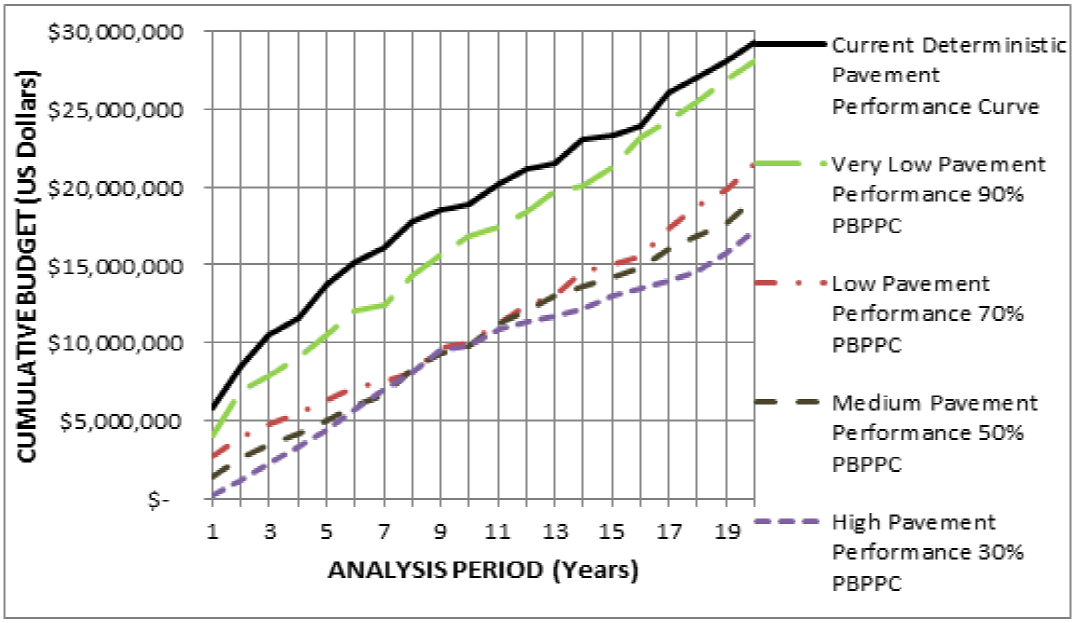

Figure 4.26 Projected Cumulative Budget Network Needs for 90%, 70%, 50%, and 30% PBPPCs Residential ST, Case 2.c

The PBPPC applied to a PCI target driven analysis present diverse pavement performance scenarios varying from a very low performance trend to a high performance trend, a high performance trend needs from 0% to 65% lower budgets than a medium performance trend to preserve the pavement network in the PCI target of 75, a low performance trend needs up to 422% higher budget than a medium performance trend, these budgets vary depending on the network's pavement condition at the first year of the analysis, the target PCI set for the analysis period, and the PBPPC used for the analysis. Average pavement network PCI is important in selecting the best fit PBPPC for the entire pavement network analysis at network management level; at project management level section or groups or sections analysis the best fit PBPPC has to be selected according to pavement history.

4.5 Comparison of Needs Analysis for Different PBPPCs

A pavement network of 15 arterial sections paved with AC is used to perform a needs analysis using the 50% PBPPC for the entire pavement network and a needs analysis in groups of sections from the same pavement network using PBPPCs according to section's history, in order to investigate the importance of selecting the best fit PBPPC. To compare results when all 15 sections are analyzed with a 50% PBPPC, the sections originally analyzed with a low performance curve are in Group 1, the sections originally analyzed with a medium performance curve are in Group 2, and the sections originally analyzed with a high performance curve are in Group 3. Table 4.14 shows the results of all 15 sections analyzed with the 50% PBPPC and the results by groups ran using low, medium, and high independent PBPPCs.

Table 4.14 Needs Analyses Comparison Using Different PBPPCs

50% Probability-Based Pavement Performance Curve						
Pavement Performance	5 Year Peiod		10 Year Period		20 Year Period	
	End of Period PCI	Cumulative Budget	End of Period PCI	Cumulative Budget	End of Period PCI	Cumulative Budget
Group 1, Five Sections	88	$ 16,736	87	$ 35,799	79	$ 84,507
Group 2, Five Sections	83	$ 30,850	82	$ 47,261	85	$ 186,538
Group 3, Five Sections	87	$ 87,038	88	$ 133,914	84	$ 195,605
Entire Network	86	$ 134,624	86	$ 216,974	83	$ 466,650
Probability-Based Pavement Performance Curves						
Pavement Performance	5 Year Peiod		10 Year Period		20 Year Period	
	End of Period PCI	Cumulative Budget	End of Period PCI	Cumulative Budget	End of Period PCI	Cumulative Budget
Five Sections (Low Performance)	86	$ 87,066	85	$ 134,065	78	$ 196,033
Five Sections (Medium Performance)	83	$ 30,850	82	$ 47,261	85	$ 186,538
Five Sections (High Performance)	88	$ 16,717	88	$ 35,782	82	$ 84,491
Entire Network	86	$ 134,633	85	$ 217,108	82	$ 467,062

Sections originally analyzed with a low performance curve in the 5 years period needed 420% less budget when analyzed with a medium performance curve. Pavements in a low performance trend have a high deterioration and need heavy

rehabilitation treatments in a short period of time. Sections analyzed with a low performance curve in a 10 years period needed 274% less budget when analyzed with a medium performance curve. Pavements in the low performance trend already received rehabilitation treatments in the first 5 or 6 years and in the remaining of the time period need maintenance treatments. Sections analyzed with a low performance curve needed 132% less budget in a 20 years period when analyzed with a medium performance curve. Pavements in a medium deterioration trend need rehabilitation treatments in the last years of the analysis period (see Table 4.13 and Tables B.25 and B.26 in Appendix B).

When sections are analyzed with a low performance curve the deterioration trend is high, while when sections are analyzed with a medium performance curve the deterioration trend is medium or average; the deterioration is lower with a medium performance curve, that explains the lower budgets (56%,73%, and 80% less for 20, 10, and 5 year periods respectively) needed for a medium PBPPC compared to the budget needed for low PBPPC; these budget differences demonstrates the importance of setting the sections in the appropriate performance curve for needs analysis.

When sections are analyzed with a high performance curve the deterioration trend is low, while when sections are analyzed with a medium performance curve the deterioration is medium or average; the deterioration is higher with a low performance curve, that explains the higher budgets (131%, 274%, and 420% more for 20, 10, and 5 year periods respectively) needed for a medium PBPPC compared to the budget needed for high PBPPC; these budget differences confirm the importance of selecting the best fitted performance curve for the pavement sections.

When comparing budgets obtained by running groups of 5 sections with low, medium, and high PBPPCs to the budgets obtained by running the entire 15 sections with a medium PBPPC, the budget differences in the needs analysis are $412 for the 20 year period, $134 for the 10 year period, and $9 for the 5 year period.

4.6 Summary and Conclusions

Case Study 1 Needs analysis

The PBPPCs are used in case study 1 to perform a needs analysis using 30%, 50%, 70%, and 90% PBPPCs, for Case 1.a and Case 1.b on the arterial AC and on the arterial AC/AC pavement networks of Milpitas, California respectively; for Case 1.c on the residential ST pavement network of Marion County, Oregon. The 50% PBPPC is used to compare average pavement performance to high and low pavement performance.

1. Cumulative budgets needed for arterial AC streets, arterial AC/AC streets, and residential ST streets in a 20 year period with high pavement performance are 19%, 54%, and 3% lower respectively than the cumulative budgets needed for an average performance. Pavements with a high performance have a low pavement deterioration rate and need less cumulative budget to preserve the network in good condition.
2. Cumulative budgets needed in a 20 year period for arterial AC streets, arterial AC/AC streets, and residential ST streets with very low pavement performance are 35%, 29%, and 74% higher respectively than the cumulative budgets needed for the average performance. Pavements with a very low performance have high

pavement deterioration rates and need higher cumulative budgets to preserve the pavement network in good condition.

For arterial AC pavement network in Case 1.a the average network untreated PCIs at the first year of the analysis are:

- Very low performance curve (90%), PCI of 57
- Low performance curve (70%), PCI of 69
- Medium performance curve (50%), PCI of 73
- High performance curve (30%), PCI of 73.

At the end of the 5 year period the cost to raise the PCI from 57 to 82 for a very low pavement performance trend is much higher than the cost of raising the PCI from 73 to 86 for a high pavement performance trend. The budget needed for the 6 first years includes rehabilitation treatments to raise the PCIs above 80, after that only maintenance treatments are recommended (see Table 4.8 and Tables B.1 through B.4 in Appendix B).

For arterial AC/AC pavement network in Case 1.b the average network untreated PCIs at the first year of the analysis are:

- Very low performance curve (90%), PCI of 68
- Low performance curve (70%), PCI of 77
- Medium performance curve (50%), PCI of 80
- High performance curve (30%), PCI of 84

At the end of the 5 year period the cost to raise the PCI from 68 to 79 for a very low pavement performance trend is much higher than the cost of raising the PCI from 80 to 89 for a high pavement performance trend. The budget needed for the 6 first years

includes rehabilitation treatments to raise the PCIs above 80, after that only maintenance treatments are recommended (see Table 4.9 and Tables B.5 through B.8 in Appendix B).

For residential ST pavement network in Case 1.c the average network untreated PCIs at the first year of the analysis are:

- Very low performance curve (90%), PCI of 60
- Low performance curve (70%), PCI of 66
- Medium performance curve (50%), PCI of 70
- High performance curve (30%), PCI of 73

At the end of the 5 year period the cost to raise the PCI from 68 to 83 for a very low pavement performance trend is much higher than the cost of raising the PCI from 73 to 86 for a high pavement performance trend. The budget needed for the 6 first years includes rehabilitation treatments to raise the PCIs above 80, after that only maintenance treatments are recommended (see Table 4.10 and Tables B.9 through B.12 in Appendix B).

Case Study 2 Target driven analysis

In case study 2 the PBPPCs are used to perform a PCI target driven analysis using 30%, 50%, 70%, and 90% PBPPCs, for Case 2.a and Case 2b on the arterial AC and on the arterial AC/AC pavement networks of Milpitas, California respectively; for Case 2.c on the residential ST pavement network of Marion County, Oregon. The 50% PBPPC is used to compare average pavement performance to high and low pavement performance.

1. Cumulative budgets needed to preserve the pavement network at a PCI of 75 for arterial AC streets, arterial AC/AC streets, and residential ST streets in a 20 year period with high pavement performance level are 29%, 33%, and 10% lower respectively than the cumulative budgets needed for an average performance level. Pavements with a high performance have low pavement deterioration rates and need less cumulative budget to preserve the network in good condition.
2. Cumulative budgets needed in a 20 year period to preserve the pavement network at a PCI of 75 for arterial AC streets, arterial AC/AC streets, and residential ST streets with very low pavement performance are 36%, 50%, and 46% higher respectively than the cumulative budgets needed for the average performance. Pavements with a very low performance level have high pavement deterioration rates and need higher cumulative budgets to preserve the pavement network in good condition.

In both case studies 1 and 2, 30%, 50%, 70%, and 90% PBPPCs are used for the analysis of the entire network, establishing the variability of the budget needs for different PBPPCs, providing information about pavement performance and budget needs at different probability performance levels. Needs analysis and PCI target driven analysis can also be performed for individual sections or groups of sections using PBPPCs.

The budget variability in needs analysis comes from the variability of the PCI inspected values at each pavement age used to develop the PBPPCs explained in Chapter 3, the model assesses the variability of the data with probability distributions displaying different budget needs ranging from low to high pavement performance. The

budget variation in the results of the network's needs analyses and the network's PCI target driven analyses is due to the PBPPC chosen, very low performance curves consider lower PCI values before treatment at the first year of analysis because of a high pavement deterioration trend. High performance curves consider higher PCI values before treatment at the first year of analysis because of a low pavement deterioration trend (see Tables B.1 through B.12 Appendix B).

4.6.1 Recommendations

The recommendation is to use the in the needs analysis the PBPPC that better fits the pavement network performance history for each functional class and pavement type. For decision-making the PBPPC that has the average untreated PCI at the first year of analysis similar to the pavement network's average PCI before the start of the needs analysis is the most likely curve to forecast pavement performance.

For the arterial AC needs analysis in Case 1.a, the network average PCI before the needs analysis for the Milpitas, California arterial network is 65, the recommendation is that the curve that better fits future pavement performance for arterial AC is the 70% PBPPC, because the untreated PCI at the first year of analysis is 69 for a low performance trend.

For the arterial AC/AC needs analysis in Case 1.b, the network average PCI before the needs analysis for the Milpitas, California arterial network is 65, the recommendation is that the curve that better fits future pavement performance for arterial AC/AC is the 90% PBPPC, because the untreated PCI at the first year of analysis is 68 for a very low performance trend.

For the residential ST needs analysis in Case 1.c, the network average PCI before the needs analysis for the Marion County, Oregon residential network is 73, the recommendation is that the curve that better fits future pavement performance for residential ST is the 30% PBPPC, because the untreated PCI at the first year of analysis is 73 for a high performance trend.

The use of PBPPCs in needs analysis at different pavement performance levels provide information about future pavement network condition and budget needs, addressing the broad uncertainty in pavement condition predictions with the inclusion of probabilities in the expectancy of future performance. Using the PBPPCs in target driven analyses also provides information about budget needs for different pavement performance levels to maintain a desired PCI pavement network condition.

Chapter 5: Applicability of Probabilistic Pavement Performance-Based Scenarios in a Pavement Management Case Study

In this chapter a case study of a needs analysis is presented using the probabilistic pavement performance-based scenarios approach described in Chapter 3. The needs analysis is performed in a pavement network composed of 15 arterial sections paved with asphalt concrete. The sections have different inspected PCI values, ranging from 52 to 94, with pavement ages from 2 to 19 years. The section's deterioration trends vary from a low to a high deterioration trend. The needs analysis in the PPPBS estimates budgets for alternate pavement deterioration scenarios. The case study demonstrates the applicability of the PPPBS approach to address the uncertainty and variability in pavement condition projections and budget needs.

5.1 Case Study 3. Needs Analysis Based on the Probabilistic Pavement Performance-Based Scenarios

A needs analysis is performed for 5, 10, and 20 year periods divided in three phases because the sections have different deterioration trends. The sections are classified and analyzed in different deterioration bands according to their deterioration trends. Table 5.1 shows the inspected PCIs, age, and the deterioration band for the sections used in the needs analysis, Figure 5.1 shows the PCI and age for the 15 pavement sections. After the analysis is conducted for each group of sections, the budget needs for each group are consolidated for the entire pavement network.

Table 5.1 Pavement Sections Data

Section Number	PCI	PCI Points Deterioration	AGE (Years)	Deterioration Band
1	94	6	5	Low
2	89	11	6	Low
3	86	14	9	Low
4	83	17	10	Low
5	75	25	18	Low
6	77	23	10	Medium
7	70*	30	14	Medium
8	68**	32	16	Medium
9	52*	48	19	Medium
10	68**	32	18	Medium
11	88	12	2	High
12	67*	33	10	High
13	56*	44	12	High
14	74	26	12	High
15	55*	45	16	High

From Table 5.1, pavement sections PCI value with (*) have a non-load related deterioration, deterioration related to environmental reasons; these are sections 7, 9, 12, 13, and 15. Pavement sections PCI value with (**) have a load related deterioration, deterioration related to traffic, these are sections 8 and 10. Pavement condition categories and recommended treatments using decision trees established by MTC-PMS are presented in Chapter 2. From MTC-PMS classification, sections with non-load related deterioration are assigned maintenance treatments (e.g. seal coat, crack seal) that do not increase the pavement structural capacity, sections with a load related deterioration are assigned maintenance treatments (e.g. overlay) that increases the structural capacity.

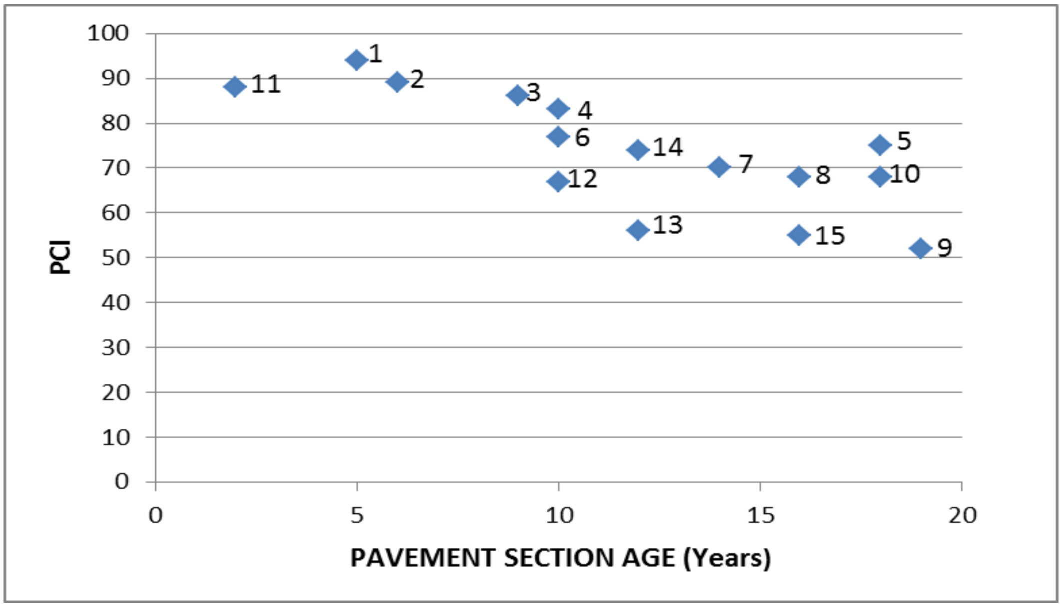

Figure 5.1 PCI and Age for the Pavement sections

Figure 5.2 shows pavement deterioration in PCI points and age for the 15 sections, the deterioration bands limits, and the location of each section in the deterioration bands. A needs analysis is performed in the low deterioration band for sections 1 to 5 (PCIs vary from 94 to 75 and ages between 5 and 18 years) that are considered with low deterioration for their ages. For sections 6 to 10, a needs analysis is performed in the medium deterioration band (section's PCIs vary from 52 to 77 and ages from 10 to 19 years) that are considered with medium deterioration for their age. A needs analysis is performed in the high deterioration band for sections 11 to 15 (PCIs vary from 55 to 88 and ages from 2 to 16 years) that are considered with high deterioration for their age.

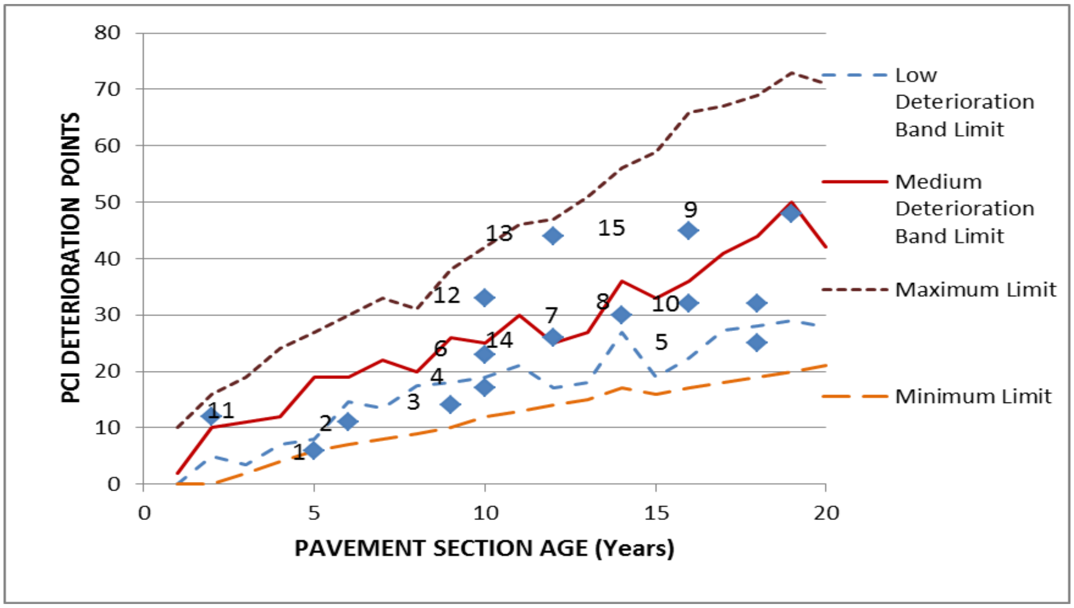

Figure 5.2 Pavement Deterioration and Age for the Pavement Sections

5.2 Conducting a Needs Analysis using the Probabilistic Pavement Performance-Based Scenarios

The needs analysis is performed to identify treatment and budget needs using a Monte Carlo simulation with 50 runs to model the variability of the cumulative deterioration PCI points over a 5, 10, and 20 year periods. The procedure to run the needs analysis is explained in Chapter 3.

As described in Chapter 3, the first step in the needs analysis using the PPPBS approach, is to select an analysis period in k years and the deterioration band in which the section will be analyzed; the deterioration band is defined according to the PCI value and age j of each section. For the first year of the analysis, the PCI is the inspected value or a projected PCI value. A CDPCI for age j of the section is calculated at year k, assigning a treatment – if any - according to the PCI trigger values. The treatment cost is calculated and accumulated over the analysis period to obtain the cumulative budget at the end of the 5, 10, or 20 year analysis period.

After this process the PCI is calculated for year k+1 by subtracting the ADR for age j from the PCI for year k. Figure 5.3 illustrates the procedure to obtain the budget needed in the analysis period for a probability performance-based scenario. This process is performed for each year of the analysis period for each section in the pavement network until all the sections have been analyzed over the entire analysis period.

The Monte Carlo simulations in the needs analysis generate random $CDPCI_j$ points within the limits of each deterioration band, ADR_j values are calculated from the random CDPCIs and are used to calculate the PCI for year k. Table 5.2 shows low, medium, and high deterioration bands limits as well as minimum and maximum ADR_j values for each band. The PCI is projected over the analysis period and treatments are proposed according to PCI trigger values from Table 2.1 in Chapter 2. The needs analysis generate PCI values and budgets for each year to be accumulated at the end of the analysis period. A needs analysis calculates the budget to preserve a pavement section or group of sections in a very good condition with PCI values over 70. A histogram is constructed using the budget needs generated from the Monte Carlo simulations. PPPBS are obtained using different percentiles of the budget needs generated from the Monte Carlo simulations.

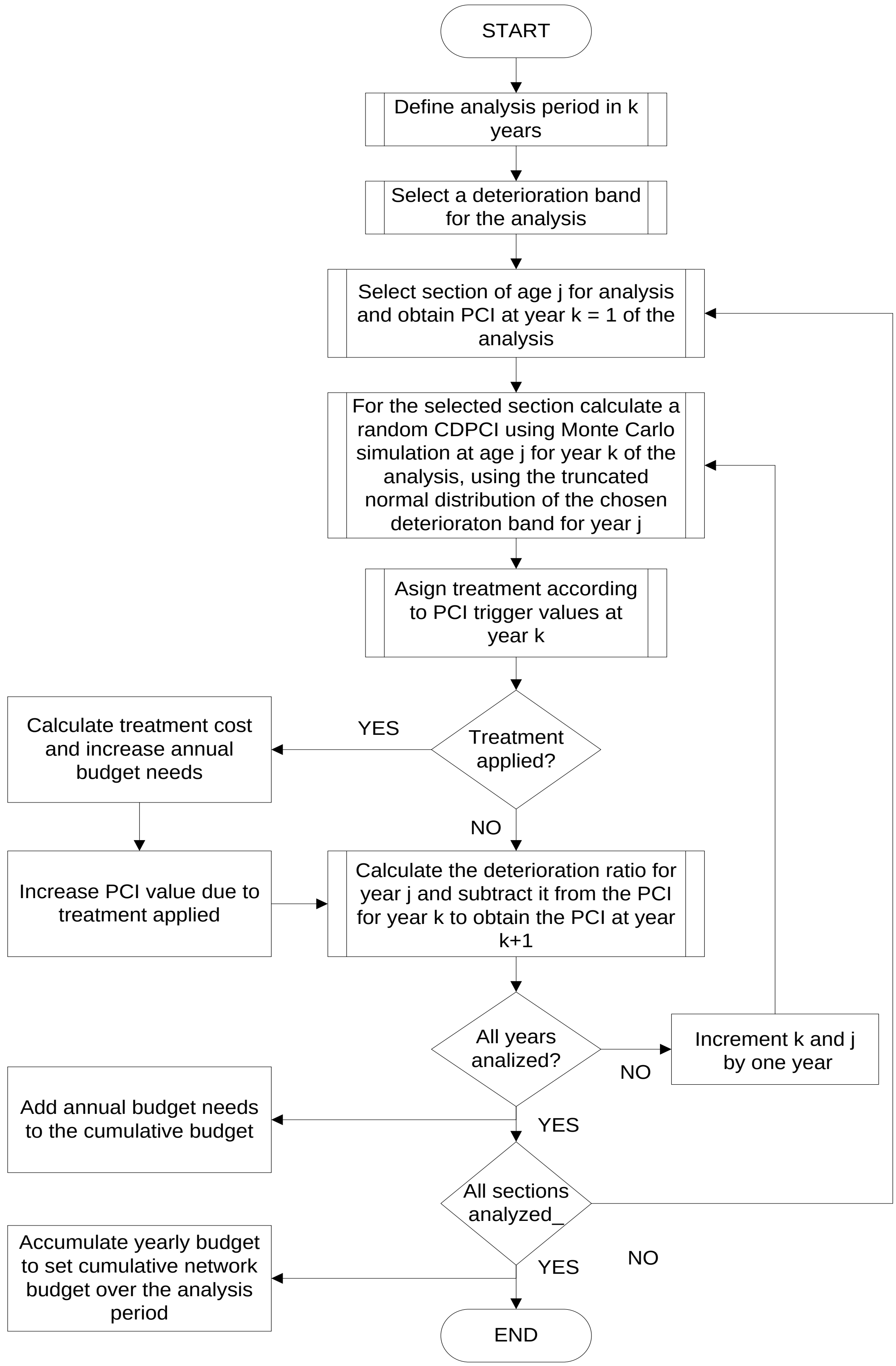

Figure 5.3 Budget Needs using a Probabilistic Pavement Performance-Based Scenario Approach

Table 5.2 Deterioration Band Limits in CDPCI Points Minimum and Maximum ADR for Low, Medium, and High Deterioration Bands

Pavement Age j	Low Deterioration Band				Medium Deterioration Band				High Deterioration Band			
	Band Limits CDPCI Points		Annual Deterioration Rate		Band Limits CDPCI Points		Annual Deterioration Rate		Band Limits CDPCI Points		Annual Deterioration Rate	
	Lower, Lowest Value	Upper, 30th Percentile	Minimum ADR	Maximum ADR	Lower, 30th Percentile	Upper, 70th Percentile	Minimum ADR	Maximum ADR	Lower, 70th Percentile	Upper, Highest Value	Minimum ADR	Maximum ADR
1	0	0	0.00	0.00	0	2	0.00	2.00	2	10	2.00	10.00
2	0	5	0.00	2.50	5	10	2.50	5.00	10	16	5.00	8.00
3	2	3	0.67	1.00	3	11	1.00	3.67	11	19	3.67	6.33
4	4	7	1.00	1.75	7	12	1.75	3.00	12	24	3.00	6.00
5	6	8	1.20	1.60	8	19	1.60	3.80	19	27	3.80	5.40
6	7	15	1.17	2.50	15	19	2.50	3.17	19	30	3.17	5.00
7	8	13	1.14	1.86	13	22	1.86	3.14	22	33	3.14	4.71
8	9	17	1.13	2.13	17	20	2.13	2.50	20	31	2.50	3.88
9	10	18	1.11	2.00	18	26	2.00	2.89	26	38	2.89	4.22
10	12	19	1.20	1.90	19	25	1.90	2.50	25	42	2.50	4.20
11	13	21	1.18	1.91	21	30	1.91	2.73	30	46	2.73	4.18
12	14	17	1.17	1.42	17	25	1.42	2.08	25	47	2.08	3.92
13	15	18	1.15	1.38	18	27	1.38	2.08	27	51	2.08	3.92
14	17	27	1.21	1.93	27	36	1.93	2.57	36	56	2.57	4.00
15	16	19	1.07	1.27	19	33	1.27	2.20	33	59	2.20	3.93
16	17	22	1.06	1.38	22	36	1.38	2.25	36	66	2.25	4.13
17	18	27	1.06	1.59	27	41	1.59	2.41	41	67	2.41	3.94
18	19	28	1.06	1.56	28	44	1.56	2.44	44	69	2.44	3.83
19	20	29	1.05	1.53	29	50	1.53	2.63	50	73	2.63	3.84
20	21	28	1.05	1.40	28	42	1.40	2.10	42	71	2.10	3.55

Table 5.3 shows an example of one simulation for PCI projections for a single arterial section with a new asphalt pavement (PCI = 100) analyzed assuming low, medium, and high deterioration scenarios without treatments for a 10 year analysis period. The CDPCIs are random generated values for each year of the analysis in each deterioration band, this way the CDPCI and the ADR can have different values in each simulation, consequently, generating different PCI values for year k. This process calculates different PCI values that can or cannot trigger a treatment to apply; affecting the budget needs estimates in each simulation.

Table 5.3 PCI Projection for Low, Medium, and High Probabilistic Pavement Performance-Based Scenarios

Low Deterioration Band	Year k	1	2	3	4	5	6	7	8	9	10
	$CDPCI_j$	0.9244	4.4606	2.9645	5.1090	7.2645	12.8775	10.8992	13.8269	15.8189	13.1097
	ADR_k	0.9244	2.2303	0.9882	1.2772	1.4529	2.1462	1.5570	1.7284	1.7577	1.3110
	PCI_k	100	99.08	96.85	95.86	94.58	93.13	90.98	89.42	87.70	85.94
Medium Deterioration Band	Year k	1	2	3	4	5	6	7	8	9	10
	$CDPCI_j$	0.8674	5.9953	4.3615	9.4720	13.1744	15.0613	16.1621	17.2021	21.2282	20.7340
	ADR_k	0.8674	2.9977	1.4538	2.3680	2.6349	2.5102	2.3089	2.1503	2.3587	2.0734
	PCI_k	100	99.13	96.13	94.68	92.31	89.68	87.17	84.86	82.71	80.35
High Deterioration Band	Year k	1	2	3	4	5	6	7	8	9	10
	$CDPCI_j$	1.7231	8.9027	9.8266	12.5714	18.4845	20.1943	30.5906	20.2916	28.1112	23.8380
	ADR_k	1.7231	4.4513	3.2755	3.1428	3.6969	3.3657	4.3701	2.5364	3.1235	2.3838
	PCI_k	100	98.28	93.83	90.55	87.41	83.71	80.34	75.97	73.44	70.31

5.2.1 Low Pavement Deterioration Scenario

Needs analysis for sections 1, 2, 3, 4, and 5 paved with AC are run for low pavement deterioration scenarios in 5, 10, and 20 year periods, using 50 Monte Carlo simulations for the CDPCI. The five sections analyzed are in very good condition with PCIs over 70 and ages from 5 to 18 years. Cumulative budget statistics at end of the analysis periods are shown in Table 5.4. Histograms for cumulative budget of the five sections group for low deterioration scenarios are shown in Figures 5.4, 5.5, and 5.6. There is a minimal difference between the minimum and maximum budgets in the needs analysis for the three analysis periods because the sections are analyzed in a low deterioration band, showing high performance and small deterioration for their age; ADR difference from minimum to maximum in the low deterioration band is less than one PCI point (see Table 5.2), and a difference of $11 between minimum and maximum budgets in the three analysis periods.

Table 5.4 Probabilistic Pavement Performance-Based Scenarios Budget Needs Analysis Statistics for Five Sections with a Low Deterioration Trend

	Low Deterioration Scenario 5 Years Period				
	Minimum	1st Quartile	2nd Quartile	3rd Quartile	Maximum
PCI	87	87	87	88	88
Budget US Dollars	$ 16,723	$ 16,727	$ 16,729	$ 16,730	$ 16,734
	Low Deterioration Scenario 10 Years Period				
	Minimum	1st Quartile	2nd Quartile	3rd Quartile	Maximum
PCI	86	87	87	87	87
Budget US Dollars	$ 35,787	$ 35,791	$ 35,793	$ 35,794	$ 35,798
	Low Deterioration Scenario 20 Years Period				
	Minimum	1st Quartile	2nd Quartile	3rd Quartile	Maximum
PCI	84	84	84	84	84
Budget US Dollars	$ 129,071	$ 129,074	$ 129,076	$ 129,078	$ 129,081

Table 5.5 shows cumulative budget needs calculated from a deterministic needs analysis performed for the same five sections for 5, 10, and 20 year analysis periods using the MTC-PMS.

Table 5.5 Deterministic Budget Needs for the Low Pavement Deterioration Band

Analysis Period	Deterministic Cumulative Budget
5 Years	$ 16,751
10 Years	$ 35,814
20 Years	$ 176,542

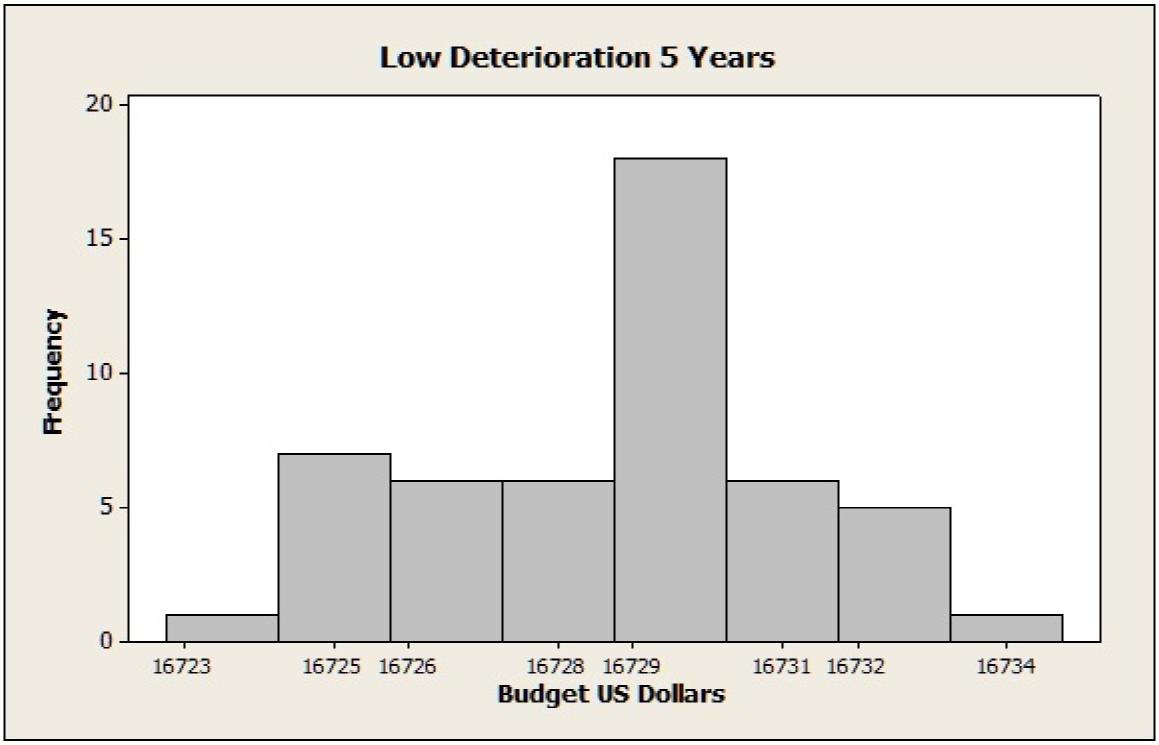

Figure 5.4 Cumulative Budget Histogram for Low Pavement Deterioration Band, 5 Year Period

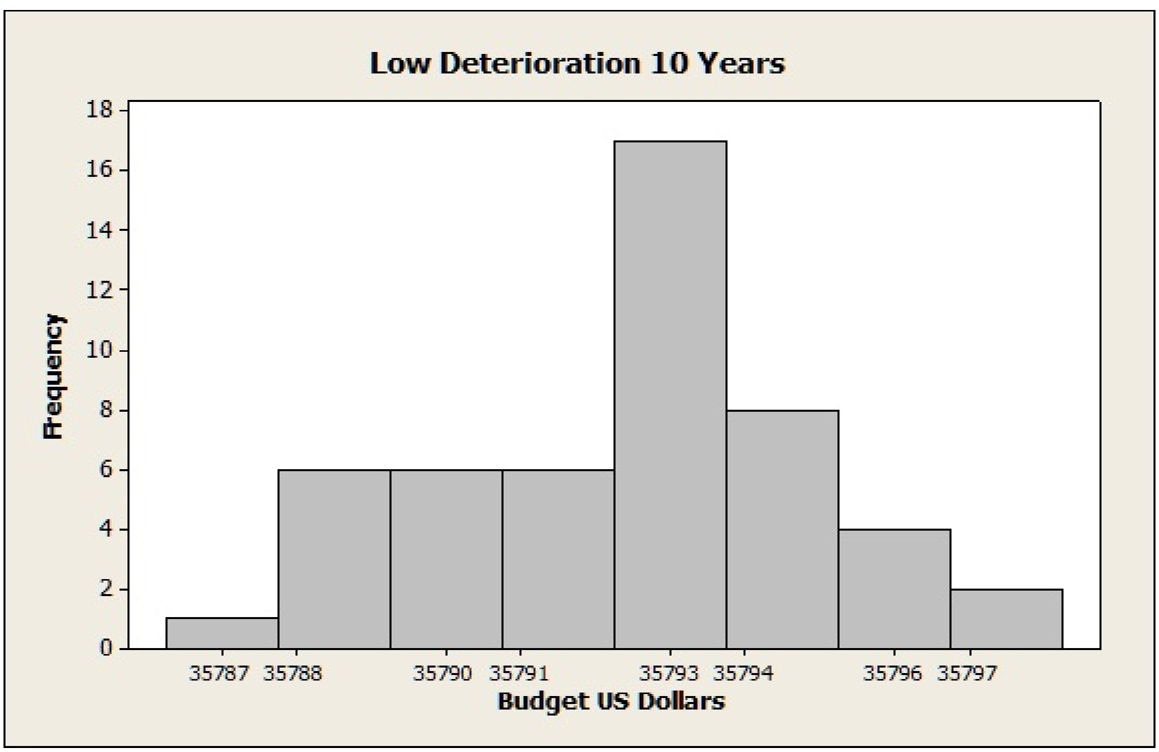

Figure 5.5 Cumulative Budget Histogram for Low Pavement Deterioration Band, 10 Year Period

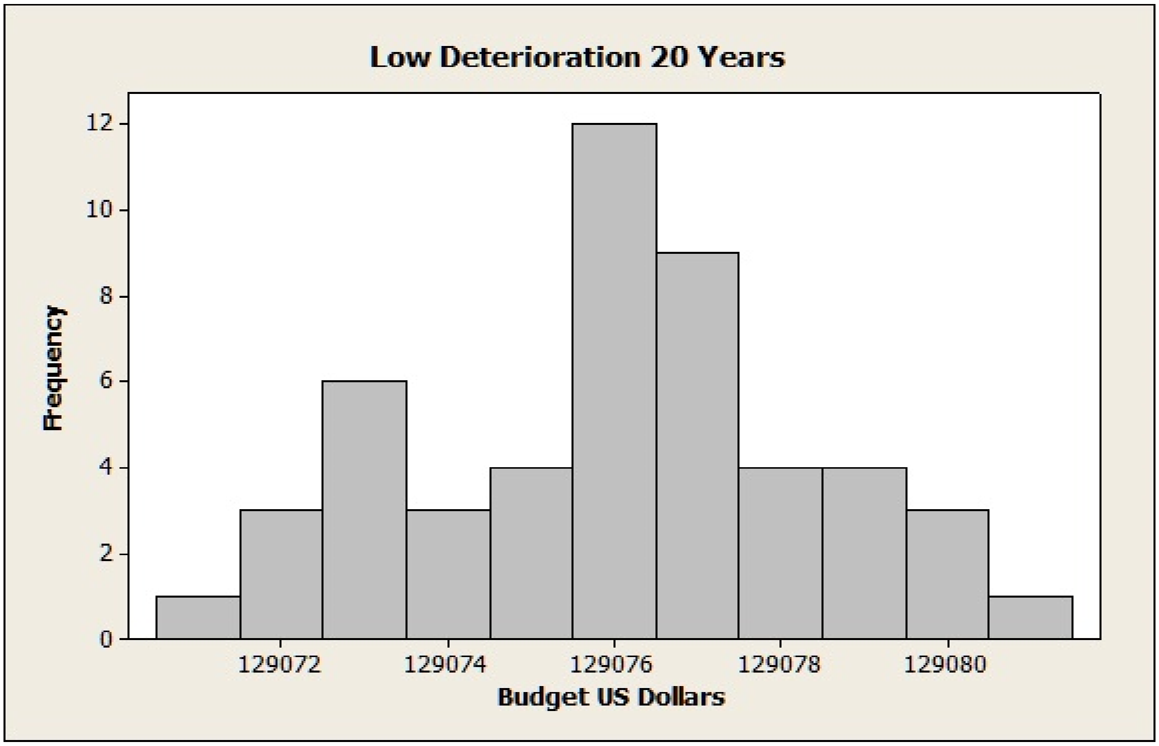

Figure 5.6 Cumulative Budget Histogram for Low Pavement Deterioration Band, 20 Year Period

5.2.2 Medium Pavement Deterioration Scenario

Needs analysis for sections 6, 7, 8, 9, and 10 paved with AC are run for medium pavement deterioration scenarios in 5, 10, and 20 year periods, using 50 Monte Carlo simulations for the CDPCI. The five sections analyzed are in good condition with PCIs over 50 and with ages from 10 to 19 years. Cumulative budget statistics at end of the analysis periods are shown in Table 5.6. Histograms for cumulative budget of the five sections group for medium deterioration scenarios are shown in Figures 5.7, 5.8, and 5.9. There is a 1% difference between the minimum and maximum budget for the 5 years period. In the 10 years period, there is a 4% difference between the minimum and maximum budget. In the 20 year period there is a 9% difference between the minimum and maximum budget. ADR difference from minimum to maximum in the medium

deterioration band is one to two PCI points (see Table 5.2), that is why the minimum and maximum budget differs up to 11%.

Table 5.6 Probabilistic Pavement Performance-Based Scenarios Budget Needs Analysis Statistics for Five Sections with a Medium Deterioration Trend

	Medium Deterioration Scenario 5 Years Period				
	Minimum	1st Quartile	2nd Quartile	3rd Quartile	Maximum
PCI	87	87	87	87	88
Budget US Dollars	$ 52,004	$ 52,007	$ 52,010	$ 52,743	$ 52,748
	Medium Deterioration Scenario 10 Years Period				
	Minimum	1st Quartile	2nd Quartile	3rd Quartile	Maximum
PCI	85	85	86	86	86
Budget US Dollars	$ 65,603	$ 67,164	$ 67,720	$ 67,801	$ 68,531
	Medium Deterioration Scenario 20 Years Period				
	Minimum	1st Quartile	2nd Quartile	3rd Quartile	Maximum
PCI	83	83	84	84	86
Budget US Dollars	$ 158,545	$ 158,957	$ 160,115	$ 162,189	$ 173,219

Table 5.7 shows cumulative budget needs calculated from a deterministic needs analysis performed for the same five sections for 5, 10, and 20 year analysis periods using the MTC-PMS.

Table 5.7 Deterministic Budget Needs for the Medium Pavement Deterioration Band

Analysis Period	Deterministic Cumulative Budget
5 Years	$ 30,874
10 Years	$ 47,320
20 Years	$ 184,087

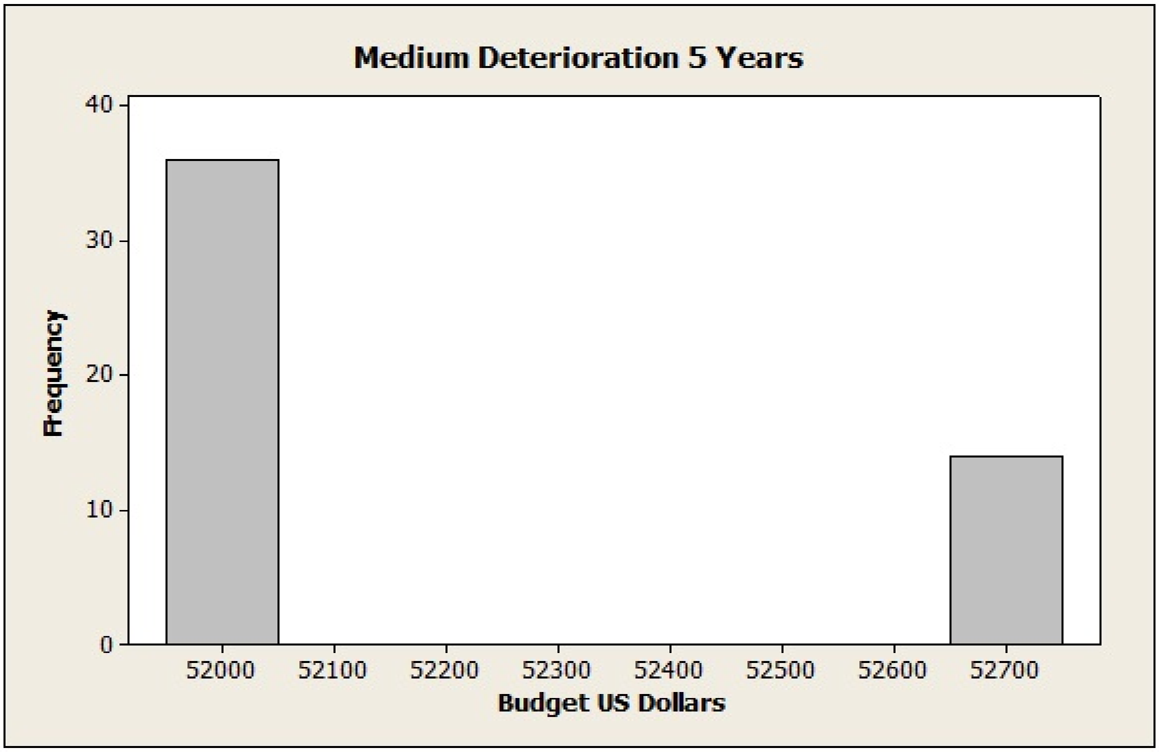

Figure 5.7 Cumulative Budget Histogram for Medium Pavement Deterioration Band, 5 Year Period

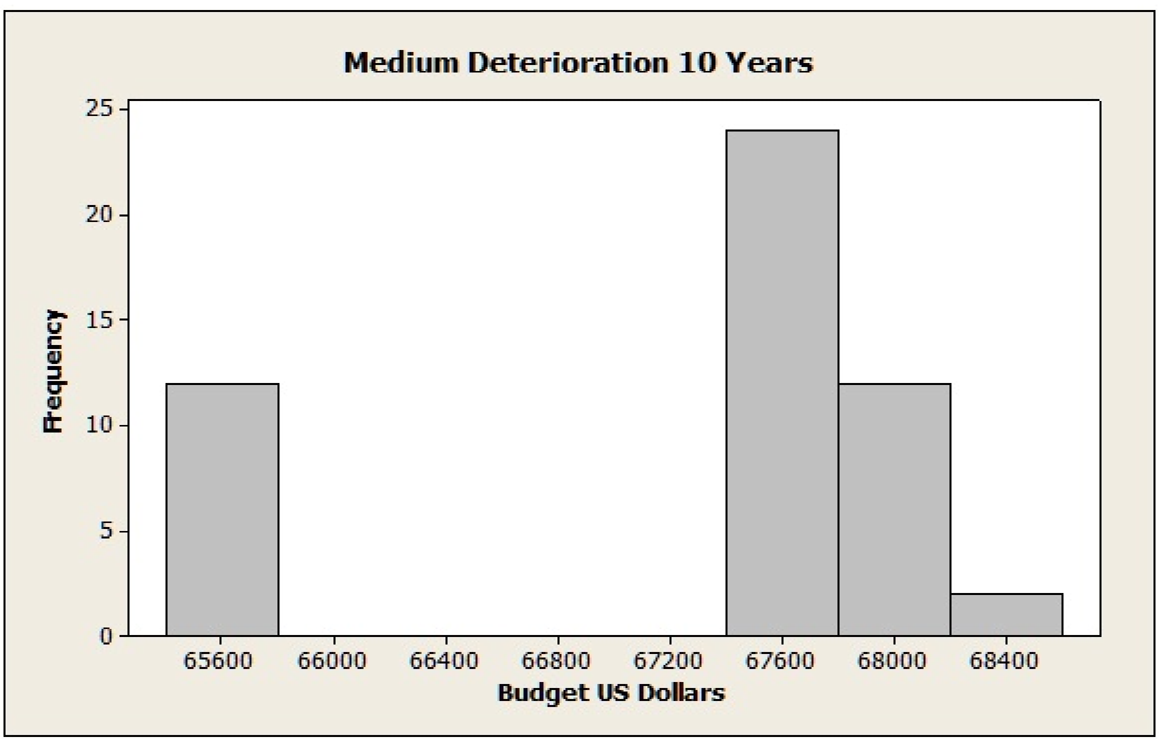

Figure 5.8 Cumulative Budget Histogram for Medium Pavement Deterioration Band, 10 Year Period

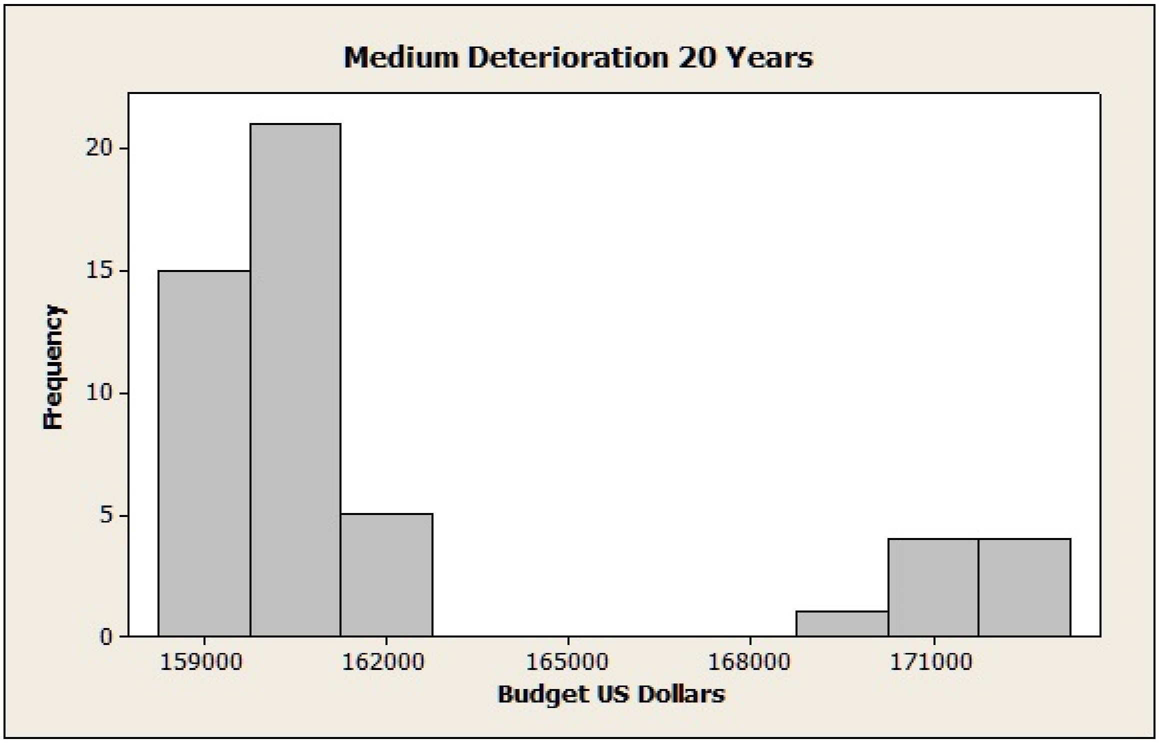

Figure 5.9 Cumulative Budget Histogram for Medium Pavement Deterioration Band, 20 Year Period

The gap in the histogram for the medium deterioration 5 year period is mainly due to a thick overlay treatment applied to section 9; in some simulations the treatment is applied in year 2 and in others is applied in year 3, the difference in cost varies from $700 to $900 from year 2 to year 3; this is why there are no values in the histogram between $52,000 and $52,700 (see Tables D.10 and D11, Appendix D).

The gap in the histogram for the medium deterioration 10 year period is mainly due to a seal coat applied to section 9. In some simulations the treatment is applied in year 10 and in others is applied in year 11. When the seal coat is applied in year 10 a thick AC overlay is applied in year 2 and when the seal coat is applied in year 11 the thick AC overlay is applied in year 3. The difference in cost is $2,000 that is why there

are no values in the histogram between $65,600 and $67,600 (see Tables D.10 and D.11, Appendix D).

The gap in the histogram for the medium deterioration 20 year period is mainly due to a seal coat and a mill and thick overlay treatments applied to section 6. In some simulations the mill and thick overlay is applied in year 15 and no more treatments are applied in the rest of the 20 year period, in other simulations a seal coat is applied in year 15 and a mill and thick overlay is applied in year 20. The difference in cost is $6,000 that is why there are no values in the histogram between $162,200 and $170,000 (see Tables D.6 and D.7, Appendix D).

5.2.3 High Pavement Deterioration Scenario

Needs analysis for sections 11, 12, 13, 14, and 15 paved with AC are run for high pavement deterioration scenarios in 5, 10, and 20 year periods, using 50 Monte Carlo simulations for the CDPCI. Sections 12, 13, and 15 are in good condition with PCIs above 50 and ages from 10 to 16 years, sections 11 and 14 are in very good condition with PCIs above 70 and ages from 2 to 12 years. Cumulative budget statistics at end of the analysis periods are shown in Table 5.8. Histogram for cumulative budget of the five sections group for high deterioration scenarios are shown in Figures 5.10, 5.11 and 5.12. There is a 3% difference between the minimum and maximum budget for the 5 year period. In the 10 year period, there is a 50% difference between minimum and maximum budget. In the 20 year period there is a 56% difference between minimum and maximum budget. ADR difference from minimum to maximum in the high deterioration band is two to three PCI points (see Table 5.2).

Table 5.8 Probabilistic Pavement Performance-Based Scenarios Budget Needs Analysis Statistics for Five Sections with a High Deterioration Trend

	High Deterioration Scenario 5 Years Period				
	Minimum	1st Quartile	2nd Quartile	3rd Quartile	Maximum
PCI	84	84	85	85	85
Budget US Dollars	$ 64,911	$ 65,671	$ 65,864	$ 65,918	$ 66,679
	High Deterioration Scenario 10 Years Period				
	Minimum	1st Quartile	2nd Quartile	3rd Quartile	Maximum
PCI	79	81	84	85	87
Budget US Dollars	$ 82,253	$ 88,184	$ 113,169	$ 117,668	$ 123,601
	High Deterioration Scenario 20 Years Period				
	Minimum	1st Quartile	2nd Quartile	3rd Quartile	Maximum
PCI	76	80	81	82	86
Budget US Dollars	$ 158,401	$ 192,064	$ 198,301	$ 206,099	$ 247,897

Table 5.9 shows cumulative budget needs calculated from a deterministic needs analysis performed for the same five sections for 5, 10, and 20 year analysis periods using the MTC-PMS.

Table 5.9 Deterministic Budget Needs for the High Pavement Deterioration Band

Analysis Period	Deterministic Cumulative Budget
5 Years	$ 86,282
10 Years	$ 133,142
20 Years	$ 193,480

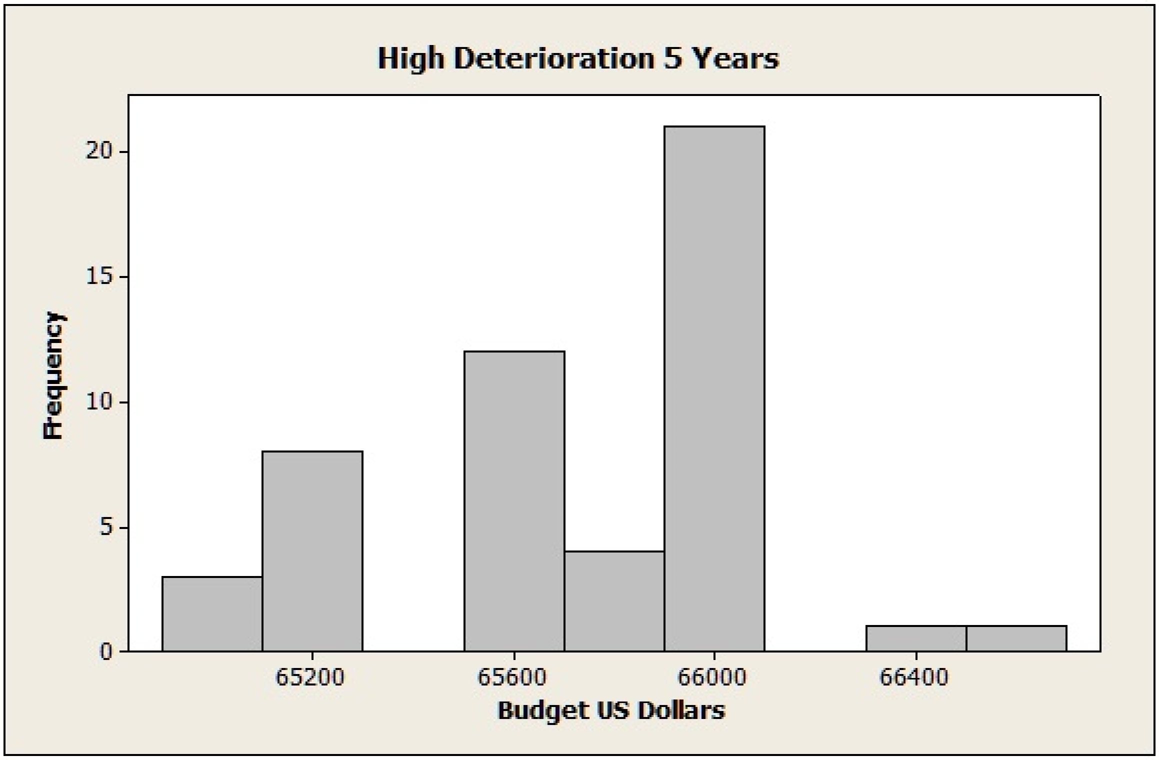

Figure 5.10 Cumulative Budget Histogram for High Pavement Deterioration Band, 5 Year Period

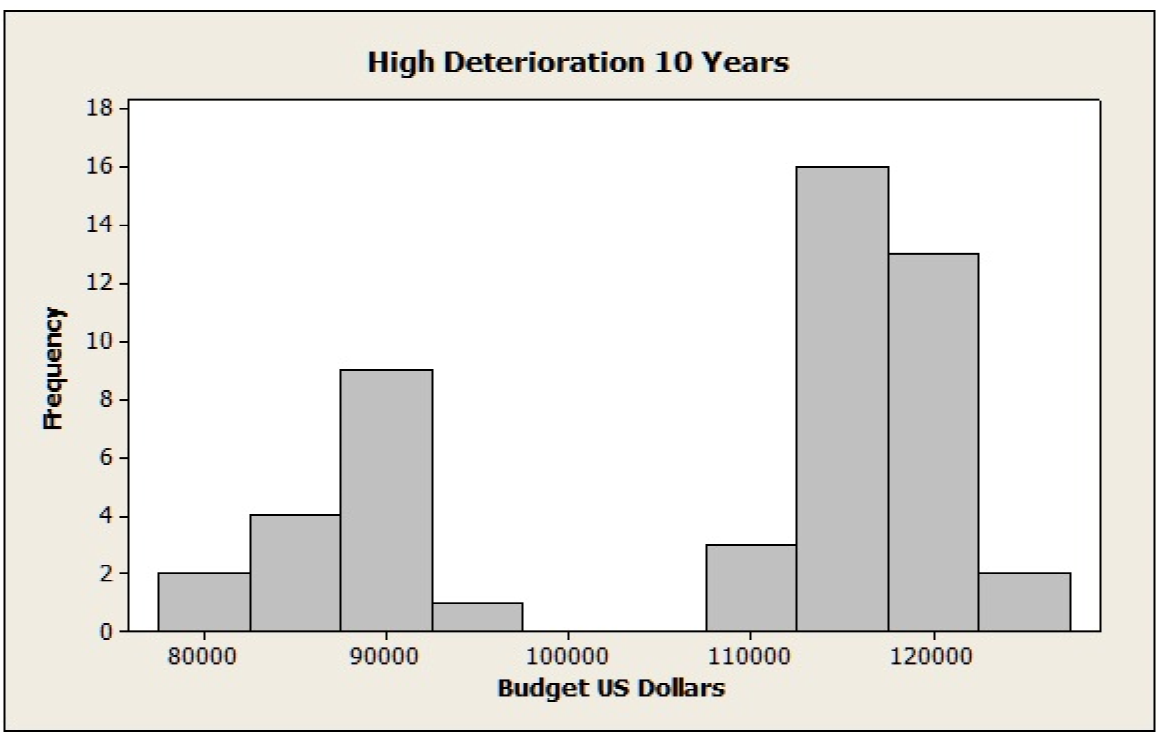

Figure 5.11 Cumulative Budget Histogram for High Pavement Deterioration Band, 10 Year Period

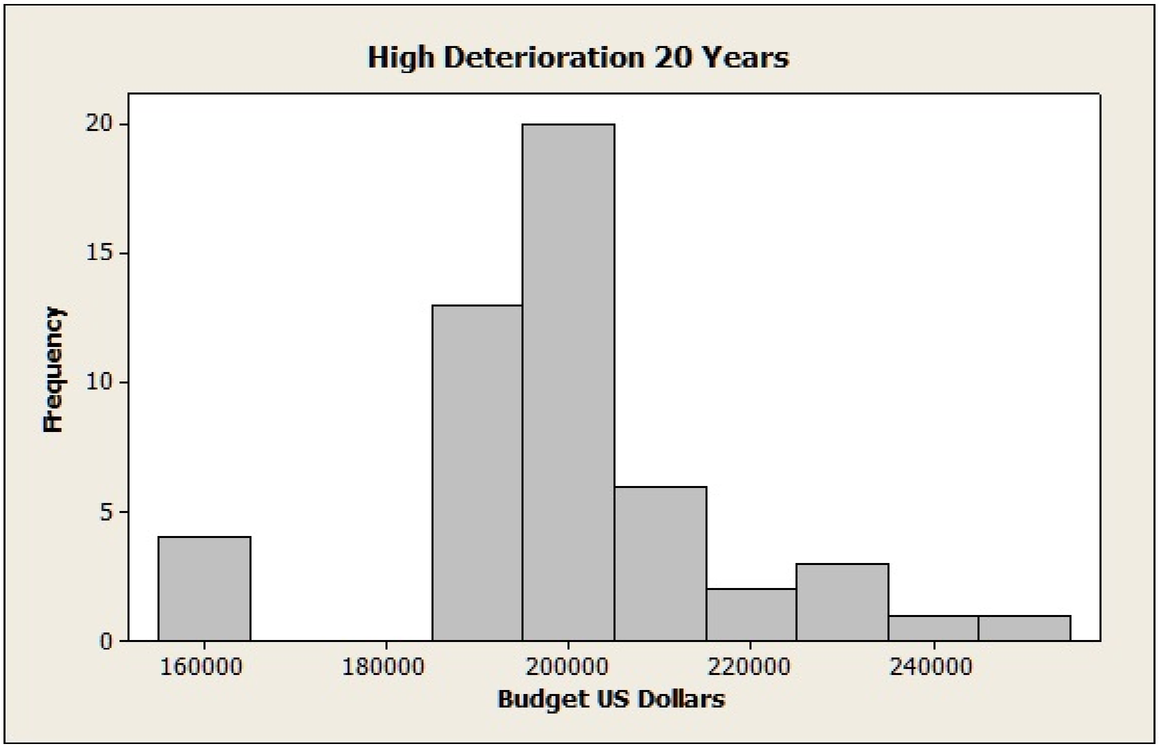

Figure 5.12 Cumulative Budget Histogram for High Pavement Deterioration Band, 20 Year Period

The gap in the histogram for the high deterioration 20 year period is mainly due to different treatments applied to section 14. In some simulations a single chip seal is applied in years 11 and 14, and a mill and thick overlay is applied in year 17; in other simulations a single chip seal is applied in years 11, 15, and 18. The difference in cost is $39,000 that is why there are no values in the histogram between $160,000 and $190,000 (see Tables D.17 and D.18, Appendix D).

The gap in the histogram for the high deterioration 10 year period is mainly due to different treatments applied to section 12. In some simulations a single chip seal is applied in year 5 and a mill and thick overlay is applied in year 8; in other simulations a single chip seal is applied in years 5, 8. The difference in cost is $30,000 that is why there are no values in the histogram between $95,000 and $110,000 (see Tables D.14 and D.15, Appendix D).

5.3 Pavement Network Needs Analysis

Needs analysis for the entire pavement network of arterial sections paved with AC from Table 5.1 is performed section by section as indicated in Figure 5.3, according to their PCI values related to age in their corresponding deterioration band, and then the section's budgets are accumulated for each simulation to obtain the cumulative network budget for each period. The needs analysis for the pavement network is conducted for 5, 10, and 20 years using 50 Monte Carlo simulations for the CDPCI. Statistics for the cumulative budget of the pavement network are shown in Table 5.10. Histograms for the cumulative budget of the pavement network are shown in Figures 5.13, 5.14 and 5.15.

There is a difference of 1% between the minimum and maximum cumulative budget for the 5 years period. In the 10 and 20 year periods, there is a 23% difference between minimum and maximum cumulative budget.

Table 5.10 Probabilistic Pavement Performance-Based Scenarios Budget Needs Analysis Statistics for the Pavement Network

	Pavement Network of 15 Arterial AC Sections 5 Years Period				
	Minimum	1st Quartile	2nd Quartile	3rd Quartile	Maximum
Budget US Dollars	$ 133,647	$ 134,420	$ 134,649	$ 135,144	$ 135,419
	Pavement Network of 15 Arterial AC Sections 10 Years Period				
	Minimum	1st Quartile	2nd Quartile	3rd Quartile	Maximum
Budget US Dollars	$ 184,026	$ 191,775	$ 216,605	$ 220,742	$ 227,022
	Pavement Network of 15 Arterial AC Sections 20 Years Period				
	Minimum	1st Quartile	2nd Quartile	3rd Quartile	Maximum
Budget US Dollars	$ 447,714	$ 483,028	$ 490,137	$ 495,758	$ 549,223

Table 5.10 shows minimum, maximum, first, second, and third quartiles cumulative budgets for the pavement network, the second quartile represent the median deterioration trend. Budget data obtained from the Monte Carlo simulations does not follow a Normal distribution, minimum, maximum, 1st, 2nd, and 3rd quartiles are used to obtain budget needs for the 5, 10, and 20 year period scenarios, other percentiles above and below the median, set by the decision-makers, can be used to obtain different budget scenarios.

Table 5.11 shows cumulative budget needs calculated from a deterministic needs analysis using the MTC-PMS for the entire pavement network for 5, 10, and 20 years analysis periods.

Table 5.11 Deterministic Budget Needs for the Pavement Network

Analysis Period	Deterministic Cumulative Budget
5 Years	$ 133,907
10 Years	$ 216,276
20 Years	$ 554,109

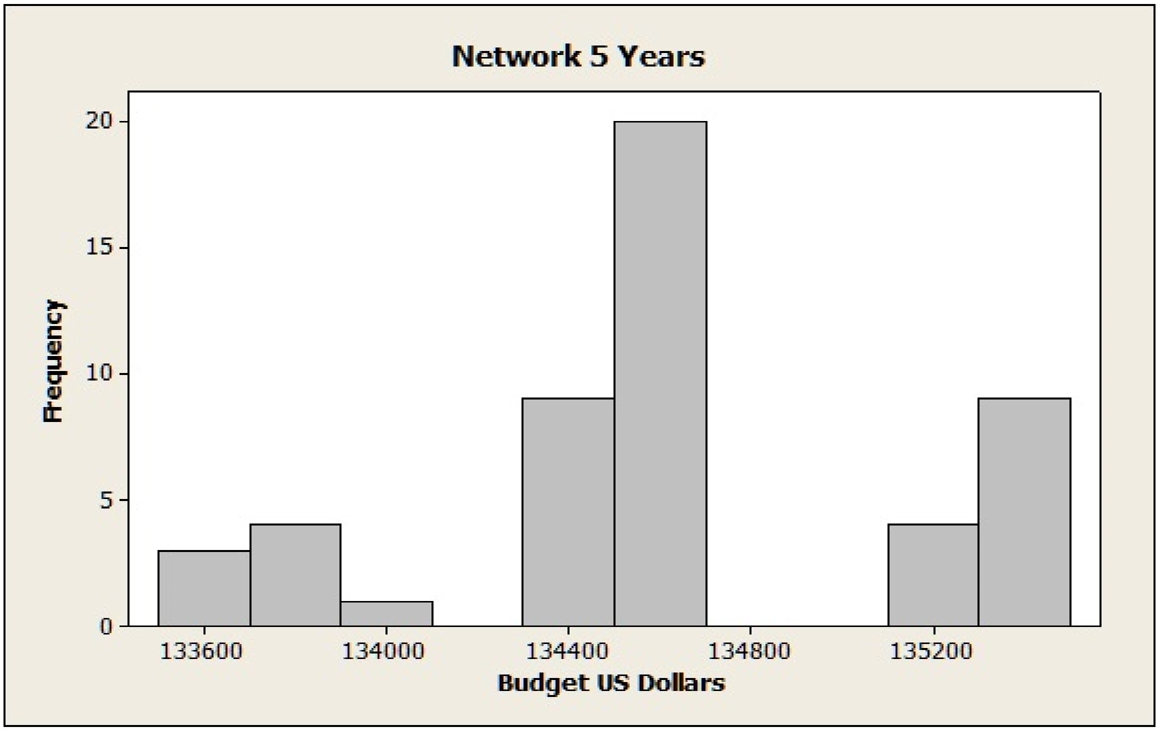

Figure 5.13 Cumulative Budget Histogram for the Pavement Network, 5 Year Period

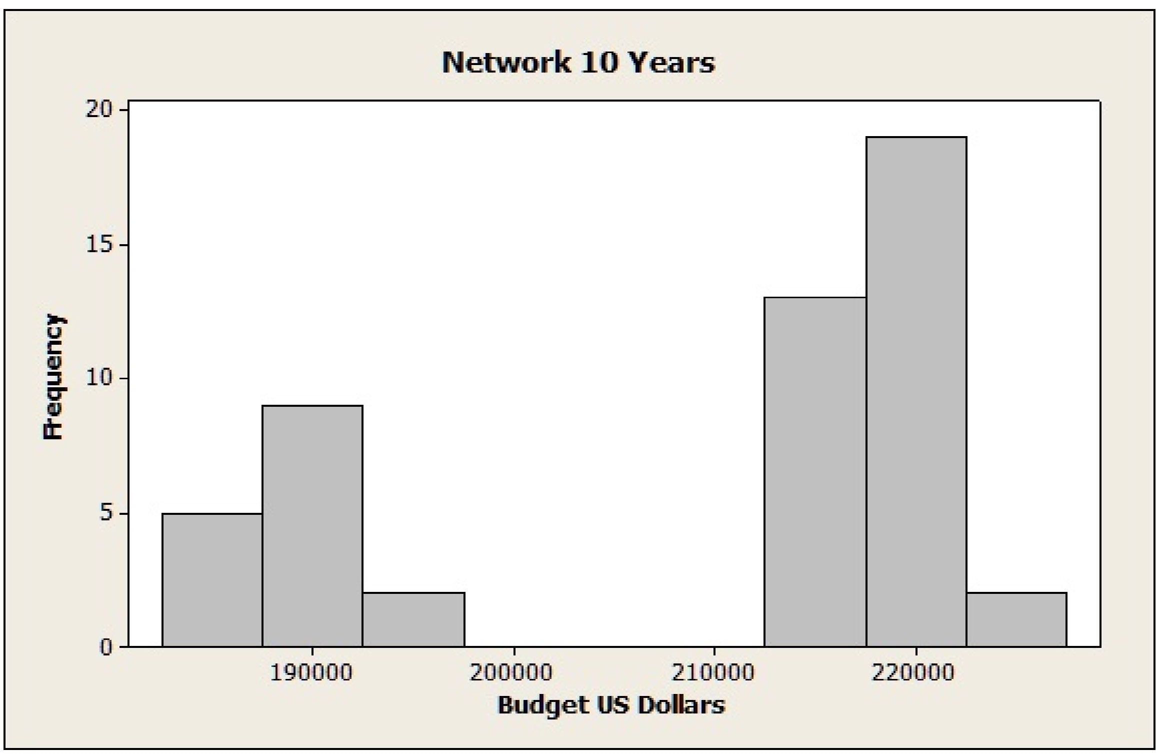

Figure 5.14 Cumulative Budget Histogram for the Pavement Network, 10 Year Period

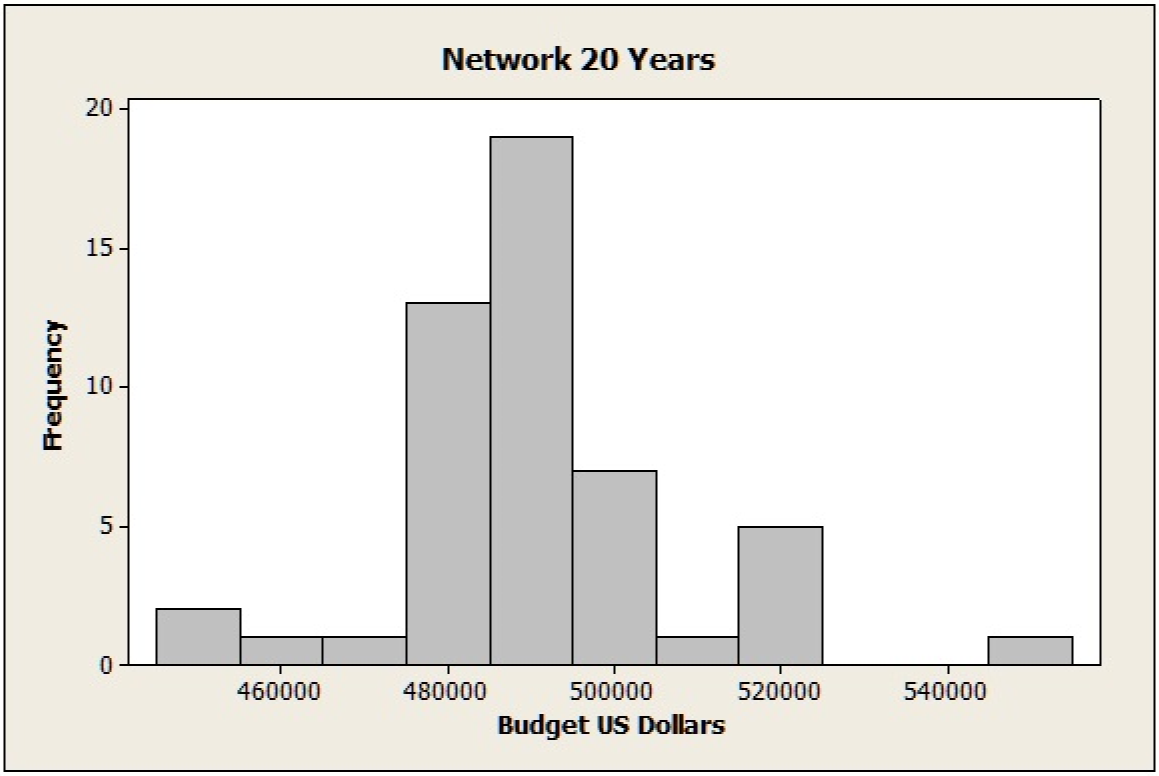

Figure 5.15 Cumulative Budget Histogram for the Pavement Network, 20 Year Period

The gaps in the network histograms are due to treatments applied in different years in some Monte Carlo simulations as described for the gaps in the medium and high deterioration histograms, the annual budget for each section is accumulated to obtain network budget. Budget needs reports for one simulation in each deterioration band are shown in Appendix D.

5.4 Comparison of Results with the Probability-Based Pavement Performance Curves and the Probabilistic Pavement Performance-Based Scenarios

A needs analysis for the 15 pavement sections shown in Table 5.1 is also performed for the 15 sections using the PBPPCs, Figure 5.16 shows the 15 PCI inspected values and 30%, 50%, 70%, and 90% PBPPCs used to analyze each section.

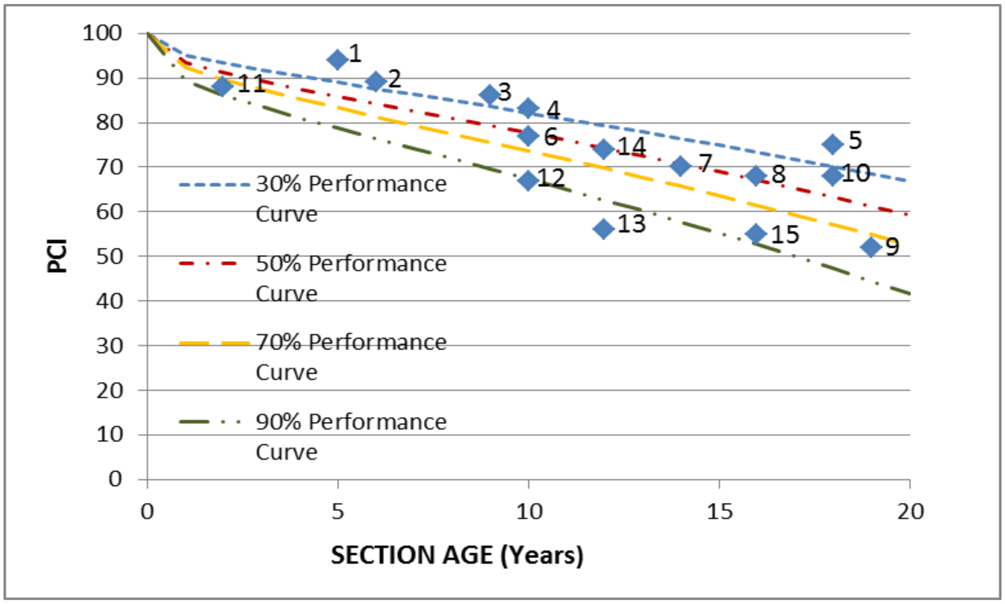

Figure 5.16 Pavement Sections and Probability-Based Pavement Performance Curves

Sections 1, 2, 3, 4, and 5 are analyzed with the 30% PBPPC that corresponds to high pavement performance, since these sections are above this curve. Sections 6, 7, 8, 10, and 14 are analyzed with the 50% PBPPC that corresponds to medium performance, since these sections are close by one PCI point to this curve. Sections 9 and 11 are analyzed using the 70% PBPPC that corresponds to low pavement performance, since these sections are close to this curve by one PCI point. Sections 12 and 15 are close to the 90% PBPPC by one or two PCI points, section 13 is below this curve; sections 12, 13, and 15 are analyzed with the 90% PBPPC that corresponds to very low pavement performance.

Table 5.12 shows a comparison of the pavement network needs analyses results using the PBPPC and the PPPBS. Budgets for the PBPPCs for each pavement performance group and for the entire network are cumulative end of period budgets. Budgets for the PPPBSs for each pavement deterioration group and for the entire network are cumulative second quartile at the end of period budgets. The second

quartile PPPBS budget values are chosen for the comparison, because second quartile is the median of the budgets obtained from the Monte Carlo simulations of the CDPCI values in the needs analysis, since median budget values are more suitable values for comparison.

Low performance for the PBPPC is equivalent to high deterioration for the PPBS, medium performance for the PBPPC is equivalent to medium deterioration for the PPPBS, and high performance for the PBPPC is equivalent to low deterioration for the PPPBS. In table 5.12 deterioration trends for the PPPBS are stated as performance trends.

From Table 5.12 pavement sections are in very good condition, with PCIs above 70, using the PBPPC and the PPPBS analysis, because the needs analysis performed gives the budget to preserve the pavement in very good condition. For low pavement performance, analyzed with the 30% PBPPC, cumulative budget needed for a 20 year period is $196,033, for high pavement deterioration, analyzed in the high deterioration band, the cumulative budget needed for the same 20 year period is $198,301 (second quartile), 1% higher than the PBPPC cumulative budget needed.

For low pavement performance sections are analyzed with the 70% and 90% PBPPCs and with the high deterioration band of the PPPBS. Cumulative budget needed for the PBPPC in a 20 year period is 1% lower than the cumulative budget needed for the PPPBS. In a 10 year period cumulative budget needed for the PBPPC is 18% higher than the cumulative budget needed for the PPPBS. In a 5 year period cumulative budget needed for the PBPPC is 32% higher than the budget needed for the PPPBS.

Table 5.12 Results of the Needs Analyses for the PBPPC and the PPPBS

Probability-Based Pavement Performance Curves						
Pavement Performance	5 Year Peiod		10 Year Period		20 Year Period	
	End of Period PCI	Cumulative Budget	End of Period PCI	Cumulative Budget	End of Period PCI	Cumulative Budget
Five Sections (Low Performance)	86	$ 87,066	85	$ 134,065	78	$ 196,033
Five Sections (Medium Performance)	83	$ 30,850	82	$ 47,261	85	$ 186,538
Five Sections (High Performance)	88	$ 16,717	88	$ 35,782	82	$ 84,491
Entire Network	86	$ 134,633	85	$ 217,108	82	$ 467,062
Probabilistic Pavement Performance-Based Scenarios						
Pavement Performance	5 Year Peiod		10 Year Period		20 Year Period	
	End of Period PCI	Cumulative Budget	End of Period PCI	Cumulative Budget	End of Period PCI	Cumulative Budget
Five Sections (High Deterioration)	85	$ 65,864	84	$ 113,169	81	$ 198,301
Five Sections (Medium Deterioration)	87	$ 52,010	86	$ 67,720	84	$ 160,115
Five Sections (Low Deterioration)	87	$ 16,729	87	$ 35,793	84	$ 129,076
Entire Network	86	$ 134,649	85	$ 216,605	83	$ 490,137

For medium pavement performance sections are analyzed with the 50% PBPPC and with the medium deterioration band of the PPPBS. Cumulative budget needed for the PBPPC in a 20 year period is 16% higher than the cumulative budget needed for the PPPBS. In a 10 year period cumulative budget needed for the PBPPC is 43% lower than the cumulative budget needed for the PPPBS. In a 5 year period cumulative budget needed for the PBPPC is 68% lower than the budget needed for the PPPBS.

For high pavement performance sections are analyzed with the 30% PBPPC and with the low deterioration band of the PPPBS. Cumulative budget needed for the PBPPC in a 20 year period is 52% lower than the cumulative budget needed for the PPPBS. In a 10 year period cumulative budget needed for the PBPPC is 0.03% lower than the cumulative budget needed for the PPPBS. In a 5 year period cumulative budget needed for the PBPPC is 0.07% lower than the budget needed for the PPPBS.

5.5 Summary and Conclusions

The PPPBSs are used in case study 3 to perform a needs analysis in the low, medium, and high deterioration bands. The case study is performed in three phases in groups of five sections from the entire pavement network placing the sections in a deterioration band according to the deterioration trends as shown in Figure 5.2 and Table 5.1.

1. Sections with a similar deterioration behavior are analyzed in a deterioration band (low, medium and high deterioration bands) attaining as many cumulative budgets as Monte Carlo simulations. The results present a range of cumulative budgets in each deterioration band to preserve the pavement sections in very good condition; a probabilistic performance-based scenario of budget needs is obtained, ranging from a minimum to a maximum cumulative budget including different percentiles of the cumulative budget from the simulations.
2. A needs analysis for the entire pavement network is achieved performing analysis of sections in each deterioration band accumulating the budget outputs from the Monte Carlo simulations for each section into an entire network budget. Using different percentiles of the cumulative network budget obtained from the Monte Carlo simulations, an entire pavement network PPPBS of budget needs is attained.
3. PPPBS budget needs analysis can be applied at the project management level for individual sections or groups of sections using low, medium, or high deterioration bands. At the network management level a PPPBS budget needs analysis can be performed for the entire pavement network selecting a

deterioration band for the whole network. A histogram of the cumulative budgets from the Monte Carlo simulations can be constructed. Different percentiles of the cumulative budgets data from the Monte Carlo simulations are used to obtain alternative budget scenarios. In this research, PPPBS are constructed using minimum, maximum, 1^{st}, 2^{nd} and 3^{rd} quartiles budget needs data for each group of sections and for the entire pavement network.

4. There is not a direct relationship between the PCI values and budget estimates obtained from the needs analyses using Monte Carlo simulation as shown in Figure 5.17, PCI values are above 80 and the budgets obtained are needed to preserve the pavement network in very good condition. However, PCI and budget can be related by means of a regression analysis. Equation 5.1, written below and plotted in Figure 5.17, relates PCI and budget in a 20 year period needs analysis for the 15 sections entire pavement network in case a budget needed to achieve a specific PCI value has to be calculated.

$$\text{Budget} = 4755254 - 127897 \times \text{PCI} + 922 \times \text{PCI}^2 \qquad (5.1)$$

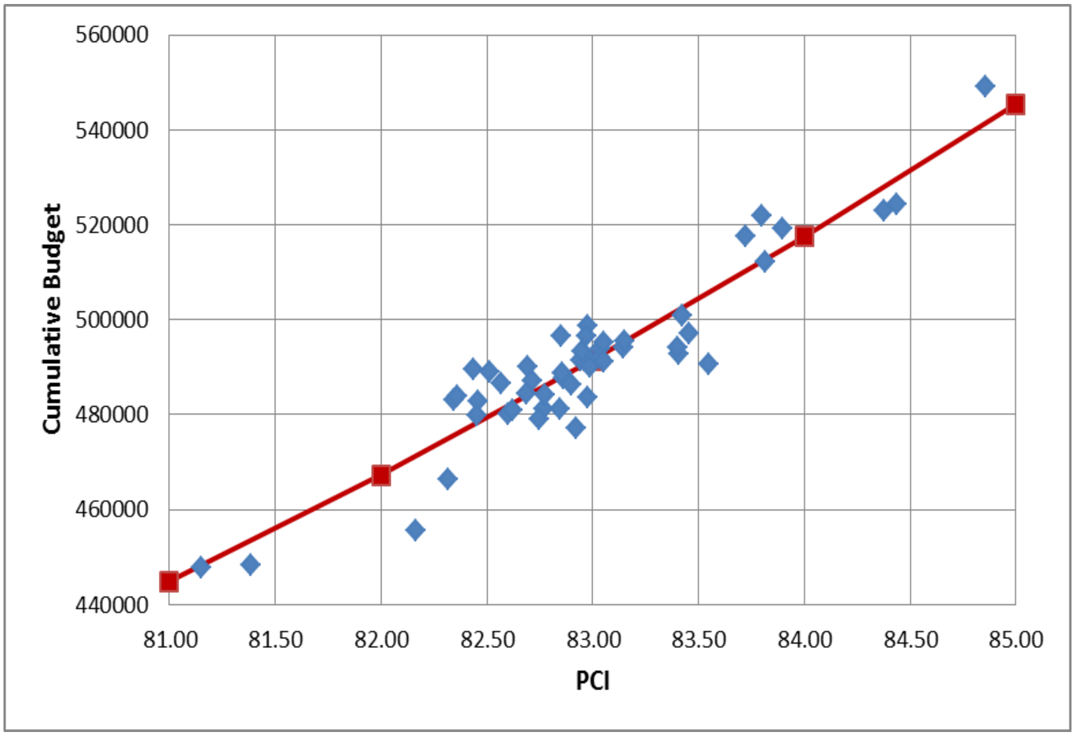

Figure 5.17 Cumulative Budget vs PCI from the Monte Carlo simulations for the Pavement Network, 20 years period, Case 3

5. Needs analysis performed with the PBPPC and the PPPBS for the purpose of comparing both approaches presented $16 difference in the 5 year period, $503 in the 10 year period, and $23,075 in the 20 year period, differences less than 0.1% for the budget needs for the 5 and 10 year periods and 5% budget needs difference for the 20 year period for the entire pavement network.
6. The results of the analyses shown in Table 5.12 strengthen the importance of selecting the best fit PBPPC for the needs analysis or the appropriate deterioration band for the sections in the PPPBS needs analysis. Both approaches present information about alternative budget needs for different pavement conditions to formulate maintenance and rehabilitation programs.

The budget variability in needs analysis comes from the variability of the PCI inspected values at each pavement age converted into CDPCI points used to develop

the PPPBSs explained in Chapter 3, the model assesses the variability of the data with probability distributions of the CDPCIs projecting pavement condition based on ADR using Monte Carlo simulation of the CDPCIs to obtain random ADR. The budget variation in the results of the network's needs analyses is due to the Monte Carlo simulation of the CDPCI values, presenting scenarios of as many budgets as the number of Monte Carlo simulations performed, from a minimum budget needed to a maximum budget needed for each deterioration band and to the ADR in each band. Low deterioration band has ADR values ranging from 0 to 2 PCI points, medium deterioration band have ADR values ranging from 0 to 5 PCI points, and high deterioration band has ADR values ranging from 2 to 10 PCI points (see table 5.2).

PPPBS present the decision-makers with budget needs from a minimum budget to a maximum budget needed to preserve the pavement network in good condition over the analysis period. Budgets for different percentiles in between are also presented (see Table 5.10).

5.5.1 Recommendations

The recommendation is to analyze sections in their best fit deterioration band and accumulate the budget needs for the entire pavement network, using the cumulative budget corresponding to the highest frequency in the histogram because it has the highest likelihood of occurrence.

For the 5 year period needs analysis of the pavement network, the recommendation is that the $134,600 budget corresponding to the 2nd quartile is the most likely choice because it has the highest frequency in the histogram (see Figure 5.13 and Table 5.10).

For the 10 year period needs analysis of the pavement network, the recommendation is that the \$220,000 budget corresponding to the 3rd quartile is the most likely choice because it has the highest frequency in the histogram (see Figure 5.14 and Table 5.10).

For the 20 year period needs analysis of the pavement network, the recommendation is that the \$490,000 budget corresponding to the 2nd quartile is the most likely choice because it has the highest frequency in the histogram (see figure 5.15 and Table 5.10)

The study was done in a small pavement network of 15 pavement sections due to the time consuming process; the PPPBS if implemented in the MTC-PMS software can be used to analyze a large pavement network reducing the time needed for the analysis.

Chapter 6: Conclusions and Recommendations

Pavement management is a systematic approach to manage a pavement network assisting decision-makers in developing cost-effective maintenance and rehabilitation strategies to preserve the pavement network at a desired level of service over time. Pavement management has three main management levels: strategic, network, and project level. At the strategic level, decisions are made at the highest level within transportation agencies and long-term goal and policies are set for the entire pavement network. At the network level, maintenance and rehabilitation programs are prepared for the entire pavement network, decisions on how to allocate the available funds for rehabilitation and maintenance are made and sections are identified for treatment. At the project level, pavement sections are individually studied to determine the most cost-effective maintenance or rehabilitation treatment for each section and decisions are focused over a short period of time (AASHTO 2012).

Pavement management systems are tools that help agencies decide how to select sections for treatment, based on pavement condition and the use of pavement performance models that forecast future pavement condition and identify maintenance and rehabilitation treatment needs for funding allocation. However, pavement management decisions are challenging due to the uncertainty in traffic projections and weather forecasting that affect pavement performance predictions when prioritizing sections for budget allocation. Performance models are classified in two groups: deterministic and probabilistic.

Deterministic models do not take into account the uncertainty of pavement performance and predict future pavement condition and budget needs as a single value.

Deterministic performance models are used at the project management level in pavement design to perform life cycle cost analysis. Deterministic performance models are also used at the network management level to forecast the overall pavement network performance, although they provide only a single output for pavement network condition.

Probabilistic models use probability distributions to address the variability of parameters involved in pavement performance prediction and budget needs estimates. The output of probabilistic models is usually future pavement conditions at different levels of risk and uncertainty.

At the network management level, probabilistic models are applied to the entire pavement network to simulate the likelihood of different deterioration trends. At the project management level, these models are applied to single sections to forecast the section's future condition at different deterioration trends.

The probabilistic approach presented in this research is based on PCIs calculated from pavement distresses. This approach addresses the uncertainty in pavement performance predictions through the development of Probability-Based Pavement Performance Curves (PBPPCs) and Probabilistic Pavement Performance-Based Scenarios (PPPBS). PBPPCs and PPPBS are developed using databases from the Metropolitan Transportation Commission in California (MTC) and are intended for use in a Pavement Management System.

The advantage of PBPPCs and PPPBS with respect to Markovian approaches is that they do not require structural, traffic, or environmental information for their development. PBPPCs and PPPBS do not use probability transition matrixes or prior

probability distributions of pavement behavior since pavement performance is predicted directly using probability distributions built from inspection records. The probability distributions of annual pavement condition data in PCIs from inspection records are used to construct PBPPCs at different probability levels, obtaining alpha, beta, and rho parameters, used in Equation 1.1, to forecast pavement performance. The probability distributions of annual pavement cumulative deterioration data in PCI points from inspection records are used to construct PPPBS. In the PPPBS approach, pavement condition is forecasted based on annual deterioration rates instead of using families of curves. Monte Carlo simulation of the annual cumulative deterioration PCI points is used to generate cumulative pavement deterioration for possible pavement performance scenarios.

6.1 Conclusions

a) PBPPCs and PPPBS predict future pavement condition starting from the present pavement condition state, utilizing alternative future pavement conditions to simulate different pavement deterioration rates based on their likelihood of occurrence. Both models present broad information about future pavement condition and budget needs estimates to the decision-makers addressing the uncertainty in pavement prediction.

b) The probability-based pavement performance curves can be implemented in MTC-PMS needs analyses for the entire network to simulate different pavement performance using alpha, beta, and rho parameters corresponding to each probabilistic performance level for the entire network, instead of using the fixed default alpha, beta, and rho parameters.

At present, an average or medium pavement performance that corresponds to a 50% performance curve is used in the deterministic model. High pavement performance use PCI curves below 50%; and low pavement performance use PCI curves above 50%. For example a 30% performance curve means that there is a 30% probability that the PCI of a certain pavement will be higher or equal to the PCI obtained from this probability performance curve. More information about future pavement performance can be obtained using alpha, beta, and rho parameters to represent different performance levels for each functional class and pavement type. At the network management level, this information can be used to develop maintenance and rehabilitation programs for the entire pavement network. At the project management level, needs analysis using different PBPPCs and decision trees can be run for individual sections to project pavement conditions and to identify the most cost effective treatments.

c) Needs analyses were conducted in Chapter 4 using 70% and 90% PBPPCs to model low performance behavior and a 30% PBPPC to model high performance behavior for AC, AC/AC, and ST pavements in a 5, 10, and 20 year periods. Budgets from the 70% and 90% PBPPCs were higher than the 50% PBPPC and budgets from the 30% PBPPC were lower than the 50% PBPPC. Pavements with a very low performance level have high pavement deterioration rates and need higher cumulative budgets to preserve the pavement network in good condition; on the contrary, pavements with a high performance have low pavement deterioration rates and need less cumulative budget to preserve the network in good condition. There was variability in the budget results for the

analysis periods when compared to the budget results for the 50% performance level for the same period. This was due to treatments recommended at different ages because of the very high, high, and low pavement deterioration trends of the PBPPCs used for the needs analysis, as described in detail for each case study in Chapter 4.

d) The variability of the data from MTC used in the development of the PBPPCs from San Francisco, California Bay area cities is reflected in the range of values of the outputs from the needs analysis in Case Study 1 (Chapter 4). If the PBPPCs are going to be used in a different area, local data should be gathered from that area to develop or calibrate the PBPPCs for the specific weathering and traffic conditions. In this research, only four pavement performance levels were applied; increasing the PBPPC probability levels should reduce the variability of the budget needs estimates.

e) The probability-based pavement performance curves implemented in target driven analyses identify sections and treatments to apply at different probability levels and obtain budget needs to preserve the pavement at a desired PCI network condition.

The PBPPCs were used in a target-driven analysis for 5, 10, and 20 year periods for AC, AC/AC, and ST pavement networks in Case Study 2 (Chapter 4), setting a target PCI of 75 for the network and using 30%, 50%, 70%, and 90% PBPPCs to model high, medium, and low performance trends to obtain budget needs. Budget needs for 90% and 70% PBPPCs were higher than the budget needs for 50% PBPPC, and the budget needs for 30% PBPPC was lower than

the budget needs for the 50% PBPPC. For 70% and 90% PBPPCs, PCIs at the first year of analysis were below the target PCI, and that is why a higher budget was needed to bring the PCI to the target value and keep it that way through the analysis period. For 30% PBPPCs, PCIs in the first year of analysis were equal or above the target PCI, and that is why a lower budget was needed to preserve the pavement network at the target PCI.

f) The probabilistic pavement performance-based scenarios can be implemented in MTC-PMS, rendering a needs analysis for the entire network or for individual sections to simulate different pavement performance scenarios using low, medium, and high pavement deterioration bands. For each deterioration band, a Monte Carlo simulation of the truncated Normal distribution of the annual cumulative deterioration PCI points can be used to calculate annual deterioration rates within the limits of the deterioration band, instead of using families of curves to project the PCI.

g) Budget needs analysis can be performed using PPPBS for the entire pavement network, using different deterioration bands for the entire network, to obtain a histogram of the budget needs built from Monte Carlo simulations. At the project management level, PPPBS can be applied for the needs analysis of individual sections that show a deterioration trend that is within a pre-established deterioration band.

h) A needs analysis was performed using the PPPBS in Case Study 3 (Chapter 5) to simulate pavement deterioration scenarios for a pavement network with 15 sections. The needs analysis was conducted using low, medium and high

deterioration bands. Budget needs using the low deterioration band were lower than the budgets needs using the medium deterioration band which represented an average deterioration. Budgets needs using the high deterioration band were higher than the budgets needs for the medium deterioration band.

i) The variability of the budgets obtained as outputs from the PPPBS is due to the variability of the data. This variability can be reduced by performing a large number of Monte Carlo simulations of the yearly cumulative deterioration PCI points, calculating annual deterioration rates to cover a range of values between the limits of the PCI cumulative deterioration band.

6.2 Contributions of Research

The major contribution of this research is the development of a probabilistic approach for pavement performance prediction for implementation in the MTC-PMS. PBPPCs and PPPBS address the uncertainty present in pavement performance predictions, and will aid agencies to make better-informed funding allocation decisions in their maintenance and rehabilitation programs.

PBPPCs and PPPBS can be used for needs analyses at the network and project management levels. The variability of the PCI projections is assessed with probability distributions, obtaining the entire spectrum of budget needs for different pavement performance scenarios; PBPPCs can also be used at the network management level for target driven scenarios, to estimate budget needs and to preserve a pavement network at a desired PCI level.

6.3 Recommendations for Future Research

a) This research was focused on developing PBPPCs to conduct needs analyses for individual pavement sections, or for the entire pavement network. Further research can use PBPPCs in needs analyses for individual sections, and dynamically adjust the pavement curve based on PCIs obtained from inspections (see Figure 6.1).

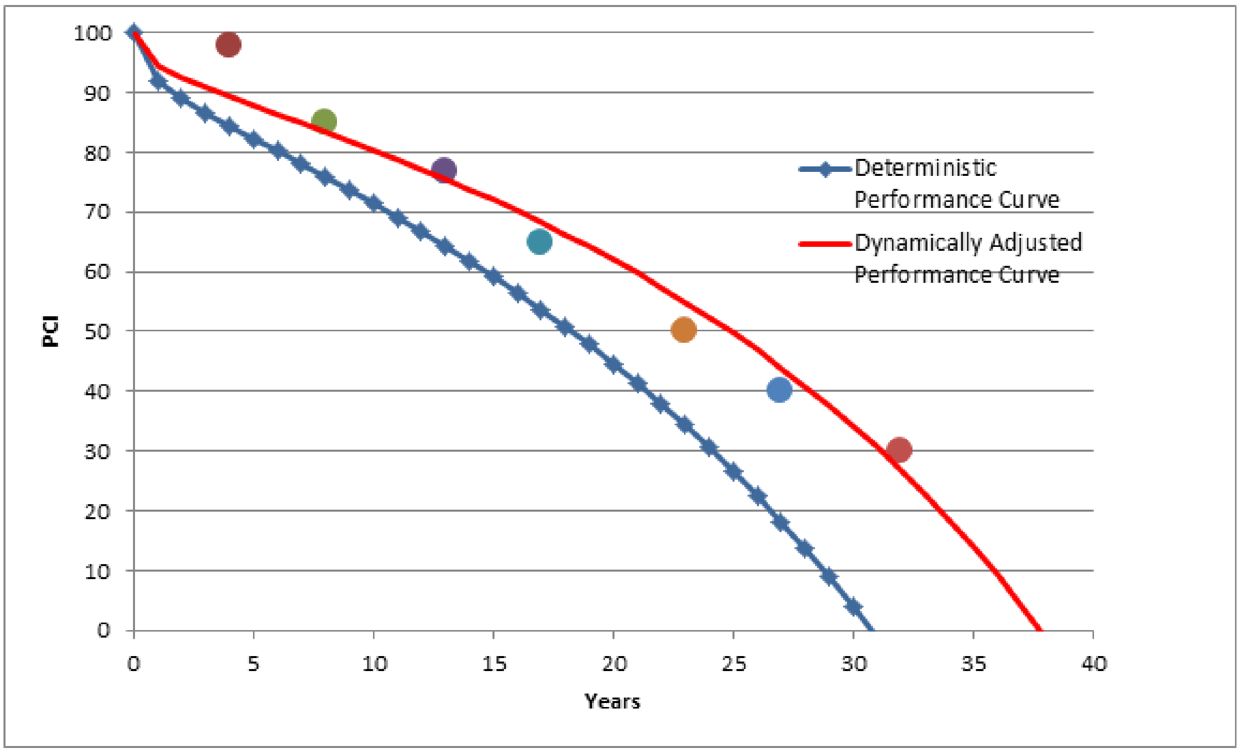

Figure 6.1 Performance Curve According to Section's History

b) The application of the PPPBS was focused only on needs analysis for arterial streets paved with asphalt concrete. Further research should be done to implement the PPPBS to perform target driven analyses for the entire pavement network, or for individual sections, looking at other pavement types.

c) Research can be done using PBPPC and PPPBS to perform budget-driven analyses that use an available budget for the analysis period as an input and predict the pavement network condition over the analysis period, showing selected sections for treatment, and treatments to apply.

d) Further research can be done using the PBPPCs or the PPPBS, applying probability distributions to the MTC-PMS decision tree to convert it into a probabilistic decision tree using probability distributions in the chance nodes and costs for the decision nodes. Expected values of cost are calculated from the probabilities of chance events from the decision tree, with the alternative with the lowest cost being the recommended alternative.

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Appendix A. Inspected PCI Data and Normal Distribution Fitting

Arterial AC inspected PCI values, outliers removed, are clustered by year in Tables A.1a and A.1b. Arterial AC/AC inspected PCI values, outliers removed, are clustered by year in Tables A.2a and A.2b. Residential ST inspected PCI values, outliers removed, are clustered by year in Tables A.3a, A.3b, A.3c, and A.3d

An example of distribution fitting graphs for years 1 to 6, for arterial AC PCI yearly values normal distribution fitting graphs, can be seen in Figures A.1 trough A.6; arterial AC/AC PCI yearly values normal distribution fitting graphs, can be seen in Figures A.7 trough A.12, and residential ST PCI yearly values normal distribution fitting graphs can be seen in Figures A.13 trough A.18. Goodness of fit for arterial AC normal distributions are shown in Table A.4; goodness of fit for arterial AC/AC normal distributions are shown in Table A.5, and goodness of fit for residential ST normal distributions are shown in Table A.6. Mean and standard deviation from these yearly normal distribution fittings were used for developing probability-based pavement performance curves in Chapters 3, 4, and 5.

Table A.1a Arterial AC Inspected PCI Values (Ages 1 to 10 Years)

Age 1 Year		Age 2 Years		Age 3 Years		Age 4 Years		Age 5 Years		Age 6 Years		Age 7 Years		Age 8 Years		Age 9 Years		Age 10 Years	
100		100	89	98		96		94	73	93		92		91		90	64	88	59
100		99	88	98		96		93	73	92		92		88		90	64	88	58
100		99	88	98		95		93		91		91		88		89	63	88	
100		99	87	98		95		93		91		91		85		89	62	86	
100		99	87	98		95		93		91		89		84		88		85	
100		98	86	98		95		93		90		89		84		87		85	
100		98	85	98		95		93		90		89		82		84		84	
100		98	84	98		94		93		89		85		82		84		83	
100		98		97		93		93		89		84		82		83		83	
100		95		97		93		93		86		83		81		83		82	
100		95		97		92		92		85		81		81		83		82	
100		95		95		91		92		85		80		81		83		82	
100		95		94		91		92		83		80		80		82		81	
100		95		94		91		92		83		79		80		82		81	
100		95		93		90		92		83		78		79		82		81	
99		95		93		90		91		83		78		78		82		81	
99		95		92		90		90		83		78		77		81		80	
99		95		92		90		88		82		77		74		81		80	
98		94		92		89		87		82		77		71		80		80	
98		94		91		89		87		82		76		69		80		78	
98		94		91		89		87		81		75				79		77	
98		93		90		87		86		81		74				78		77	
98		93		90		87		86		81		67				77		76	
98		93		89		85		84		81						77		76	
97		92		89		83		83		81						77		75	
97		92		87		82		83		81						77		75	
97		92		87		82		83		80						76		75	
96		91		86		82		82		80						76		75	
92		91		84		82		82		80						76		75	
90		90		83		76		81		79						75		75	
		90		82				80		74						74		73	
		90		82				77		72						74		73	
		90		82				77		70						73		71	
		90		82				77								73		69	
		89		81				77								71		69	
		89						76								70		69	
		89						76								65		66	
		89						76								65		62	
		89						75								64		61	
		89						74								64		59	

Table A.1b Arterial AC Inspected PCI Values (Ages 11 to 20 Years)

Age 11 Years		Age 12 Years		Age 13 Years		Age 14 Years		Age 15 Years		Age 16 Years		Age 17 Years		Age 18 Years		Age 19 Years		Age 20 Years	
87	71	86	75	85		83	44	84	65	83	69	82	46	81	56	78	71	61	74
87	71	86	72	84		83		84	63	83	69	81	45	80	56	51	27	61	50
87	70	86	71	84		82		84	62	83	68	80	44	80	55	68	48	79	77
84	70	86	68	83		82		84	62	82	67	79	43	77	54	44	40	77	51
84	70	86	68	83		81		83	55	82	67	79	42	76	54	47	54	59	
84	69	85	68	83		81		83	54	82	67	78	38	76	54	44		75	
83	69	85	64	82		81		83	53	82	67	78	33	76	53	54		79	
83	68	85	59	82		80		83	53	81	66	78		75	52	78		58	
82	66	85	58	82		76		83	52	81	63	76		75	52	50		71	
82	65	85	57	82		76		83	51	81	61	76		75	52	50		58	
81	65	85	56	82		73		83	51	80	60	75		75	52	50		52	
81	65	85	54	82		73		82	49	80	60	75		74	52	80		35	
81	65	84	53	81		73		82	44	80	59	75		74	52	73		79	
80	65	84	53	81		73		82	41	79	59	75		73	52	79		47	
80	63	83		81		72		81	38	79	58	72		72	47	79		60	
80	63	83		79		72		81		79	57	72		72	45	71		58	
79	61	83		79		72		81		79	57	72		72	41	47		69	
79	60	83		79		71		79		79	57	72		72	36	62		45	
79	60	82		77		71		78		79	50	71		72	31	62		66	
78	55	82		77		71		77		79	47	70		71		49		57	
78	54	81		76		70		77		78	42	70		70		70		67	
78		81		76		68		76		77	41	69		70		72		42	
78		80		75		68		75		77	40	67		69		73		75	
77		79		71		67		75		76	38	67		69		78		73	
77		79		67		65		72		76	38	65		69		37		70	
76		79		67		65		72		75	36	65		69		74		63	
76		78		60		65		72		75	34	64		67		33		61	
75		78		58		64		72		75	34	64		67		51		79	
75		78		58		64		72		74	34	62		67		69		64	
75		78		57		63		72		74		60		67		67		73	
75		78		54		63		71		72		60		64		60		72	
75		78		50		62		70		72		60		64		69		75	
75		78		49		62		70		72		59		64		72		58	
75		77				59		70		71		59		62		44		29	
74		76				58		70		70		59		62		76		55	
73		76				56		68		69		57		62		72		75	
73		76				54		67		69		56		60		62		67	
73		75				54		67		69		54		58		71		68	
72		75				51		66		69		48		58		44		59	
72		75				48		66		69		48		58		69		72	

Table A.2a Arterial AC/AC Inspected PCI Values (Ages 1 to 10 Years)

Age 11 Years		Age 12 Years		Age 13 Years		Age 14 Years		Age 15 Years		Age 16 Years		Age 17 Years		Age 18 Years		Age 19 Years		Age 20 Years	
87	69	85	64	84	67	83	54	84	58	83		82	47	76		80		78	
85	67	84	60	84	67	83		83	57	83		82	44	74		79		78	
85	67	83	60	83	67	82		81	57	83		81		73		78		75	
83	66	83	59	82	67	78		79	56	83		81		73		78		75	
83	65	83	59	82	65	77		77	56	83		80		73		77		75	
83	65	82	58	82	63	77		77	56	81		79		72		77		71	
83	64	80	57	81	63	77		76	56	81		77		72		77		70	
83	64	79		81	62	76		76	56	81		77		71		74		68	
82	62	79		79	60	76		74	56	79		77		71		73		63	
82	61	79		79	58	75		73	56	79		76		69		72		63	
81	60	78		78	57	75		73	50	78		74		68		69		63	
81		78		78	57	74		72	50	78		74		68		68		63	
81		77		78	57	73		71	48	78		73		67		67		63	
81		77		78	55	73		69		77		72		67		66		63	
80		76		77	55	73		69		76		71		67		64		63	
80		76		77		73		69		76		71		67		64		62	
79		76		77		72		69		75		65		65		62		62	
79		76		77		72		69		74		63		62		61		62	
79		75		76		71		68		72		62		62		60		58	
78		74		76		70		68		68		62		61		60		57	
78		74		76		70		67		68		62		60		59		57	
78		73		75		69		66		67		62		60		58		56	
78		73		75		68		66		66		62		60		58		55	
78		73		74		66		66		66		62		59		58		55	
77		73		74		62		66		66		62		59		58		55	
77		72		73		59		66		65		62		56		58		54	
75		72		71		59		66		61		61		56		57		54	
75		72		71		58		66		59		58		55		57		54	
75		72		71		58		63		58		57		55		55		53	
75		72		71		58		63		57		55		51		52		51	
74		72		71		58		63		56		54		51		51		47	
74		71		71		57		62		52		54		48		48		45	
74		71		71		56		61		51		53		48		48		45	
73		71		70		56		61				53		48		48		45	
72		70		70		56		60				49		48		44		45	
71		69		69		56		60				49		48				35	
71		68		69		56		60				49		48					
70		67		69		56		60				49		47					
70		67		69		55		59				49		47					
70		67		68		55		59				49							

Table A.2b Arterial AC/AC Inspected PCI Values (Ages 11 to 20 Years)

Age 11 Years		Age 12 Years		Age 13 Years		Age 14 Years		Age 15 Years		Age 16 Years		Age 17 Years		Age 18 Years		Age 19 Years		Age 20 Years	
87	71	86	75	85		83	44	84	65	83	69	82	46	81	56	78	71	61	74
87	71	86	72	84		83		84	63	83	69	81	45	80	56	51	27	61	50
87	70	86	71	84		82		84	62	83	68	80	44	80	55	68	48	79	77
84	70	86	68	83		82		84	62	82	67	79	43	77	54	44	40	77	51
84	70	86	68	83		81		83	55	82	67	79	42	76	54	47	54	59	
84	69	85	68	83		81		83	54	82	67	78	38	76	54	44		75	
83	69	85	64	82		81		83	53	82	67	78	33	76	53	54		79	
83	68	85	59	82		80		83	53	81	66	78		75	52	78		58	
82	66	85	58	82		76		83	52	81	63	76		75	52	50		71	
82	65	85	57	82		76		83	51	81	61	76		75	52	50		58	
81	65	85	56	82		73		83	51	80	60	75		75	52	50		52	
81	65	85	54	82		73		82	49	80	60	75		74	52	80		35	
81	65	84	53	81		73		82	44	80	59	75		74	52	73		79	
80	65	84	53	81		73		82	41	79	59	75		73	52	79		47	
80	63	83		81		72		81	38	79	58	72		72	47	79		60	
80	63	83		79		72		81		79	57	72		72	45	71		58	
79	61	83		79		72		81		79	57	72		72	41	47		69	
79	60	83		79		71		79		79	57	72		72	36	62		45	
79	60	82		77		71		78		79	50	71		72	31	62		66	
78	55	82		77		71		77		79	47	70		71		49		57	
78	54	81		76		70		77		78	42	70		70		70		67	
78		81		76		68		76		77	41	69		70		72		42	
78		80		75		68		75		77	40	67		69		73		75	
77		79		71		67		75		76	38	67		69		78		73	
77		79		67		65		72		76	38	65		69		37		70	
76		79		67		65		72		75	36	65		69		74		63	
76		78		60		65		72		75	34	64		67		33		61	
75		78		58		64		72		75	34	64		67		51		79	
75		78		58		64		72		74	34	62		67		69		64	
75		78		57		63		72		74		60		67		67		73	
75		78		54		63		71		72		60		64		60		72	
75		78		50		62		70		72		60		64		69		75	
75		78		49		62		70		72		59		64		72		58	
75		77				59		70		71		59		62		44		29	
74		76				58		70		70		59		62		76		55	
73		76				56		68		69		57		62		72		75	
73		76				54		67		69		56		60		62		67	
73		75				54		67		69		54		58		71		68	
72		75				51		66		69		48		58		44		59	
72		75				48		66		69		48		58		69		72	

Table A.3a Residential ST Inspected PCI Values (Ages 1 to 5 Years)

Age 1 Year					Age 2 years					Age 3 Years					Age 4 Years					Age 5 Years				
98	91	88	85		95	87	82			97	88	80			94	87	84	80	74	92	87	82	79	75
95	91	88	85		95	87	82			97	88	80			93	87	84	80	73	92	87	82	79	75
95	91	88			94	87	82			97	88	79			93	87	84	80	73	91	86	82	79	75
95	91	88			92	87	82			96	87	79			90	86	84	80	73	91	86	82	79	75
95	91	88			92	87	82			96	87	79			90	86	84	80	73	91	86	82	79	74
95	91	87			92	87	82			96	87	78			90	86	84	80	72	91	86	82	79	74
93	90	87			92	87	82			96	87	77			90	86	84	80	72	90	86	82	79	74
93	90	87			92	87	82			95	87	77			90	86	84	80	72	90	86	82	79	74
93	90	87			91	86	81			94	87	76			90	86	84	80	71	90	86	82	79	74
93	90	87			91	86	81			93	86	76			90	86	84	80	71	90	86	82	79	74
93	90	87			90	86	81			92	86	76			89	86	84	79	71	90	86	82	78	74
93	90	87			90	85	81			92	86	76			89	86	84	79	71	90	85	82	78	73
93	90	87			90	85	81			92	85	75			89	86	84	79	71	89	85	82	78	73
93	90	87			90	85	81			92	85	75			89	86	84	79	70	89	85	82	78	73
93	90	87			90	85	80			92	85	75			89	86	83	79	70	89	85	82	78	72
92	90	87			90	85	80			92	85				89	86	83	78		89	85	82	78	71
92	90	87			90	85	80			92	85				89	86	83	78		89	85	82	78	71
92	90	87			89	85	80			91	85				89	86	83	78		88	85	81	78	70
92	89	87			89	85	80			91	85				89	86	83	78		88	85	81	77	70
92	89	86			89	85				91	85				89	86	83	78		88	84	81	77	69
92	89	86			89	85				91	85				89	85	83	78		88	84	81	77	69
92	89	86			89	85				90	85				89	85	83	77		88	84	81	77	68
92	89	86			89	85				90	85				89	85	83	77		88	84	81	77	68
92	89	86			89	84				90	84				89	85	83	77		88	84	81	77	68
92	89	86			89	84				90	84				89	85	82	77		88	84	81	77	67
92	89	86			89	84				90	84				89	85	82	77		88	84	81	77	67
92	89	86			89	84				90	84				88	85	82	77		88	83	81	76	66
92	89	86			89	84				89	84				88	85	82	77		88	83	81	76	65
92	89	86			89	84				89	84				88	85	82	76		88	83	81	76	65
92	89	86			89	84				89	84				88	85	82	76		87	83	80	76	65
92	89	86			89	84				89	83				87	85	82	76		87	83	80	76	65
92	89	86			88	84				89	83				87	85	81	76		87	83	80	76	
92	88	85			88	84				89	83				87	85	81	76		87	83	80	76	
92	88	85			88	84				89	83				87	85	81	75		87	83	80	76	
91	88	85			88	84				89	83				87	85	81	75		87	83	80	76	
91	88	85			88	83				89	82				87	85	81	75		87	83	80	76	
91	88	85			88	83				89	82				87	85	81	75		87	83	80	76	
91	88	85			88	83				89	80				87	84	81	74		87	83	80	76	
91	88	85			88	83				89	80				87	84	81	74		87	83	80	76	
91	88	85			87	83				88	80				87	84	80	74		87	83	80	76	

Table A.3b Residential ST Inspected PCI Values (Ages 6 to 10 Years)

Age 6 Years					Age 7 Years					Age 8 Years					Age 9 Years					Age 10 Years				
92	87	83	80	73	91	85	82	78	74	89	85	82	76	66	87	83	78	73	64	85	82	75	62	
92	86	83	80	73	90	85	82	78	74	89	85	82	76	66	87	83	78	73	64	85	81	75	61	
91	86	83	80	73	90	85	82	78	73	89	85	81	76	66	87	83	78	73	64	85	81	75	59	
91	86	83	80	73	90	85	82	78	73	89	85	81	76	66	87	83	78	73	64	85	81	74	59	
90	86	82	79	73	89	85	82	78	72	89	84	81	76	66	87	83	78	73	63	85	81	74	59	
89	86	82	79	73	89	85	82	78	72	89	84	81	75	65	87	83	78	73	63	85	81	74	59	
89	85	82	79	73	88	85	82	78	72	88	84	81	75	65	87	83	77	73	63	85	81	74	58	
89	85	82	79	72	88	85	82	78	72	88	84	81	75	65	87	83	77	73	63	85	81	74	58	
89	85	82	79	72	88	85	82	78	72	88	84	81	75	65	87	83	77	72	63	85	81	74	57	
89	85	82	79	72	88	85	82	78	71	88	84	81	75	65	87	82	77	71	62	85	81	74	56	
89	85	82	79	72	88	85	82	77	70	87	84	81	74	64	87	82	77	71	62	84	81	73	56	
89	85	82	78	72	88	84	82	77	70	87	84	81	74	64	86	82	77	70	61	84	81	72	55	
89	85	82	78	72	88	84	82	77	69	87	84	81	74	63	86	82	77	70	61	84	81	72	54	
89	85	82	78	72	88	84	82	77	68	87	84	81	74	63	86	82	77	70	59	84	81	72	54	
89	85	82	78	72	88	84	82	77	68	87	84	81	73	63	86	82	77	70	59	84	81	72	54	
89	85	82	78	72	87	84	81	77	68	87	84	81	73	62	86	82	76	70	57	84	80	71	53	
89	84	82	78	72	87	84	81	77	67	86	84	81	73	61	86	82	76	70	57	84	80	71	52	
89	84	82	78	70	87	84	81	77	67	86	83	80	73	60	86	82	76	69	56	84	80	70	51	
89	84	82	78	70	87	84	81	77	66	86	83	80	73	59	86	81	76	69	54	84	80	70	51	
89	84	81	77	70	87	84	81	77	65	86	83	80	72	58	86	81	76	69	52	84	80	70	51	
89	84	81	77	70	87	84	81	77	64	86	83	80	72	58	86	81	76	69	51	83	80	69	50	
88	84	81	77	70	87	84	81	76	64	86	83	80	72	58	85	81	76	69	50	83	80	69	50	
88	84	81	77	69	87	84	81	76	63	86	83	80	72	57	85	81	76	69	50	83	80	68	44	
88	84	81	77	69	87	84	81	76	63	86	83	79	72	54	85	81	76	68	49	83	79	68	43	
88	84	81	77	68	86	83	80	76	61	86	83	79	71	54	85	81	76	68	49	83	79	68	42	
88	84	81	77	68	86	83	80	76	60	86	83	79	71	53	85	81	76	68	48	83	79	67	40	
88	84	81	77	68	86	83	80	76	58	86	83	79	71	53	85	80	75	68	47	83	79	67		
88	84	81	76	68	86	83	80	76	58	86	83	78	71	50	85	80	75	67	47	83	79	67		
88	84	81	76	68	86	83	80	76	57	85	83	78	71		84	80	75	66	46	83	79	67		
88	84	81	76	68	86	83	80	76		85	82	78	70		84	80	75	66	45	83	79	66		
88	84	80	76	66	86	83	80	75		85	82	78	70		84	80	75	66	45	83	79	66		
88	84	80	75	66	86	83	80	75		85	82	78	70		84	80	75	66		83	79	65		
88	84	80	75	66	86	83	80	75		85	82	77	69		84	80	75	66		83	78	65		
88	83	80	75	64	86	83	80	75		85	82	77	69		84	79	75	66		82	78	65		
87	83	80	75	64	86	83	79	75		85	82	77	69		84	79	75	65		82	78	65		
87	83	80	75	63	86	83	79	75		85	82	77	69		84	79	74	65		82	77	64		
87	83	80	75	63	86	83	79	74		85	82	77	68		84	79	74	65		82	77	64		
87	83	80	74	62	86	83	79	74		85	82	77	67		84	79	74	65		82	77	64		
87	83	80	74	61	86	83	79	74		85	82	77	67		84	79	74	65		82	76	63		
87	83	80	74	61	86	83	79	74		85	82	76	67		84	79	74	65		82	75	63		

Table A.3c Residential ST Inspected PCI Values (Ages 11 to 15 Years)

Age 11 Years					Age 12 Years					Age 13 Years					Age 14 Years					Age 15 Years				
82	78	71	50		79	74	58			76	63				73	50				70	40			
82	78	71	50		79	73	56			76	62				73	49				70	34			
82	77	70	50		79	73	56			76	61				73	49				70	34			
82	77	70	50		78	73	55			76	61				72	48				69	31			
82	77	70	49		78	72	55			75	60				72	47				68	30			
82	77	70	48		78	72	53			75	60				72	46				68	28			
82	77	69	48		78	71	51			75	59				72	46				68	28			
82	77	69	48		78	70	50			74	59				71	46				67	23			
82	76	69	43		78	70	50			74	58				70	41				67	20			
81	76	69	42		78	70	49			74	58				70	38				66	16			
81	76	69	42		78	69	49			74	58				70	26				66				
81	76	69	40		78	69	49			73	58				69					65				
81	76	68	40		78	68	48			73	57				69					65				
81	76	68	40		78	68	48			73	56				68					65				
81	76	68	39		78	68	48			72	56				68					64				
81	76	68	37		78	68	47			72	55				68					64				
81	76	67	36		77	67	47			72	52				67					64				
80	76	67			77	67	44			72	51				67					64				
80	75	67			77	66	43			72	51				63					64				
80	75	67			77	66	43			72	50				63					63				
80	75	67			77	66	42			71	47				63					62				
80	75	66			76	65	42			71	45				62					61				
80	75	66			76	65	41			71	45				62					61				
79	74	64			76	65	38			70	44				61					60				
79	74	64			76	65	37			69	35				61					59				
79	74	63			76	65	33			68	30				60					59				
79	74	61			76	64	30			67					60					58				
79	73	60			75	63				67					59					57				
79	73	60			75	62				67					59					56				
78	73	60			75	62				67					58					55				
78	73	59			75	62				66					55					55				
78	73	58			75	61				65					55					54				
78	73	58			75	61				65					54					53				
78	72	58			75	61				64					53					51				
78	72	54			75	60				64					53					50				
78	72	53			74	60				64					53					48				
78	72	53			74	60				64					52					47				
78	72	53			74	58				64					52					45				
78	71	52			74	58				63					51					44				
78	71	51			74	58				63					50					40				

Table A.3d Residential ST Inspected PCI Values (Ages 16 to 20 Years)

Age 16 Years					Age 17 Years					Age 18 Years					Age 19 Years					Age 20 Years				
66	19				62					56					53					50				
66	11				62					54					52					50				
66	10				62					53					51					44				
64					62					51					47					43				
64					61					51					47					43				
63					61					50					46					42				
63					59					50					44					40				
63					58					50					44					38				
63					58					49					43					33				
62					58					48					43									
61					57					48					42									
61					57					42					41									
61					56					42					41									
61					56					41					41									
60					55					41					40									
59					54					37					40									
58					53					37					36									
58					52										32									
58					50										32									
58					46										30									
57					46										24									
55					46										22									
54					44										18									
54					44										16									
52					42																			
52					40																			
52					39																			
50					39																			
48					32																			
47					30																			
47					29																			
45					29																			
45					21																			
42					12																			
41																								
41																								
37																								
35																								
34																								
29																								

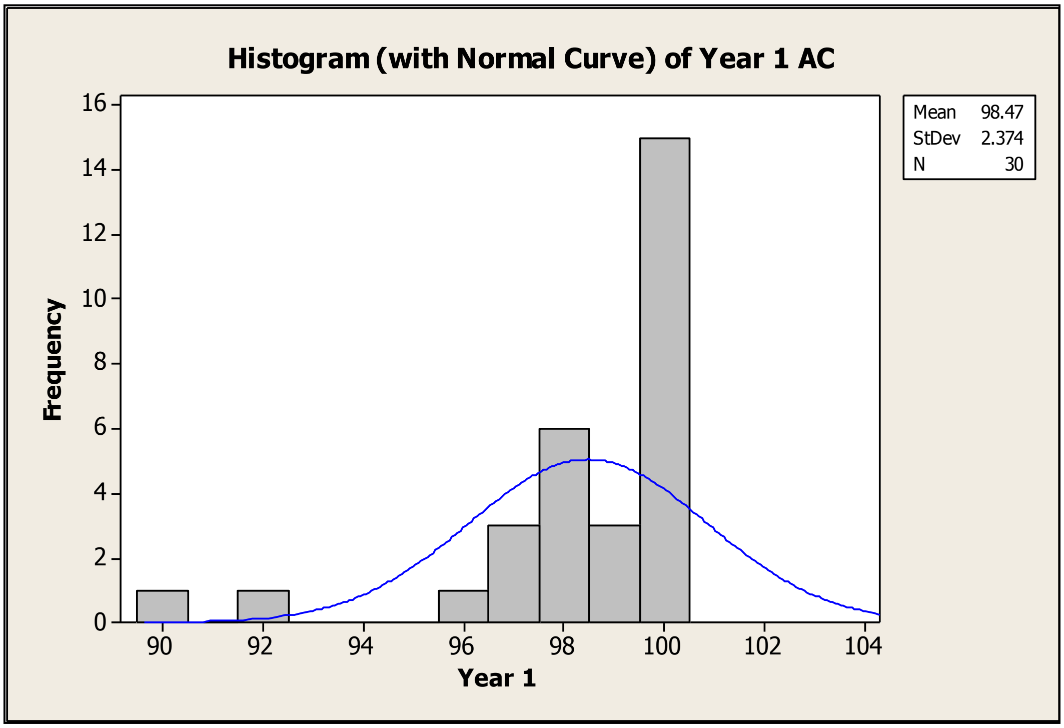

Figure A.1 Year 1 AC PCI Distribution Fitting

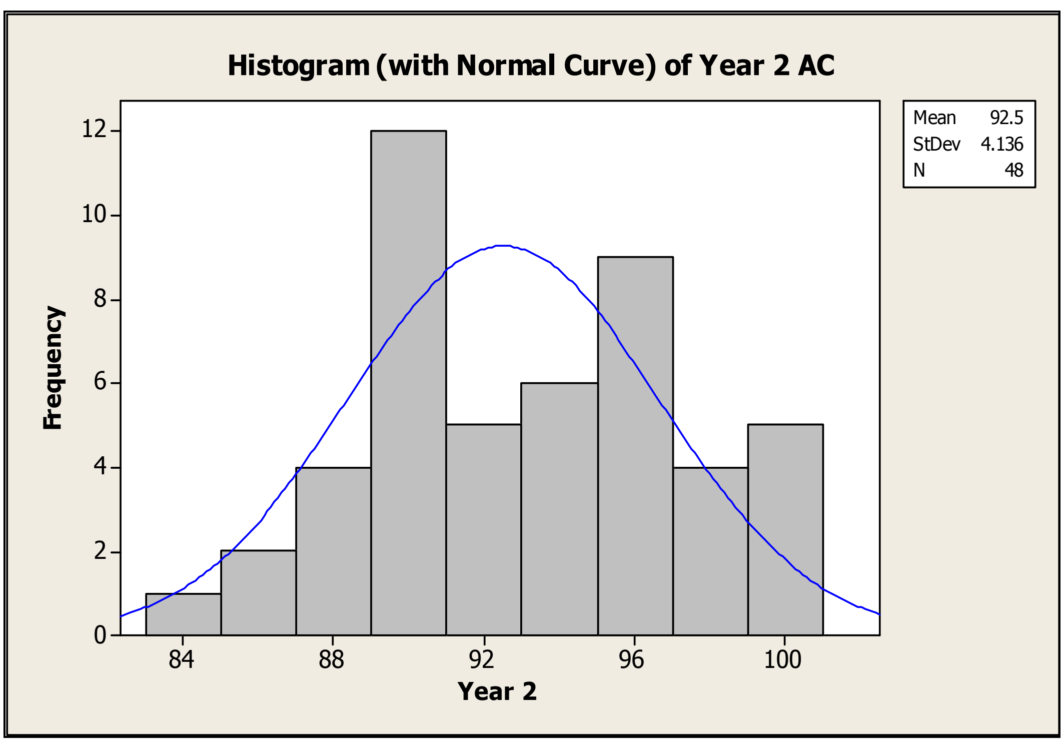

Figure A.2 Year 2 AC PCI Distribution Fitting

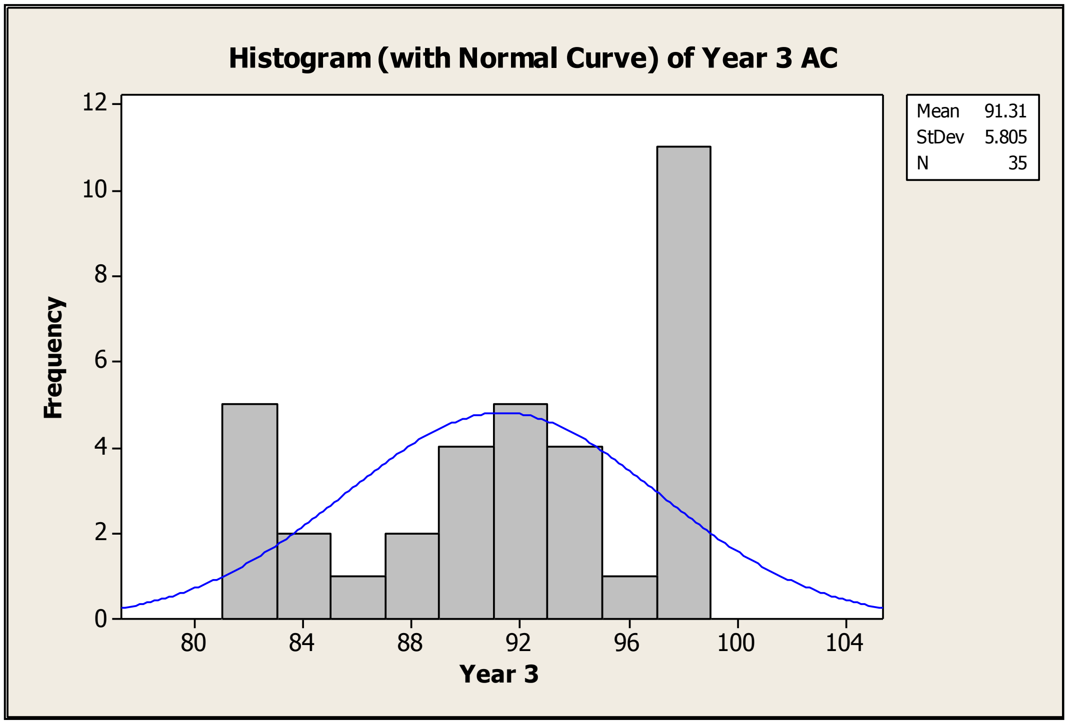

Figure A.3 Year 3 AC PCI Distribution Fitting

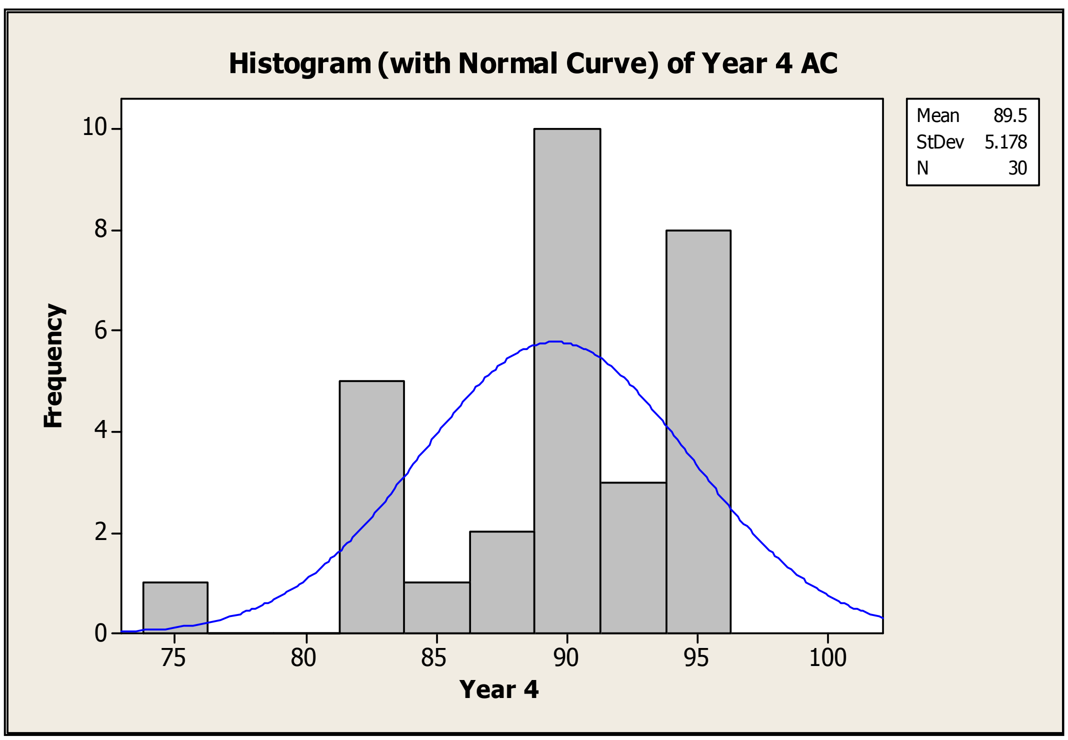

Figure A.4 Year 4 AC PCI Distribution Fitting

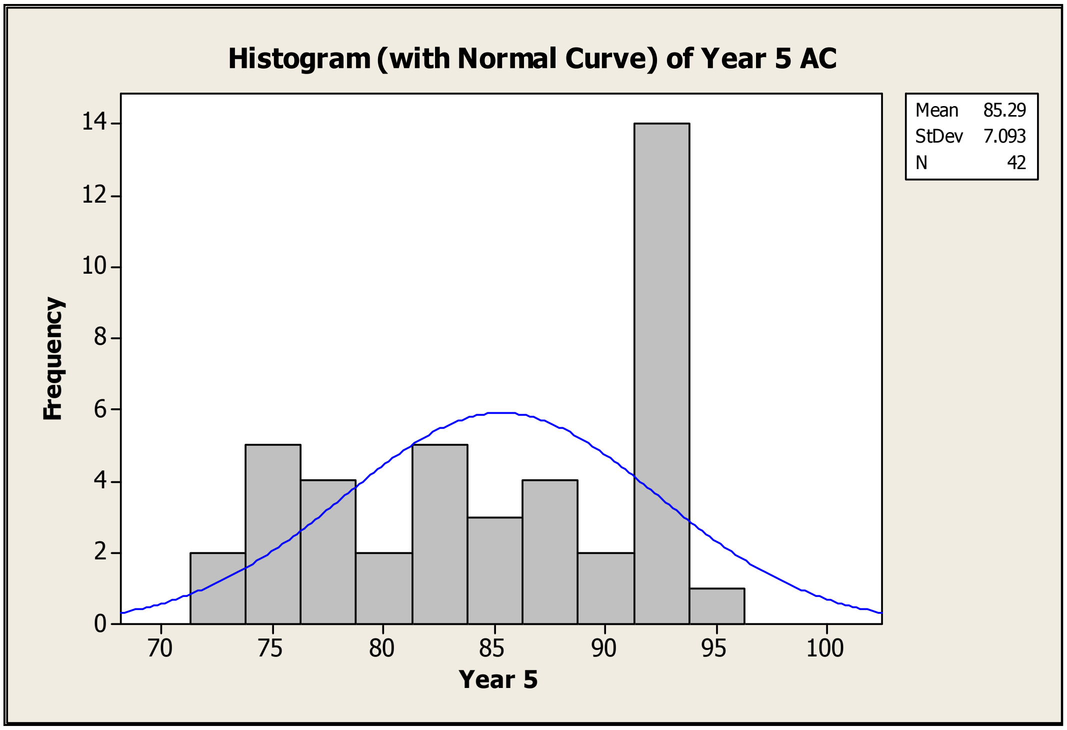

Figure A.5 Year 5 AC PCI Distribution Fitting

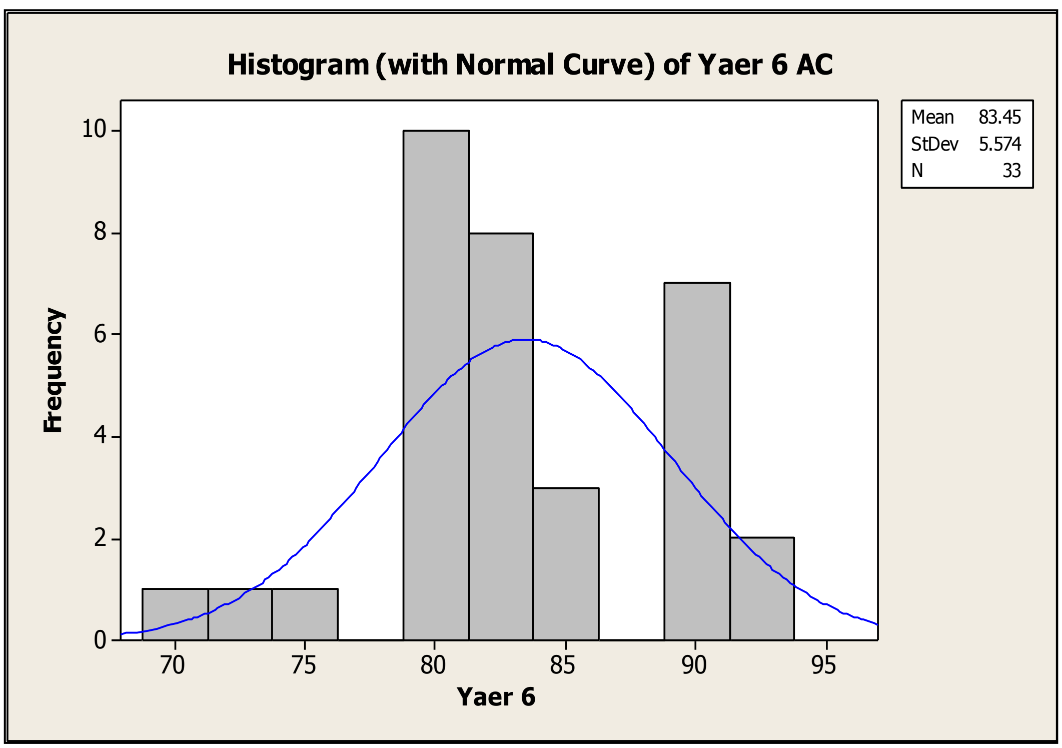

Figure A.6 Year 6 AC PCI Distribution Fitting

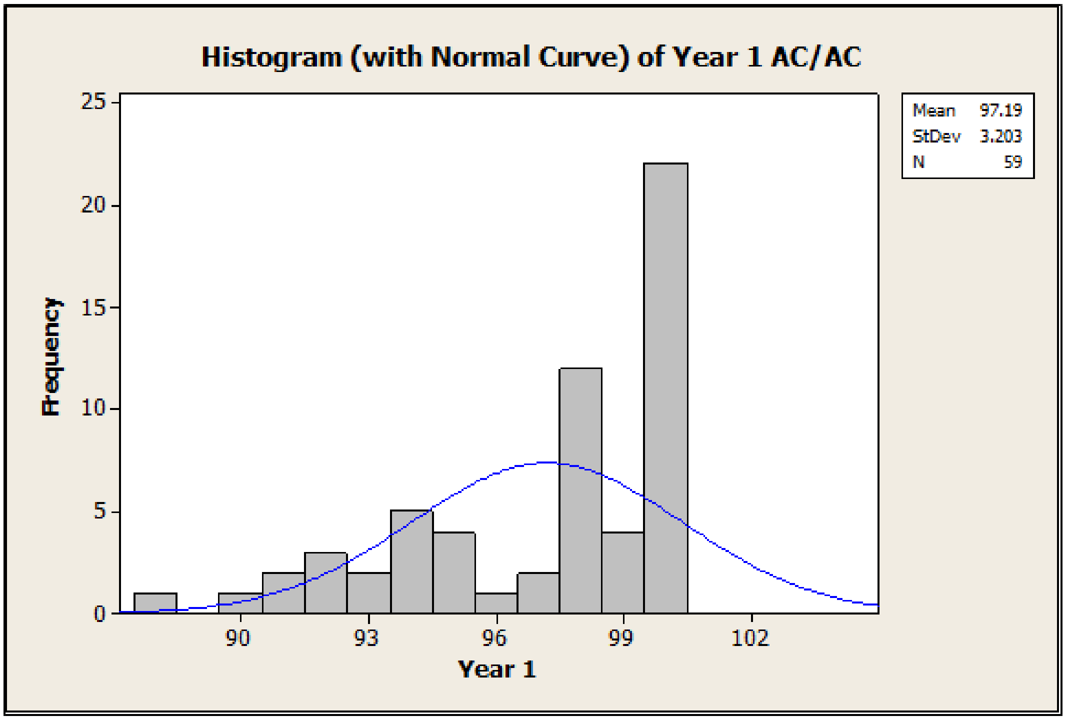

Figure A.7. Year 1 AC/AC PCI Distribution Fitting

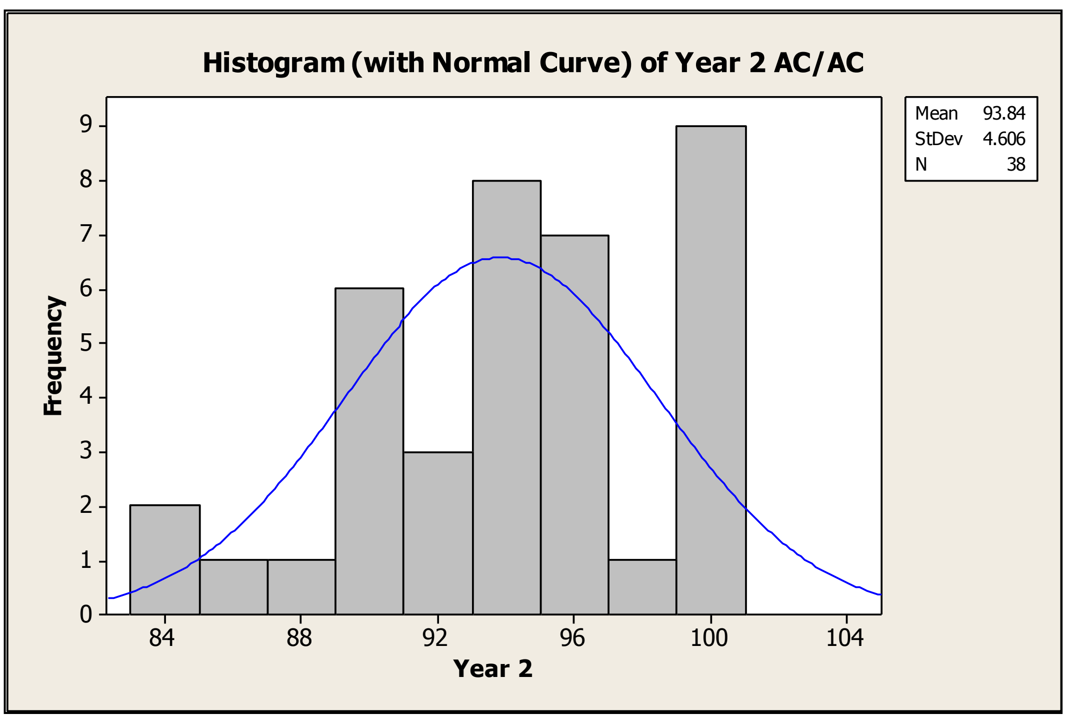

Figure A.8. Year 2 AC/AC PCI Distribution Fitting

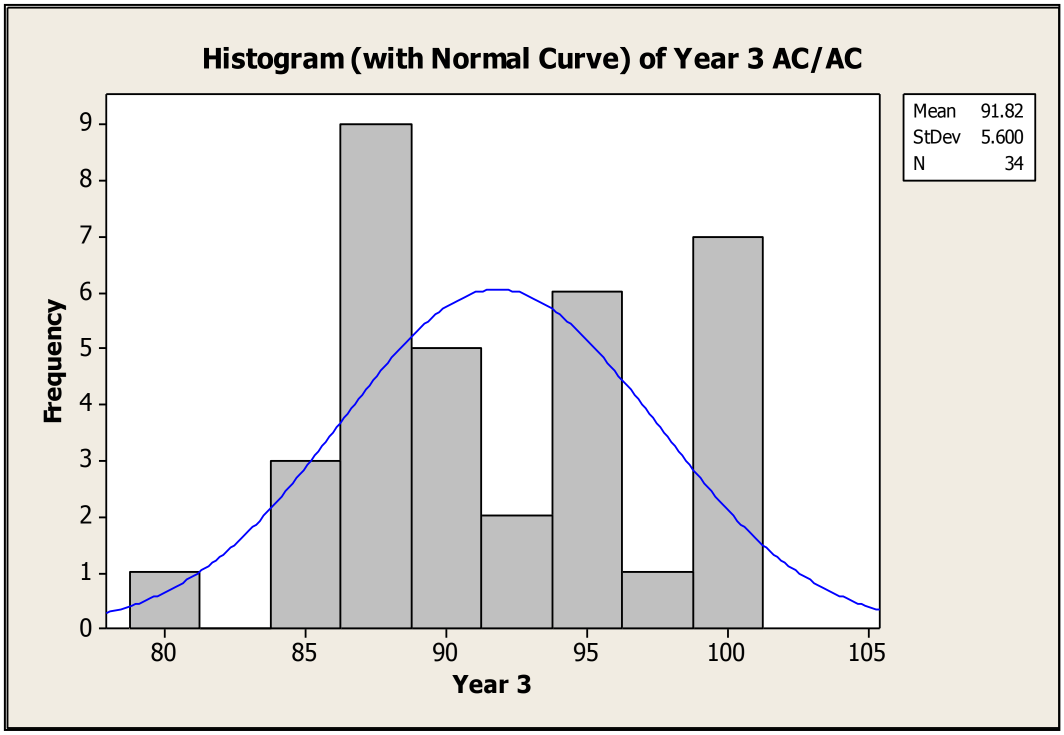

Figure A.9. Year 3 AC/AC PCI Distribution Fitting

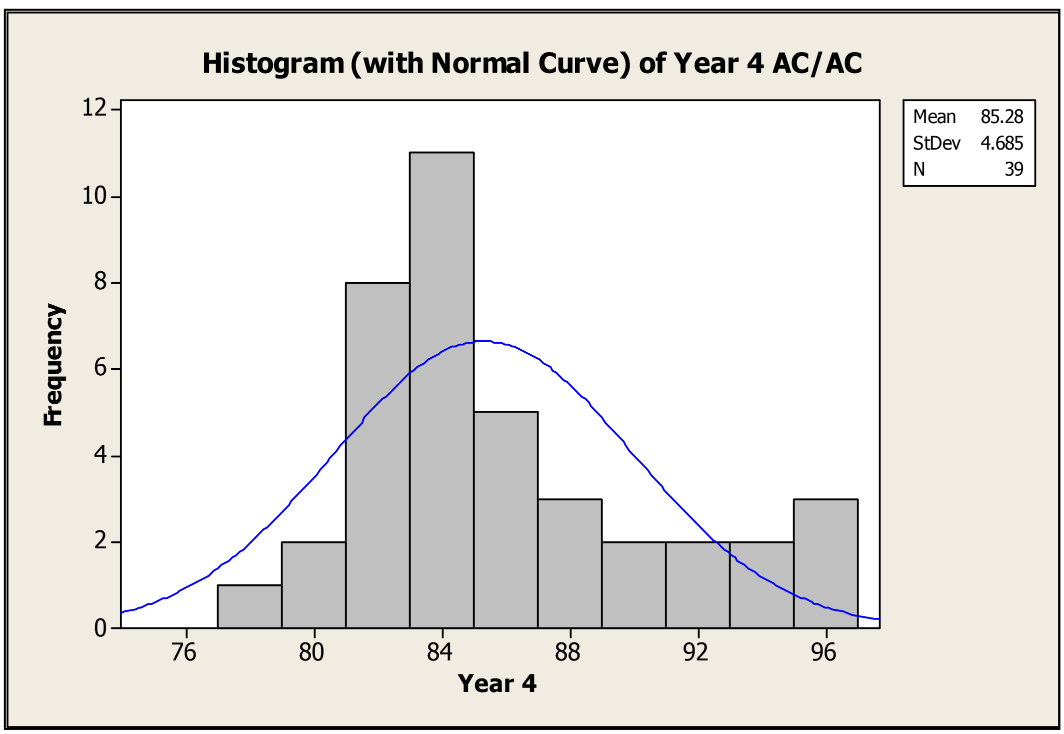

Figure A.10. Year 4 AC/AC PCI Distribution Fitting

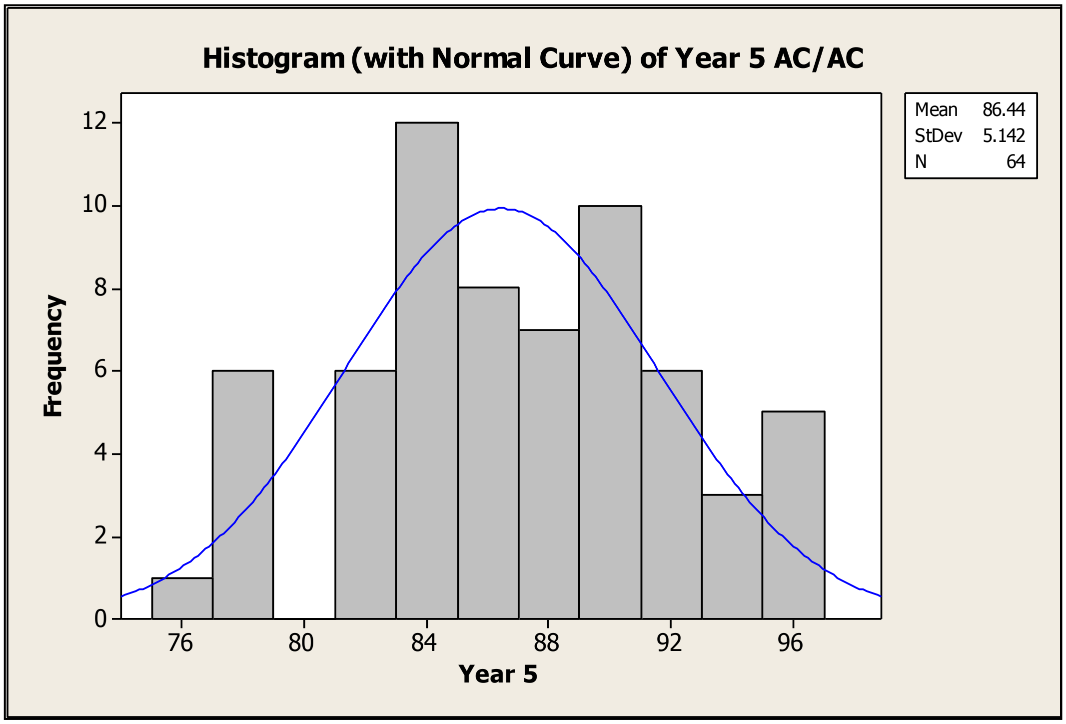

Figure A.11. Year 5 AC/AC PCI Distribution Fitting

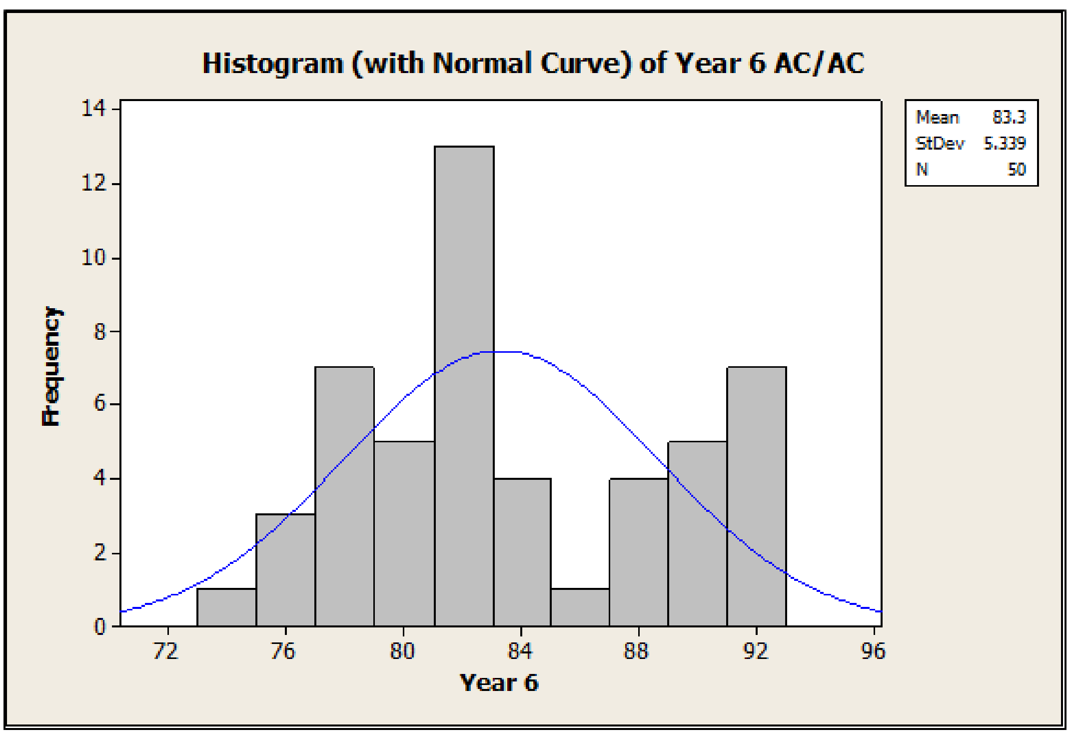

Figure A.12. Year 6 AC/AC PCI Distribution Fitting

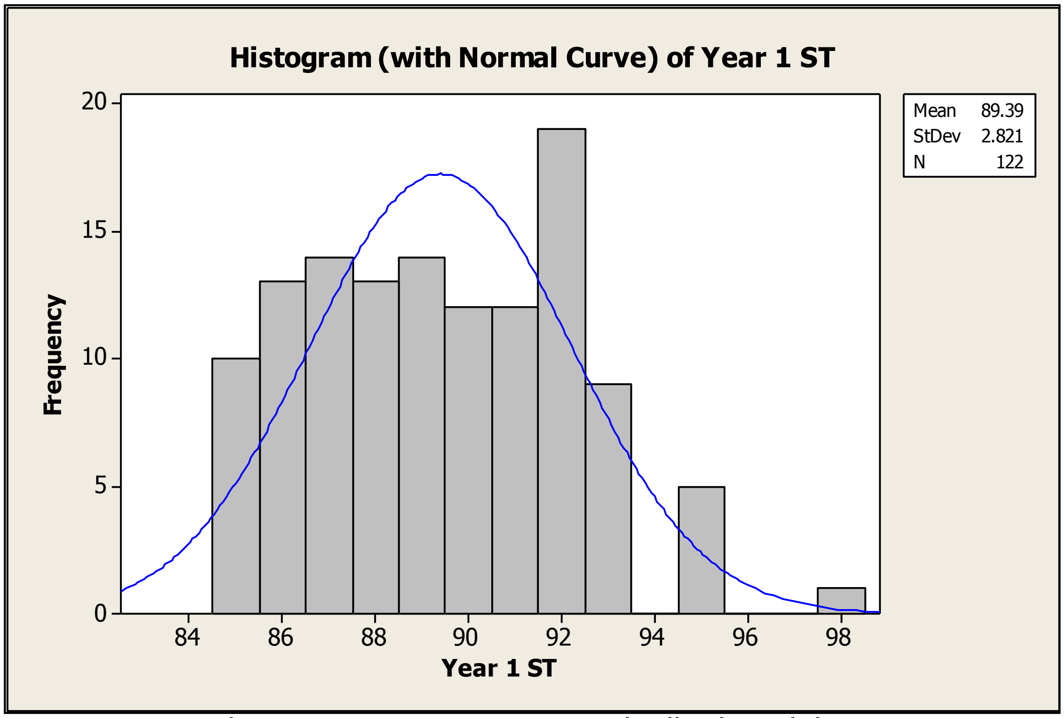

Figure A.13. Year 1 ST PCI Distribution Fitting

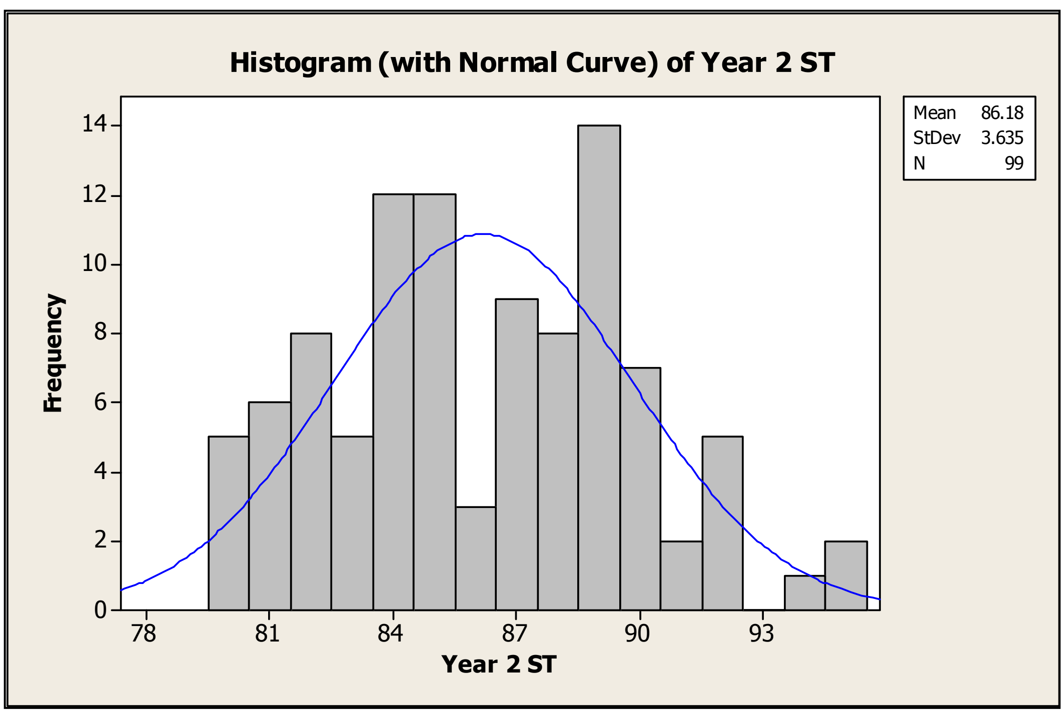

Figure A.14. Year 2 ST PCI Distribution Fitting

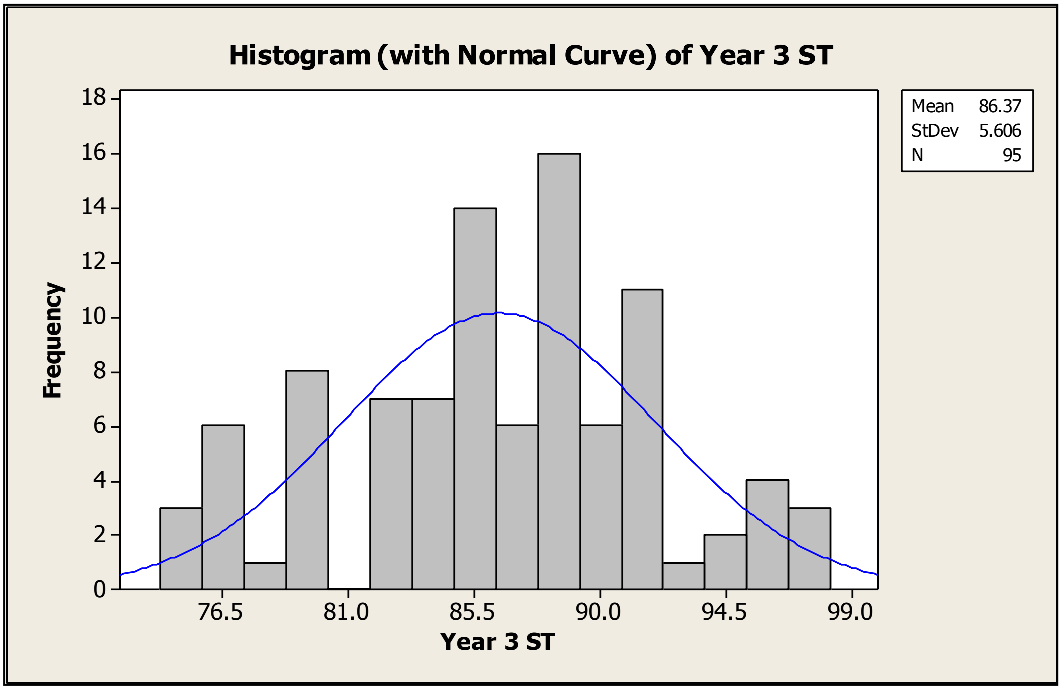

Figure A.15. Year 3 ST PCI Distribution Fitting

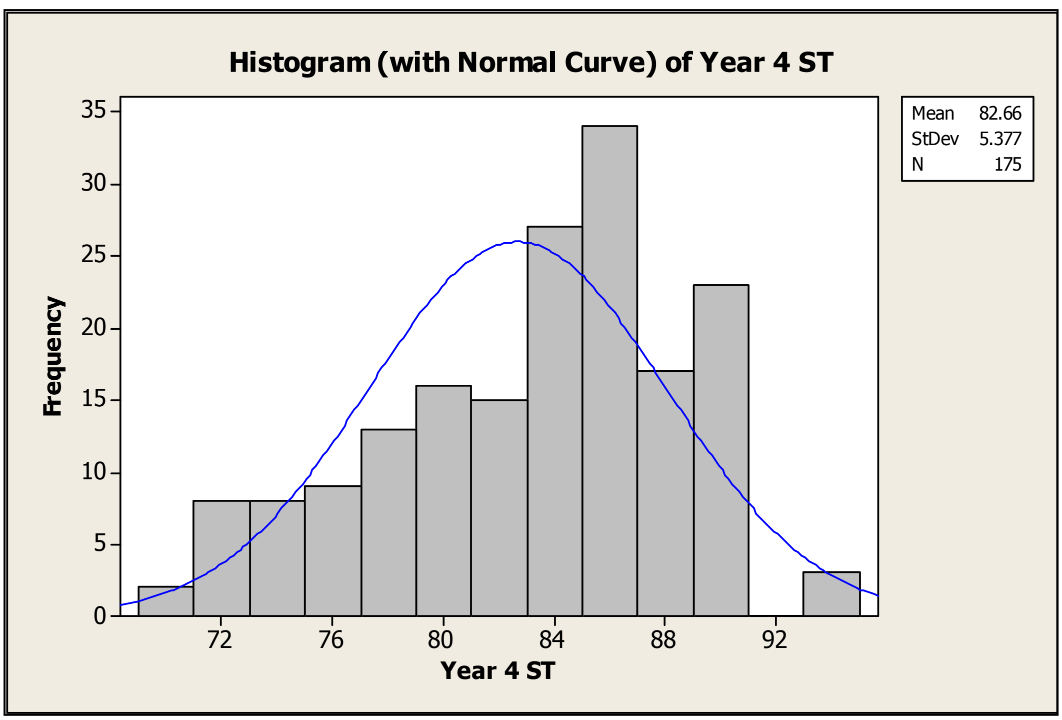

Figure A.16. Year 4 ST PCI Distribution Fitting

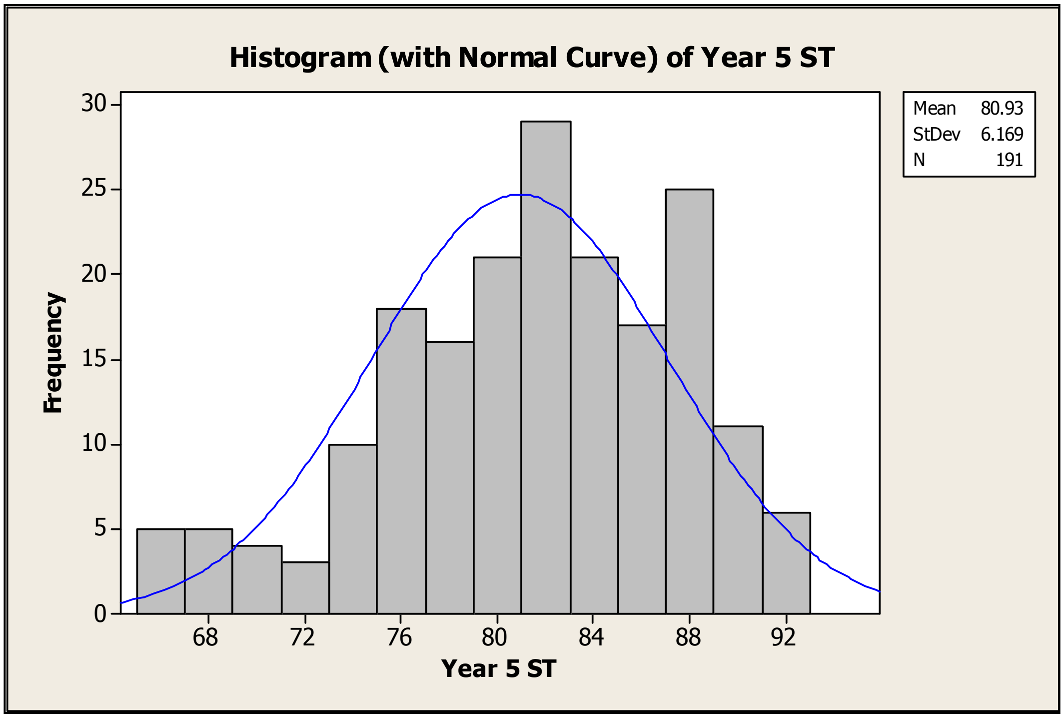

Figure A.17. Year 5 ST PCI Distribution Fitting

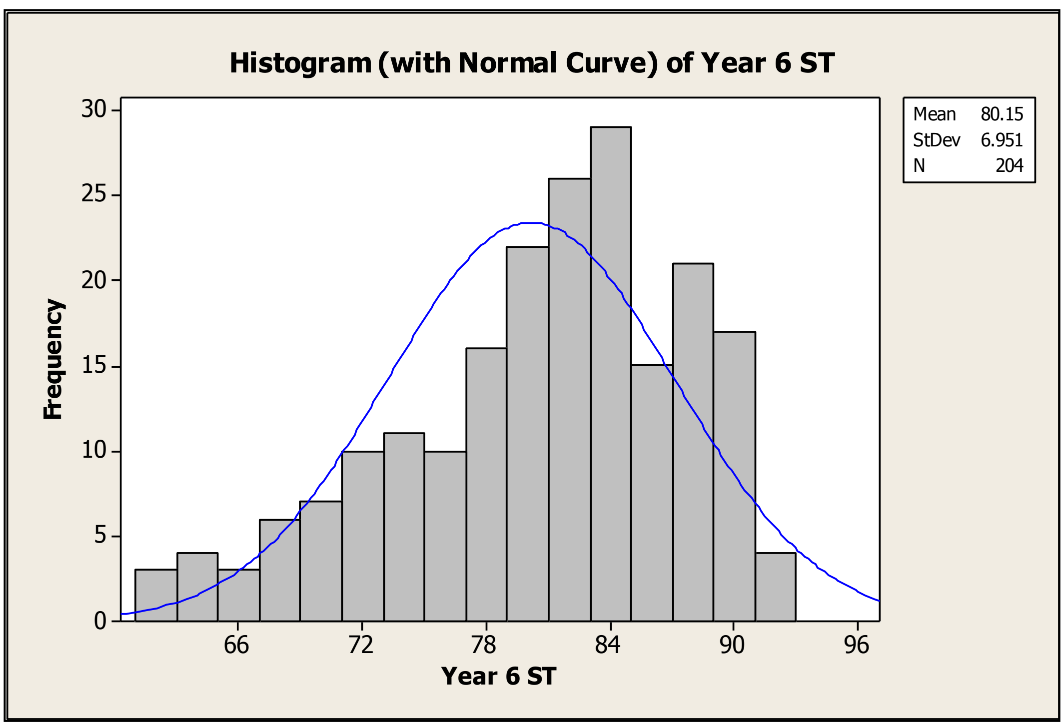

Figure A.18. Year 6 ST PCI Distribution Fitting

Table A.4 Arterial AC PCI Goodness of Fit for Normal Distributions

Year	Kolmogorov-Smirnov			Anderson-Darling		Chi-Squared		
	Statistic	Cr. Value	P-Value	Statistic	Cr. Value	Statistic	Cr. Value	P-Value
1	0.2592	0.2899	0.0289	3.2092	3.9074	1.5933	9.2103	0.4508
2	0.1231	0.2306	0.4272	0.6795	3.9074	4.3459	15.0860	0.5008
3	0.1506	0.2690	0.3681	1.0803	3.9074	1.1355	11.3450	0.7685
4	0.1615	0.2899	0.3738	0.8313	3.9074	0.0956	9.2103	0.9533
5	0.1852	0.2461	0.0982	1.7314	3.9074	2.9821	11.3450	0.3944
6	0.1689	0.2768	0.2716	0.9370	3.9074	17.5720	9.2103	<0.001
7	0.1547	0.3295	0.5872	0.5795	3.9074	1.1230	9.2103	0.5704
8	0.1377	0.3524	0.7941	0.3751	3.9074	5.6577	9.2103	0.0591
9	0.1177	0.2406	0.5372	0.8164	3.9074	2.8749	13.2770	0.5790
10	0.1529	0.2461	0.2531	0.9154	3.9074	2.5469	13.2770	0.6363
11	0.1129	0.2051	0.3899	0.5454	3.9074	3.6164	15.0860	0.6059
12	0.2055	0.2177	0.0178	2.9752	3.9074	11.7540	13.2770	0.0193
13	0.2342	0.2768	0.0448	2.6482	3.9074	6.3400	9.2103	0.0420
14	0.0988	0.2490	0.7824	0.4192	3.9074	0.4856	15.0860	0.9926
15	0.1346	0.2157	0.2485	1.7503	3.9074	7.1272	13.2770	0.1293
16	0.1755	0.1930	0.0249	3.1112	3.9074	6.8808	15.0860	0.2297
17	0.1194	0.2330	0.4782	1.0117	3.9074	2.6456	13.2770	0.6188
18	0.1327	0.2084	0.2291	1.0545	3.9074	6.5243	15.0860	0.2585
19	0.1696	0.2380	0.1336	1.2957	3.9074	7.7979	13.2770	0.0993
20	0.1010	0.2433	0.7227	0.7491	3.9074	2.7664	11.3450	0.4291

Table A.5 Arterial AC/AC PCI Goodness of Fit for Normal Distributions

Year	Kolmogorov-Smirnov			Anderson-Darling		Chi-Squared		
	Statistic	Cr. Value	P-Value	Statistic	Cr. Value	Statistic	Cr. Value	P-Value
1	0.2443	0.2084	0.0014	3.7717	3.9074	5.9774	11.3450	0.1127
2	0.1462	0.2584	0.3560	0.9602	3.9074	2.8310	9.2103	0.2428
3	0.1635	0.2728	0.2905	1.1601	3.9074	4.3339	9.2103	0.1145
4	0.2254	0.2552	0.0319	1.8722	3.9074	14.0060	13.2770	0.0073
5	0.0729	0.2003	0.8612	0.4637	3.9074	7.4355	15.0860	0.1902
6	0.1762	0.2260	0.0791	1.1999	3.9074	11.8130	13.2770	0.0188
7	0.1589	0.2728	0.3220	1.0036	3.9074	13.4690	11.3450	0.0037
8	0.1529	0.2433	0.2416	0.8218	3.9074	1.0900	13.2770	0.8959
9	0.0794	0.2239	0.8793	0.3045	3.9074	1.7088	13.2770	0.7891
10	0.1301	0.2260	0.3363	0.4838	3.9074	15.0860	11.0700	0.7411
11	0.1312	0.2239	0.3160	0.7896	3.9074	4.1369	15.0860	0.5299
12	0.1312	0.2330	0.3616	0.7155	3.9074	1.9477	15.0860	0.8563
13	0.0944	0.2157	0.6756	0.6960	3.9074	5.0970	13.2770	0.2775
14	0.1980	0.2490	0.0697	1.7765	3.9074	13.2780	11.3450	0.0041
15	0.0869	0.2197	0.7863	0.4378	3.9074	1.1387	13.2770	0.8881
16	0.1595	0.2768	0.3343	1.0147	3.9074	4.4176	11.3450	0.2198
17	0.1344	0.2461	0.3989	0.9635	3.9074	8.6828	13.2770	0.0695
18	0.1468	0.2552	0.3368	0.9676	3.9074	1.6128	11.3450	0.6565
19	0.1115	0.2690	0.7358	0.6030	3.9074	4.5549	13.2770	0.3361
20	0.1408	0.2653	0.4341	0.4777	3.9074	5.3134	13.2770	0.2566

Table A.6 Residential ST PCI Goodness of Fit for Normal Distributions

Year	Kolmogorov-Smirnov			Anderson-Darling		Chi-Squared		
	Statistic	Cr. Value	P-Value	Statistic	Cr. Value	Statistic	Cr. Value	P-Value
1	0.10516	0.12295	0.12527	0.12295	2.5018	10.159	12.592	0.11812
2	0.11231	0.13469	0.15239	0.94567	2.5018	8.4459	11.07	0.13331
3	0.09114	0.13746	0.38581	0.69537	2.5018	8.0473	12.592	0.23466
4	0.13574	0.10266	0.00284	2.6382	2.5018	18.164	14.067	0.01125
5	0.07691	0.09826	0.19805	1.3756	2.5018	7.0581	14.067	0.42285
6	0.11383	0.09508	0.00929	2.7462	2.5018	36.534	14.067	<0.001
7	0.12733	0.09775	0.00346	4.1768	2.5018	26.717	14.067	<0.001
8	0.17137	0.09801	<0.001	6.0759	2.5018	30.43	14.067	<0.001
9	0.12401	0.09725	0.00451	4.7203	2.5018	20.08	14.067	0.0054
10	0.18724	0.11125	<0.001	6.624	2.5018	27.21	14.067	<0.001
11	0.16137	0.11602	0.00139	7.1158	2.5018	29.473	12.592	<0.001
12	0.149	0.13128	0.01543	3.8063	2.5018	19.284	12.592	0.00371
13	0.11381	0.16443	0.33412	1.406	2.5018	3.2619	9.4877	0.515
14	0.12542	0.18659	0.36795	0.80699	2.5018	6.6739	9.4877	0.15416
15	1.15816	0.18841	0.14695	2.3051	2.5018	6.3777	9.4877	0.17266
16	0.15666	0.20283	0.21777	1.8911	2.5018	1.9499	7.8147	0.58286
17	0.15005	0.22743	0.38949	1.1607	2.5018	3.8949	7.8147	0.27304
18	0.21066	0.31796	0.38357	0.6488	2.5018	1.6876	3.8415	0.19392
19	0.22276	0.26931	0.15827	0.81286	2.5018	1.0891	5.9915	0.58012
20	0.17209	0.43001	0.91347	0.2968	2.5018			

Appendix B. StreetSaver® Reports from Needs Analyses and PCI Target Driven Analyses

Needs analysis StreetSaver® reports for a 20 year period from the City of Milpitas, California arterial streets paved with AC, used in Chapter 4 for case study 1.a conducted using 90%, 70%, 50%, and 30% PBPPCs are shown in Tables B.1, B.2, B.3, and B.4. Needs analysis StreetSaver® reports for a 20 years period from the City of Milpitas, California arterial streets paved with AC/AC, used in Chapter 4 for case study 1.b conducted using 90%, 70%, 50%, and 30% PBPPCs are shown in Tables B.5, B.6, B.7, and B.8. Tables B.9, B.10, B.11, and B.12 show needs analysis StreetSaver® reports from Marion County, Oregon residential streets paved with ST, used in Chapter 4 for case study 1.c, conducted using 90%, 70%, 50%, and 30% PBPPCs.

Table B.1 Arterial AC Projected PCI and Budget Needs for 90% PBPPC
(Case Study 1.a)

MILPITAS

Needs - Projected PCI/Cost Summary

Inflation Rate = 0.00 % Printed: 10/29/2013

Year	PCI Treated	PCI Untreated	PM Cost	Rehab Cost	Cost
2013	73	57	$110,839	$3,497,325	$3,608,164
2014	76	54	$10,502	$2,004,500	$2,015,002
2015	77	52	$5,121	$1,330,895	$1,336,016
2016	80	49	$609,265	$929,827	$1,539,092
2017	82	46	$354,478	$1,364,707	$1,719,185
2018	86	44	$806,358	$687,441	$1,493,799
2019	84	41	$225,242	$0	$225,242
2020	85	38	$837,116	$0	$837,116
2021	83	35	$202,947	$0	$202,947
2022	83	32	$718,437	$0	$718,437
2023	84	29	$386,772	$0	$386,772
2024	83	27	$390,929	$0	$390,929
2025	82	24	$300,107	$0	$300,107
2026	83	21	$875,412	$0	$875,412
2027	82	18	$171,438	$150,626	$322,064
2028	80	16	$162,292	$28,197	$190,489
2029	78	13	$88,235	$0	$88,235
2030	78	11	$575,114	$0	$575,114
2031	84	9	$4,102,483	$0	$4,102,483
2032	84	7	$1,662,997	$0	$1,662,997

% PM	PM Total Cost	Rehab Total Cost	Total Cost
55.76%	$12,596,084	$9,993,518	$22,589,602

Criteria: Functional Class = A - Arterial AND Surface Type = A - AC

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Table B.2 Arterial AC Projected PCI and Budget Needs for 70% PBPPC (Case Study 1.a)

MILPITAS

Needs - Projected PCI/Cost Summary

Inflation Rate = 3.00 % Printed: 09/15/2013

Year	PCI Treated	PCI Untreated	PM Cost	Rehab Cost	Cost
2011	81	69	$505,717	$1,810,732	$2,316,449
2012	80	67	$499	$255,252	$255,751
2013	81	65	$147,713	$595,446	$743,159
2014	79	63	$172,645	$8,012	$180,657
2015	82	61	$178,993	$1,015,398	$1,194,391
2016	86	59	$1,014,150	$922,441	$1,936,591
2017	85	57	$292,939	$0	$292,939
2018	85	54	$481,817	$0	$481,817
2019	85	52	$1,076,256	$0	$1,076,256
2020	84	50	$830,882	$0	$830,882
2021	85	48	$745,090	$0	$745,090
2022	84	45	$609,944	$72,086	$682,030
2023	84	43	$1,150,632	$0	$1,150,632
2024	83	40	$417,175	$0	$417,175
2025	84	38	$1,631,649	$0	$1,631,649
2026	84	35	$1,023,180	$0	$1,023,180
2027	84	33	$1,707,600	$0	$1,707,600
2028	82	30	$122,482	$0	$122,482
2029	82	28	$680,457	$0	$680,457
2030	82	25	$1,185,966	$0	$1,185,966

% PM	PM Total Cost	Rehab Total Cost	Total Cost
74.92%	$13,975,786	$4,679,367	$18,655,153

Table B.3 Arterial AC Projected PCI and Budget Needs for 50% PBPPC (Case Study 1.a)

MILPITAS

Needs - Projected PCI/Cost Summary

Inflation Rate = 3.00 % Printed: 09/15/2013

Year	PCI Treated	PCI Untreated	PM Cost	Rehab Cost	Cost
2011	84	73	$795,172	$1,211,651	$2,006,823
2012	83	72	$411	$276,264	$276,675
2013	85	70	$79,657	$614,717	$694,374
2014	85	68	$175,830	$338,514	$514,344
2015	84	66	$204,243	$0	$204,243
2016	87	64	$946,362	$175,597	$1,121,959
2017	86	63	$357,999	$0	$357,999
2018	86	61	$311,623	$0	$311,623
2019	86	59	$888,536	$0	$888,536
2020	85	57	$375,002	$0	$375,002
2021	85	54	$346,757	$0	$346,757
2022	85	52	$1,303,262	$0	$1,303,262
2023	84	50	$409,396	$0	$409,396
2024	84	48	$614,397	$0	$614,397
2025	84	45	$1,053,224	$0	$1,053,224
2026	84	43	$1,559,261	$0	$1,559,261
2027	84	40	$864,533	$0	$864,533
2028	84	38	$1,485,549	$0	$1,485,549
2029	84	35	$1,128,840	$0	$1,128,840
2030	84	33	$1,215,209	$0	$1,215,209

% PM	PM Total Cost	Rehab Total Cost	Total Cost
84.36%	$14,115,263	$2,616,743	$16,732,006

Table B.4 Arterial AC Projected PCI and Budget Needs for 30% PBPPC (Case Study 1.a)

MILPITAS

Needs - Projected PCI/Cost Summary

Inflation Rate = 3.00 % Printed: 10/01/2013

Year	PCI Treated	PCI Untreated	PM Cost	Rehab Cost	Cost
2011	87	78	$1,115,791	$607,491	$1,723,282
2012	86	77	$308	$160,096	$160,404
2013	88	76	$78,266	$350,136	$428,402
2014	87	74	$19,233	$244,766	$263,999
2015	86	73	$46,273	$0	$46,273
2016	89	71	$986,639	$0	$986,639
2017	87	70	$38,238	$0	$38,238
2018	87	68	$320,800	$0	$320,800
2019	86	66	$186,665	$0	$186,665
2020	85	65	$395,125	$0	$395,125
2021	86	63	$811,864	$0	$811,864
2022	85	61	$182,332	$0	$182,332
2023	85	59	$610,900	$0	$610,900
2024	85	57	$1,036,273	$0	$1,036,273
2025	84	55	$450,924	$0	$450,924
2026	85	53	$1,679,485	$0	$1,679,485
2027	84	51	$448,281	$0	$448,281
2028	83	49	$606,106	$0	$606,106
2029	84	47	$1,463,030	$0	$1,463,030
2030	84	44	$1,702,497	$0	$1,702,497

% PM	PM Total Cost	Rehab Total Cost	Total Cost
89.94%	**$12,179,030**	**$1,362,489**	**$13,541,519**

Table B.5 Arterial AC/AC Projected PCI and Budget Needs for 90% PBPPC (Case Study 1.b)

MILPITAS

Needs - Projected PCI/Cost Summary

Inflation Rate = 0.00 % Printed: 10/29/2013

Year	PCI Treated	PCI Untreated	PM Cost	Rehab Cost	Cost
2013	80	68	$289,447	$2,243,220	$2,532,667
2014	78	65	$116,872	$195,308	$312,180
2015	79	63	$26,972	$623,730	$650,702
2016	78	61	$1,345	$353,403	$354,748
2017	79	59	$55,471	$530,260	$585,731
2018	85	57	$432,166	$836,815	$1,268,981
2019	84	54	$481,928	$0	$481,928
2020	84	52	$432,929	$0	$432,929
2021	81	50	$22,327	$0	$22,327
2022	81	48	$407,697	$0	$407,697
2023	80	46	$290,508	$0	$290,508
2024	79	44	$129,920	$0	$129,920
2025	79	42	$619,541	$0	$619,541
2026	81	40	$1,588,027	$0	$1,588,027
2027	84	38	$2,017,279	$0	$2,017,279
2028	84	36	$276,119	$421,026	$697,145
2029	82	34	$201,373	$0	$201,373
2030	81	32	$300,003	$0	$300,003
2031	85	30	$1,583,212	$0	$1,583,212
2032	85	28	$961,624	$0	$961,624

% PM	PM Total Cost	Rehab Total Cost	Total Cost
66.29%	$10,234,760	$5,203,762	$15,438,522

Table B.6 Arterial AC/AC Projected PCI and Budget Needs for 70% PBPPC (Case Study 1.b)

MILPITAS

Needs - Projected PCI/Cost Summary

Inflation Rate = 3.00 % Printed: 09/15/2013

Year	PCI Treated	PCI Untreated	PM Cost	Rehab Cost	Cost
2011	82	77	$318,680	$436,203	$754,883
2012	82	75	$47,852	$437,140	$484,992
2013	85	73	$51,670	$1,056,632	$1,108,302
2014	84	71	$149,558	$15,025	$164,583
2015	83	69	$29,548	$0	$29,548
2016	84	67	$416,797	$0	$416,797
2017	87	65	$229,602	$1,176,848	$1,406,450
2018	86	63	$161,353	$0	$161,353
2019	85	61	$109,547	$0	$109,547
2020	84	59	$29,627	$0	$29,627
2021	83	57	$320,597	$0	$320,597
2022	82	55	$198,389	$0	$198,389
2023	81	53	$330,698	$0	$330,698
2024	82	51	$1,412,265	$0	$1,412,265
2025	81	49	$642,441	$0	$642,441
2026	81	47	$1,239,279	$0	$1,239,279
2027	84	45	$2,749,956	$0	$2,749,956
2028	83	43	$599,455	$0	$599,455
2029	83	41	$1,107,081	$0	$1,107,081
2030	85	39	$2,424,526	$0	$2,424,526

% PM	PM Total Cost	Rehab Total Cost	Total Cost
80.10%	$12,568,921	$3,121,848	$15,690,769

Table B.7 Arterial AC/AC Projected PCI and Budget Needs for 50% PBPPC (Case Study 1.b)

MILPITAS

Needs - Projected PCI/Cost Summary

Inflation Rate = 3.00 % Printed: 09/15/2013

Year	PCI Treated	PCI Untreated	PM Cost	Rehab Cost	Cost
2011	86	80	$417,539	$440,224	$857,763
2012	84	78	$47,461	$72,499	$119,960
2013	84	76	$51,624	$158,434	$210,058
2014	85	75	$153,152	$223,759	$376,911
2015	85	73	$28,901	$276,080	$304,981
2016	90	71	$506,282	$892,790	$1,399,072
2017	89	69	$64,574	$0	$64,574
2018	88	68	$76,614	$0	$76,614
2019	87	66	$135,006	$0	$135,006
2020	86	64	$61,444	$0	$61,444
2021	85	62	$220,439	$0	$220,439
2022	84	60	$10,356	$0	$10,356
2023	83	58	$21,119	$0	$21,119
2024	82	56	$324,802	$0	$324,802
2025	81	54	$108,750	$0	$108,750
2026	80	52	$672,900	$0	$672,900
2027	81	50	$1,198,918	$0	$1,198,918
2028	81	48	$1,137,368	$0	$1,137,368
2029	85	46	$3,728,574	$0	$3,728,574
2030	84	45	$890,705	$0	$890,705

% PM	PM Total Cost	Rehab Total Cost	Total Cost
82.69%	$9,856,528	$2,063,786	$11,920,314

Criteria: Functional Class = A - Arterial AND Surface Type = O - AC/AC

Table B.8 Arterial AC/AC Projected PCI and Budget Needs for 30% PBPPC (Case Study 1.b)

MILPITAS

Needs - Projected PCI/Cost Summary

Inflation Rate = 3.00 % Printed: 10/01/2013

Year	PCI Treated	PCI Untreated	PM Cost	Rehab Cost	Cost
2011	91	84	$424,641	$743,228	$1,167,869
2012	89	82	$50,238	$0	$50,238
2013	88	81	$50,416	$62,769	$113,185
2014	90	79	$152,970	$416,392	$569,362
2015	89	78	$26,559	$0	$26,559
2016	92	76	$543,410	$80,520	$623,930
2017	91	75	$58,255	$0	$58,255
2018	90	73	$62,880	$0	$62,880
2019	89	71	$157,061	$0	$157,061
2020	89	70	$363,967	$0	$363,967
2021	88	68	$214,296	$0	$214,296
2022	87	66	$21	$0	$21
2023	86	65	$8,926	$0	$8,926
2024	84	63	$56,523	$0	$56,523
2025	83	61	$133,715	$0	$133,715
2026	82	59	$160,287	$0	$160,287
2027	82	57	$321,388	$0	$321,388
2028	80	55	$77,133	$0	$77,133
2029	79	53	$83	$0	$83
2030	80	51	$1,327,472	$0	$1,327,472

% PM	PM Total Cost	Rehab Total Cost	Total Cost
76.28%	$4,190,241	$1,302,909	$5,493,150

Table B.9 Residential ST Projected PCI and Budget Needs for 90% PBPPC (Case Study 1.c)

Performance Curve - MARION CO. OREGON

Needs - Projected PCI/Cost Summary

Inflation Rate = 3.00 % Printed: 11/06/2013

Year	PCI Treated	PCI Untreated	PM Cost	Rehab Cost	Cost
2013	73	60	$10,935	$4,060,990	$4,071,925
2014	75	58	$808	$2,838,135	$2,838,943
2015	78	55	$0	$2,495,446	$2,495,446
2016	78	52	$17,172	$1,912,035	$1,929,207
2017	83	49	$4,767	$4,444,094	$4,448,861
2018	83	46	$5,496	$1,283,273	$1,288,769
2019	84	43	$17,086	$781,738	$798,824
2020	82	41	$996,092	$0	$996,092
2021	83	38	$434,099	$914,091	$1,348,190
2022	86	35	$343,625	$1,789,598	$2,133,223
2023	86	32	$258,309	$2,052,729	$2,311,038
2024	86	30	$585,501	$316,906	$902,407
2025	85	27	$256,844	$300,038	$556,882
2026	83	25	$142,839	$211,982	$354,821
2027	86	23	$1,228,456	$1,583,258	$2,811,714
2028	85	21	$792,413	$12,671	$805,084
2029	84	20	$792,197	$486,606	$1,278,803
2030	87	18	$995,193	$2,312,181	$3,307,374
2031	85	16	$730,281	$0	$730,281
2032	85	14	$307,467	$1,038,386	$1,345,853

% PM	PM Total Cost	Rehab Total Cost	Total Cost
21.55%	$7,919,580	$28,834,157	$36,753,737

Table B.10 Residential ST Projected PCI and Budget Needs for 70% PBPPC (Case Study 1.c)

Performance Curve - MARION CO. OREGON

Needs - Projected PCI/Cost Summary

Inflation Rate = 3.00 % Printed: 05/26/2013

Year	PCI Treated	PCI Untreated	PM Cost	Rehab Cost	Cost
2013	80	66	$16,362	$4,403,264	$4,419,626
2014	79	63	$760	$1,344,516	$1,345,276
2015	81	61	$0	$1,509,423	$1,509,423
2016	84	58	$24,757	$2,433,881	$2,458,638
2017	83	55	$2,471	$1,054,401	$1,056,872
2018	81	52	$2,148	$77,371	$79,519
2019	84	49	$25,353	$918,784	$944,137
2020	83	46	$1,099,323	$0	$1,099,323
2021	83	42	$363,814	$661,651	$1,025,465
2022	86	39	$387,332	$1,154,206	$1,541,538
2023	83	36	$418,073	$0	$418,073
2024	83	33	$133,310	$986,982	$1,120,292
2025	84	31	$31,248	$613,281	$644,529
2026	82	28	$97,916	$397,086	$495,002
2027	84	26	$1,355,310	$604,632	$1,959,942
2028	85	24	$635,847	$413,650	$1,049,497
2029	83	22	$599,725	$171,197	$770,922
2030	85	20	$522,365	$2,582,021	$3,104,386
2031	84	18	$486,124	$233,581	$719,705
2032	83	16	$53,063	$518,832	$571,895

% PM	PM Total Cost	Rehab Total Cost	Total Cost
23.75%	$6,255,301	$20,078,759	$26,334,060

Criteria: Functional Class = R - Residential/Local AND Surface Type = S - ST

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Table B.11 Residential ST Projected PCI and Budget Needs for 50% PBPPC (Case Study 1.c)

Performance Curve - MARION CO. OREGON

Needs - Projected PCI/Cost Summary

Inflation Rate = 3.00 % Printed: 10/21/2012

Year	PCI Treated	PCI Untreated	PM Cost	Rehab Cost	Cost
2013	81	70	$15,098	$3,370,466	$3,385,564
2014	82	67	$1,880	$1,992,215	$1,994,095
2015	84	65	$0	$1,884,278	$1,884,278
2016	85	62	$22,867	$1,199,246	$1,222,113
2017	84	59	$5,041	$407,558	$412,599
2018	83	56	$2,113	$29,732	$31,845
2019	83	52	$26,988	$202,528	$229,516
2020	82	49	$885,057	$0	$885,057
2021	82	45	$506,676	$311,140	$817,816
2022	85	41	$520,436	$988,318	$1,508,754
2023	83	38	$310,406	$0	$310,406
2024	83	34	$84,439	$856,468	$940,907
2025	83	32	$20,449	$618,703	$639,152
2026	83	29	$38,168	$411,569	$449,737
2027	85	27	$1,090,107	$1,555,098	$2,645,205
2028	86	25	$647,817	$728,031	$1,375,848
2029	85	22	$716,990	$101,552	$818,542
2030	85	20	$388,331	$229,271	$617,602
2031	84	17	$304,169	$330,217	$634,386
2032	83	14	$163,473	$126,986	$290,459

% PM	PM Total Cost	Rehab Total Cost	Total Cost
27.26%	$5,750,505	$15,343,376	$21,093,881

Table B.12 Residential ST Projected PCI and Budget Needs for 30% PBPPC (Case Study 1.c)

Performance Curve - MARION CO. OREGON

Needs - Projected PCI/Cost Summary

Inflation Rate = 3.00 % Printed: 10/09/2013

Year	PCI Treated	PCI Untreated	PM Cost	Rehab Cost	Cost
2013	83	73	$12,471	$3,440,863	$3,453,334
2014	83	71	$1,044	$1,274,807	$1,275,851
2015	88	68	$1,232	$2,646,934	$2,648,166
2016	87	64	$20,996	$625,107	$646,103
2017	86	61	$3,307	$0	$3,307
2018	84	56	$5,087	$57,989	$63,076
2019	84	52	$26,367	$51,056	$77,423
2020	84	47	$959,711	$0	$959,711
2021	83	43	$292,324	$149,100	$441,424
2022	84	39	$694,427	$335,939	$1,030,366
2023	82	36	$178,247	$0	$178,247
2024	83	34	$6,060	$555,823	$561,883
2025	84	31	$25,036	$958,209	$983,245
2026	82	28	$13,063	$0	$13,063
2027	83	25	$1,183,734	$833,370	$2,017,104
2028	85	22	$401,666	$1,085,682	$1,487,348
2029	85	18	$832,376	$478,249	$1,310,625
2030	87	15	$223,667	$1,845,929	$2,069,596
2031	86	12	$46,907	$483,696	$530,603
2032	85	9	$98,668	$658,298	$756,966

% PM	PM Total Cost	Rehab Total Cost	Total Cost
24.51%	$5,026,390	$15,481,051	$20,507,441

PCI target driven analysis StreetSaver® reports for a 20 years period from the City of Milpitas, California arterial streets paved with AC, used in Chapter 4 for case study 2.a conducted using a target PCI of 75 for 90%, 70%, 50%, and 30% PBPPCs are shown in Tables B.13, B.14, B.15, and B.16. PCI target driven analysis StretSaver® reports for a 20 years period from the City of Milpitas, California arterial streets paved with AC/AC, used in Chapter 4 for case study 2.b, conducted using a target PCI of 75 for 90%, 70%, 50%, and 30% probability levels of pavement performance are shown in Tables B.16, B.17, B.18, and B.19. Tables B.20, B.21, B.22, and B.23 show PCI target driven analysis StreetSaver® reports from Marion County, Oregon residential streets paved with ST, used in Chapter 4 for case study 2.c, conducted using a target PCI of 75 for 90%, 70%, 50%, and 30% PBPPCs.

Table B.13 Arterial AC Budget Needs for PCI=75 Target Driven Scenario 90% PBPPC (Case Study 2.a)

MILPITAS

Target-Driven Scenarios
Pavement Network Condition Lane Miles

Interest: .00% Inflation: .00% Printed: 10/30/2013

Annual budget needs to meet target objectives

Year	Arterial	Collector	Res/Loc	Other	Preventative Maintenance	Total
2013	$3,608,164	$0	$0	$0	$110,839	$3,608,164
2014	$2,015,002	$0	$0	$0	$10,502	$2,015,002
2015	$629,972	$0	$0	$0	$5,121	$629,972
2016	$571,508	$0	$0	$0	$2,391	$571,508
2017	$705,662	$0	$0	$0	$7,752	$705,662
2018	$308,365	$0	$0	$0	$296,049	$308,365
2019	$436,874	$0	$0	$0	$313,527	$436,874
2020	$646,606	$0	$0	$0	$138,947	$646,606
2021	$257,130	$0	$0	$0	$53,903	$257,130
2022	$506,583	$0	$0	$0	$69,163	$506,583
2023	$398,993	$0	$0	$0	$248,367	$398,993
2024	$389,259	$0	$0	$0	$152,065	$389,259
2025	$414,846	$0	$0	$0	$165,240	$414,846
2026	$492,613	$0	$0	$0	$70,507	$492,613
2027	$915,065	$0	$0	$0	$89,668	$915,065
2028	$540,291	$0	$0	$0	$14,303	$540,291
2029	$615,299	$0	$0	$0	$23,248	$615,299
2030	$214,458	$0	$0	$0	$72,933	$214,458
2031	$999,977	$0	$0	$0	$999,977	$999,977
2032	$621,827	$0	$0	$0	$86,757	$621,827
					Average Yearly Total:	$764,425
					Grand Total:	$15,288,494

Table B.14 Arterial AC Budget Needs for PCI=75 Target Driven Scenario 70% PBPPC (Case Study 2.a)

MILPITAS

Target-Driven Scenarios
Pavement Network Condition Lane Miles

Interest: 5.00% Inflation: 3.00% Printed: 09/15/2013

Annual budget needs to meet target objectives

Year	Arterial	Collector	Res/Loc	Other	Preventative Maintenance	Total
2011	$993,404	$0	$0	$0	$383,588	$993,404
2012	$469,707	$0	$0	$0	$63,256	$469,707
2013	$399,562	$0	$0	$0	$50,860	$399,562
2014	$541,850	$0	$0	$0	$108,160	$541,850
2015	$329,404	$0	$0	$0	$43,105	$329,404
2016	$334,545	$0	$0	$0	$334,545	$334,545
2017	$434,636	$0	$0	$0	$302,625	$434,636
2018	$445,495	$0	$0	$0	$194,246	$445,495
2019	$699,559	$0	$0	$0	$172,830	$699,559
2020	$1,125,996	$0	$0	$0	$32,297	$1,125,996
2021	$114,718	$0	$0	$0	$114,718	$114,718
2022	$1,502,251	$0	$0	$0	$80,233	$1,502,251
2023	$63,011	$0	$0	$0	$63,011	$63,011
2024	$796,573	$0	$0	$0	$197,856	$796,573
2025	$1,426,833	$0	$0	$0	$116,983	$1,426,833
2026	$352,388	$0	$0	$0	$1,818	$352,388
2027	$745,612	$0	$0	$0	$105,294	$745,612
2028	$1,199,295	$0	$0	$0	$1,864	$1,199,295
2029	$461,559	$0	$0	$0	$157,396	$461,559
2030	$789,956	$0	$0	$0	$193,247	$789,956
					Average Yearly Total:	$661,318
					Grand Total:	$13,226,354

Table B.15 Arterial AC Budget Needs for PCI=75 Target Driven Scenario 50% PBPPC (Case Study 2.a)

MILPITAS

Target-Driven Scenarios
Pavement Network Condition Lane Miles

Interest: 5.00% **Inflation: 3.00%** Printed: 09/23/2013

Annual budget needs to meet target objectives

Year	Arterial	Collector	Res/Loc	Other	Preventative Maintenance	Total
2011	$437,260	$0	$0	$0	$296,975	$437,260
2012	$166,689	$0	$0	$0	$411	$166,689
2013	$246,836	$0	$0	$0	$3,649	$246,836
2014	$301,414	$0	$0	$0	$180,555	$301,414
2015	$290,190	$0	$0	$0	$128,909	$290,190
2016	$426,109	$0	$0	$0	$426,109	$426,109
2017	$339,274	$0	$0	$0	$167,491	$339,274
2018	$340,422	$0	$0	$0	$83,950	$340,422
2019	$432,642	$0	$0	$0	$268,488	$432,642
2020	$584,796	$0	$0	$0	$91,489	$584,796
2021	$537,688	$0	$0	$0	$71,139	$537,688
2022	$718,155	$0	$0	$0	$168,851	$718,155
2023	$534,881	$0	$0	$0	$139,569	$534,881
2024	$307,110	$0	$0	$0	$125,024	$307,110
2025	$555,330	$0	$0	$0	$96,496	$555,330
2026	$665,332	$0	$0	$0	$48,890	$665,332
2027	$1,390,267	$0	$0	$0	$115,812	$1,390,267
2028	$113,098	$0	$0	$0	$113,098	$113,098
2029	$1,156,496	$0	$0	$0	$36,487	$1,156,496
2030	$243,426	$0	$0	$0	$110,917	$243,426
					Average Yearly Total:	$489,371
					Grand Total:	$9,787,415

Table B.16 Arterial AC Budget Needs for PCI=75 Target Driven Scenario 30% PBPPC (Case Study 2.a)

MILPITAS

Target-Driven Scenarios
Pavement Network Condition Lane Miles

Interest: 5.00% **Inflation: 3.00%** Printed: 10/01/2013

Annual budget needs to meet target objectives

Year	Arterial	Collector	Res/Loc	Other	Preventative Maintenance	Total
2011	$0	$0	$0	$0	$0	$0
2012	$0	$0	$0	$0	$0	$0
2013	$0	$0	$0	$0	$0	$0
2014	$204,675	$0	$0	$0	$204,675	$204,675
2015	$356,871	$0	$0	$0	$219,856	$356,871
2016	$272,038	$0	$0	$0	$1,630	$272,038
2017	$194,464	$0	$0	$0	$2,334	$194,464
2018	$338,631	$0	$0	$0	$1,805	$338,631
2019	$351,801	$0	$0	$0	$192,316	$351,801
2020	$272,146	$0	$0	$0	$245,114	$272,146
2021	$415,648	$0	$0	$0	$117,998	$415,648
2022	$364,076	$0	$0	$0	$291,918	$364,076
2023	$399,098	$0	$0	$0	$81,819	$399,098
2024	$717,945	$0	$0	$0	$40,825	$717,945
2025	$358,078	$0	$0	$0	$39,064	$358,078
2026	$345,518	$0	$0	$0	$211,283	$345,518
2027	$574,931	$0	$0	$0	$238,092	$574,931
2028	$820,211	$0	$0	$0	$140,658	$820,211
2029	$509,748	$0	$0	$0	$113,827	$509,748
2030	$442,756	$0	$0	$0	$40,709	$442,756
					Average Yearly Total:	$346,932
					Grand Total:	$6,938,635

Table B.17 Arterial AC/AC Budget Needs for PCI=75 Target Driven Scenario
90% PBPPC (Case Study 2.b)

MILPITAS

Target-Driven Scenarios
Pavement Network Condition Lane Miles

Interest: .00% **Inflation: .00%** Printed: 10/30/2013

Annual budget needs to meet target objectives

Year	Arterial	Collector	Res/Loc	Other	Preventative Maintenance	Total
2013	$1,781,409	$0	$0	$0	$289,447	$1,781,409
2014	$116,872	$0	$0	$0	$116,872	$116,872
2015	$362,761	$0	$0	$0	$26,585	$362,761
2016	$837,482	$0	$0	$0	$1,217	$837,482
2017	$538,380	$0	$0	$0	$8,120	$538,380
2018	$106,703	$0	$0	$0	$106,703	$106,703
2019	$193,534	$0	$0	$0	$193,534	$193,534
2020	$254,313	$0	$0	$0	$254,313	$254,313
2021	$316,145	$0	$0	$0	$56,047	$316,145
2022	$1,093,558	$0	$0	$0	$34,829	$1,093,558
2023	$0	$0	$0	$0	$0	$0
2024	$165,893	$0	$0	$0	$4,061	$165,893
2025	$361,486	$0	$0	$0	$102,292	$361,486
2026	$450,993	$0	$0	$0	$83,266	$450,993
2027	$132,746	$0	$0	$0	$97,447	$132,746
2028	$755,423	$0	$0	$0	$603,932	$755,423
2029	$590,955	$0	$0	$0	$396,833	$590,955
2030	$150,900	$0	$0	$0	$47,357	$150,900
2031	$588,117	$0	$0	$0	$443,350	$588,117
2032	$1,243,794	$0	$0	$0	$1,133,114	$1,243,794
					Average Yearly Total:	$502,073
					Grand Total:	$10,041,464

Table B.18 Arterial AC/AC Budget Needs for PCI=75 Target Driven Scenario
70% PBPPC (Case Study 2.b)

MILPITAS

Target-Driven Scenarios
Pavement Network Condition Lane Miles

Interest: 5.00% **Inflation: 3.00%** Printed: 09/15/2013

Annual budget needs to meet target objectives

Year	Arterial	Collector	Res/Loc	Other	Preventative Maintenance	Total
2011	$0	$0	$0	$0	$0	$0
2012	$5,350	$0	$0	$0	$5,350	$5,350
2013	$213,935	$0	$0	$0	$213,935	$213,935
2014	$248,491	$0	$0	$0	$248,491	$248,491
2015	$451,400	$0	$0	$0	$152,441	$451,400
2016	$159,599	$0	$0	$0	$1,081	$159,599
2017	$451,755	$0	$0	$0	$10,227	$451,755
2018	$309,035	$0	$0	$0	$219,728	$309,035
2019	$210,396	$0	$0	$0	$210,396	$210,396
2020	$389,502	$0	$0	$0	$217,132	$389,502
2021	$540,762	$0	$0	$0	$13,401	$540,762
2022	$398,164	$0	$0	$0	$39,380	$398,164
2023	$793,467	$0	$0	$0	$10,678	$793,467
2024	$541,010	$0	$0	$0	$958	$541,010
2025	$1,058,040	$0	$0	$0	$39,982	$1,058,040
2026	$0	$0	$0	$0	$0	$0
2027	$1,544,730	$0	$0	$0	$154,460	$1,544,730
2028	$0	$0	$0	$0	$0	$0
2029	$109,089	$0	$0	$0	$109,089	$109,089
2030	$1,344,037	$0	$0	$0	$1,344,037	$1,344,037
					Average Yearly Total:	$438,438
					Grand Total:	$8,768,762

Table B.19 Arterial AC/AC Budget Needs for PCI=75 Target Driven Scenario 50% PBPPC (Case Study 2.b)

MILPITAS

Target-Driven Scenarios
Pavement Network Condition Lane Miles

Interest: 5.00% Inflation: 3.00% Printed: 09/23/2013

Annual budget needs to meet target objectives

Year	Arterial	Collector	Res/Loc	Other	Preventative Maintenance	Total
2011	$0	$0	$0	$0	$0	$0
2012	$0	$0	$0	$0	$0	$0
2013	$0	$0	$0	$0	$0	$0
2014	$44,760	$0	$0	$0	$44,760	$44,760
2015	$218,906	$0	$0	$0	$218,906	$218,906
2016	$189,987	$0	$0	$0	$189,987	$189,987
2017	$210,629	$0	$0	$0	$210,629	$210,629
2018	$294,070	$0	$0	$0	$28,479	$294,070
2019	$984,116	$0	$0	$0	$44,692	$984,116
2020	$0	$0	$0	$0	$0	$0
2021	$153,767	$0	$0	$0	$153,767	$153,767
2022	$271,996	$0	$0	$0	$271,996	$271,996
2023	$259,097	$0	$0	$0	$259,097	$259,097
2024	$404,234	$0	$0	$0	$91,851	$404,234
2025	$559,547	$0	$0	$0	$0	$559,547
2026	$634,426	$0	$0	$0	$543	$634,426
2027	$977,764	$0	$0	$0	$0	$977,764
2028	$833,019	$0	$0	$0	$1,311	$833,019
2029	$0	$0	$0	$0	$0	$0
2030	$668,386	$0	$0	$0	$213,889	$668,386
					Average Yearly Total:	$335,235
					Grand Total:	$6,704,704

Table B.20 Arterial AC/AC Budget Needs for PCI=75 Target Driven Scenario 30% PBPPC (Case Study 2.b)

MILPITAS

Target-Driven Scenarios

Pavement Network Condition Lane Miles

Interest: 5.00% **Inflation: 3.00%** Printed: 10/01/2013

Annual budget needs to meet target objectives

Year	Arterial	Collector	Res/Loc	Other	Preventative Maintenance	Total
2011	$0	$0	$0	$0	$0	$0
2012	$0	$0	$0	$0	$0	$0
2013	$0	$0	$0	$0	$0	$0
2014	$0	$0	$0	$0	$0	$0
2015	$0	$0	$0	$0	$0	$0
2016	$0	$0	$0	$0	$0	$0
2017	$62,930	$0	$0	$0	$62,930	$62,930
2018	$216,290	$0	$0	$0	$216,290	$216,290
2019	$196,854	$0	$0	$0	$196,854	$196,854
2020	$208,460	$0	$0	$0	$208,460	$208,460
2021	$314,216	$0	$0	$0	$52,756	$314,216
2022	$267,721	$0	$0	$0	$63,112	$267,721
2023	$126,669	$0	$0	$0	$126,669	$126,669
2024	$256,602	$0	$0	$0	$256,602	$256,602
2025	$362,145	$0	$0	$0	$252,309	$362,145
2026	$357,506	$0	$0	$0	$88,166	$357,506
2027	$914,508	$0	$0	$0	$23,959	$914,508
2028	$267,531	$0	$0	$0	$47	$267,531
2029	$354,470	$0	$0	$0	$203	$354,470
2030	$573,931	$0	$0	$0	$13,012	$573,931
					Average Yearly Total:	$223,992
					Grand Total:	$4,479,833

Table B.21 Residential ST Budget Needs for PCI=75 Target Driven Scenario 90% PBPPC (Case Study 2.c)

Performance Curve - MARION CO. OREGON

Target-Driven Scenarios
Pavement Network Condition Lane Miles

Interest: 5.00% **Inflation: 3.00%** Printed: 06/24/2013

Annual budget needs to meet target objectives

Year	Arterial	Collector	Res/Loc	Other	Preventative Maintenance	Total
2013	$0	$0	$4,071,925	$0	$10,935	$4,071,925
2014	$0	$0	$2,838,943	$0	$808	$2,838,943
2015	$0	$0	$1,013,165	$0	$0	$1,013,165
2016	$0	$0	$1,135,197	$0	$17,172	$1,135,197
2017	$0	$0	$1,484,629	$0	$4,767	$1,484,629
2018	$0	$0	$1,551,583	$0	$3,351	$1,551,583
2019	$0	$0	$361,196	$0	$18,239	$361,196
2020	$0	$0	$1,939,862	$0	$994,742	$1,939,862
2021	$0	$0	$1,209,883	$0	$431,830	$1,209,883
2022	$0	$0	$1,259,835	$0	$9,189	$1,259,835
2023	$0	$0	$571,869	$0	$201,795	$571,869
2024	$0	$0	$1,005,010	$0	$140,411	$1,005,010
2025	$0	$0	$1,270,705	$0	$247,887	$1,270,705
2026	$0	$0	$409,175	$0	$14,370	$409,175
2027	$0	$0	$1,222,124	$0	$993,247	$1,222,124
2028	$0	$0	$1,883,771	$0	$1,267,062	$1,883,771
2029	$0	$0	$1,112,257	$0	$7,242	$1,112,257
2030	$0	$0	$1,094,712	$0	$905,046	$1,094,712
2031	$0	$0	$1,501,247	$0	$179,798	$1,501,247
2032	$0	$0	$1,178,388	$0	$479,892	$1,178,388
					Average Yearly Total:	$1,405,774
					Grand Total:	$28,115,476

Table B.22 Residential ST Budget Needs for PCI=75 Target Driven Scenario 70% PBPPC (Case Study 2.c)

Performance Curve - MARION CO. OREGON

Target-Driven Scenarios
Pavement Network Condition Lane Miles

Interest: 5.00% Inflation: 3.00% Printed: 10/14/2013

Annual budget needs to meet target objectives

Year	Arterial	Collector	Res/Loc	Other	Preventative Maintenance	Total
2013	$0	$0	$2,721,853	$0	$16,362	$2,721,853
2014	$0	$0	$1,168,419	$0	$760	$1,168,419
2015	$0	$0	$847,815	$0	$0	$847,815
2016	$0	$0	$680,402	$0	$23,126	$680,402
2017	$0	$0	$909,964	$0	$2,265	$909,964
2018	$0	$0	$831,761	$0	$1,490	$831,761
2019	$0	$0	$353,060	$0	$21,868	$353,060
2020	$0	$0	$644,781	$0	$3,945	$644,781
2021	$0	$0	$1,517,276	$0	$855,625	$1,517,276
2022	$0	$0	$403,690	$0	$14,830	$403,690
2023	$0	$0	$1,167,235	$0	$378,930	$1,167,235
2024	$0	$0	$1,209,339	$0	$222,357	$1,209,339
2025	$0	$0	$522,073	$0	$12,044	$522,073
2026	$0	$0	$1,572,394	$0	$461,830	$1,572,394
2027	$0	$0	$471,891	$0	$13,339	$471,891
2028	$0	$0	$574,485	$0	$10,371	$574,485
2029	$0	$0	$1,760,183	$0	$1,377,500	$1,760,183
2030	$0	$0	$1,451,003	$0	$468,916	$1,451,003
2031	$0	$0	$992,322	$0	$422,729	$992,322
2032	$0	$0	$1,691,421	$0	$340,143	$1,691,421
					Average Yearly Total:	$1,074,568
					Grand Total:	$21,491,367

Table B.23 Residential ST Budget Needs for PCI=75 Target Driven Scenario 50% PBPPC (Case Study 2.c)

Performance Curve - MARION CO. OREGON

Target-Driven Scenarios

Pavement Network Condition Lane Miles

Interest: 5.00% **Inflation: 3.00%** Printed: 06/24/2013

Annual budget needs to meet target objectives

Year	Arterial	Collector	Res/Loc	Other	Preventative Maintenance	Total
2013	$0	$0	$1,421,375	$0	$14,978	$1,421,375
2014	$0	$0	$1,138,246	$0	$1,880	$1,138,246
2015	$0	$0	$853,887	$0	$0	$853,887
2016	$0	$0	$699,662	$0	$20,716	$699,662
2017	$0	$0	$846,564	$0	$4,257	$846,564
2018	$0	$0	$1,007,770	$0	$1,093	$1,007,770
2019	$0	$0	$720,756	$0	$23,333	$720,756
2020	$0	$0	$1,627,699	$0	$365,790	$1,627,699
2021	$0	$0	$992,255	$0	$306,109	$992,255
2022	$0	$0	$423,041	$0	$17,585	$423,041
2023	$0	$0	$1,437,059	$0	$419,201	$1,437,059
2024	$0	$0	$879,869	$0	$23,401	$879,869
2025	$0	$0	$1,014,971	$0	$396,268	$1,014,971
2026	$0	$0	$526,382	$0	$114,813	$526,382
2027	$0	$0	$647,990	$0	$201,036	$647,990
2028	$0	$0	$535,428	$0	$12,396	$535,428
2029	$0	$0	$1,279,423	$0	$871,573	$1,279,423
2030	$0	$0	$845,368	$0	$10,012	$845,368
2031	$0	$0	$741,028	$0	$363,284	$741,028
2032	$0	$0	$1,562,660	$0	$1,255,565	$1,562,660
					Average Yearly Total:	$960,072
					Grand Total:	$19,201,433

Table B.24 Residential ST Budget Needs for PCI=75 Target Driven Scenario 30% PBPPC (Case Study 2.c)

Performance Curve - MARION CO. OREGON

Target-Driven Scenarios

Pavement Network Condition Lane Miles

Interest: 5.00% **Inflation: 3.00%** Printed: 10/09/2013

Annual budget needs to meet target objectives

Year	Arterial	Collector	Res/Loc	Other	Preventative Maintenance	Total
2013	$0	$0	$182,062	$0	$12,471	$182,062
2014	$0	$0	$974,274	$0	$1,044	$974,274
2015	$0	$0	$1,106,772	$0	$1,232	$1,106,772
2016	$0	$0	$1,055,985	$0	$16,823	$1,055,985
2017	$0	$0	$1,047,130	$0	$3,632	$1,047,130
2018	$0	$0	$1,365,441	$0	$3,558	$1,365,441
2019	$0	$0	$1,240,532	$0	$20,184	$1,240,532
2020	$0	$0	$1,197,257	$0	$6,358	$1,197,257
2021	$0	$0	$1,425,267	$0	$265,649	$1,425,267
2022	$0	$0	$237,878	$0	$20,532	$237,878
2023	$0	$0	$1,084,692	$0	$580,604	$1,084,692
2024	$0	$0	$412,560	$0	$7,850	$412,560
2025	$0	$0	$344,788	$0	$13,250	$344,788
2026	$0	$0	$451,050	$0	$9,678	$451,050
2027	$0	$0	$851,986	$0	$382,793	$851,986
2028	$0	$0	$479,293	$0	$8,857	$479,293
2029	$0	$0	$571,588	$0	$10,815	$571,588
2030	$0	$0	$598,815	$0	$9,634	$598,815
2031	$0	$0	$1,136,445	$0	$889,072	$1,136,445
2032	$0	$0	$1,438,526	$0	$924,530	$1,438,526
					Average Yearly Total:	$860,117
					Grand Total:	$17,202,341

Needs analysis reports in a 20 year period for section 15 from Chapter 4, analyzed with a 90% PBPPC and with a 50% PBPPC are shown in Tables B.25 and B.26

Table B.25 Arterial AC Section 15 Projected PCI and Budget Needs for Low Performance PBPPC (Chapter 4 Comparison of needs analysis with different PBPPCs)

Needs Projected PCI
90% PBPC Low Performance

Inspected PCI = 55 Age = 16 Years

Year	PCI Treated	Treatment	Cost
2010	55	Do Nothing	$ -
2011	52	Do Nothing	$ -
2012	100	Thick AC Overlay (2.5)	$ 25,296.57
2013	90	Do Nothing	$ -
2014	87	Crack Seal (C)	$ 16.73
2015	85	Do Nothing	$ -
2016	84	Crack Seal (C)	$ 42.25
2017	89	Seal Coat (S)	$ 2,610.07
2018	86	Do Nothing	$ -
2019	84	Crack Seal (C)	$ 40.85
2020	82	Do Nothing	$ -
2021	81	Crack Seal (C)	$ 61.39
2022	87	Seal Coat (S)	$ 3,025.78
2023	84	Do Nothing	$ -
2024	82	Do Nothing	$ -
2025	79	Do Nothing	$ -
2026	77	Do Nothing	$ -
2027	75	Do Nothing	$ -
2028	73	Do Nothing	$ -
2029	71	Do Nothing	$ -
		Total Cost	$ 31,093.63

Table B.26 Arterial AC Section 15 Projected PCI and Budget Needs for Medium Performance PBPPC (Chapter 4 Comparison of needs analysis with different PBPPCs)

Needs Projected PCI
50% PBPC Medium Performance

Inspected PCI = 74 Age = 12 Years

Year	PCI Treated	Treatment	Cost
2010	83	Seal Coat (S)	$ 3,288.89
2011	82	Do Nothing	$ -
2012	82	Crack Seal (C)	$ 46.08
2013	80	Do Nothing	$ -
2014	81	Crack Seal (C)	$ 53.13
2015	87	Seal Coat (S)	$ 3,812.72
2016	85	Do Nothing	$ -
2017	84	Do Nothing	$ -
2018	82	Do Nothing	$ -
2019	81	Do Nothing	$ -
2020	79	Do Nothing	$ -
2021	77	Do Nothing	$ -
2022	76	Do Nothing	$ -
2023	74	Do Nothing	$ -
2024	72	Do Nothing	$ -
2025	71	Do Nothing	$ -
2026	100	Mill and Thick Overlay	$ 44,575.18
2027	93	Do Nothing	$ -
2028	91	Crack Seal (C)	$ -
2029	90	Crack Seal (C)	$ -
		Total Cost	$ 51,776.00

Appendix C. Truncated CDPCI Points Distributions Graphs

Examples of plotted truncated probability density functions of cumulative deterioration PCI points tabulated using equation 3.5 from Chapter 3, and examples of plotted truncated cumulative distribution functions tabulated using equation 3.6 from Chapter 3, can be seen in figures C.1 through C.12.

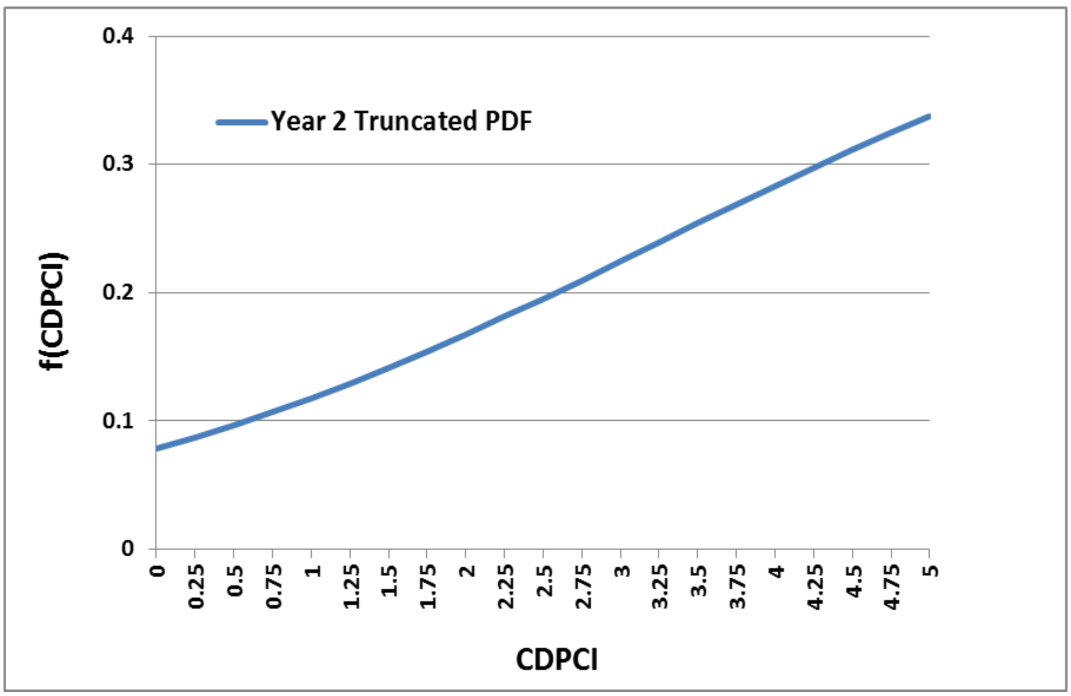

Figure C.1 Truncated PDF of Low CDPCI Points Year 2

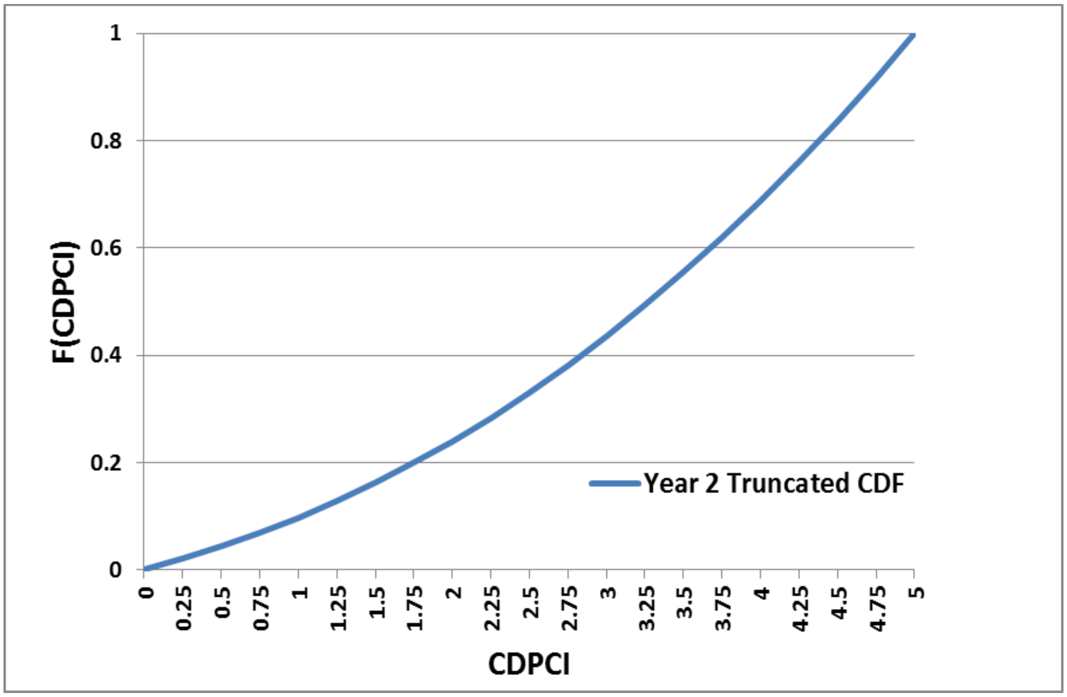

Figure C.2 Truncated CDF of Low CDPCI Points Year 2

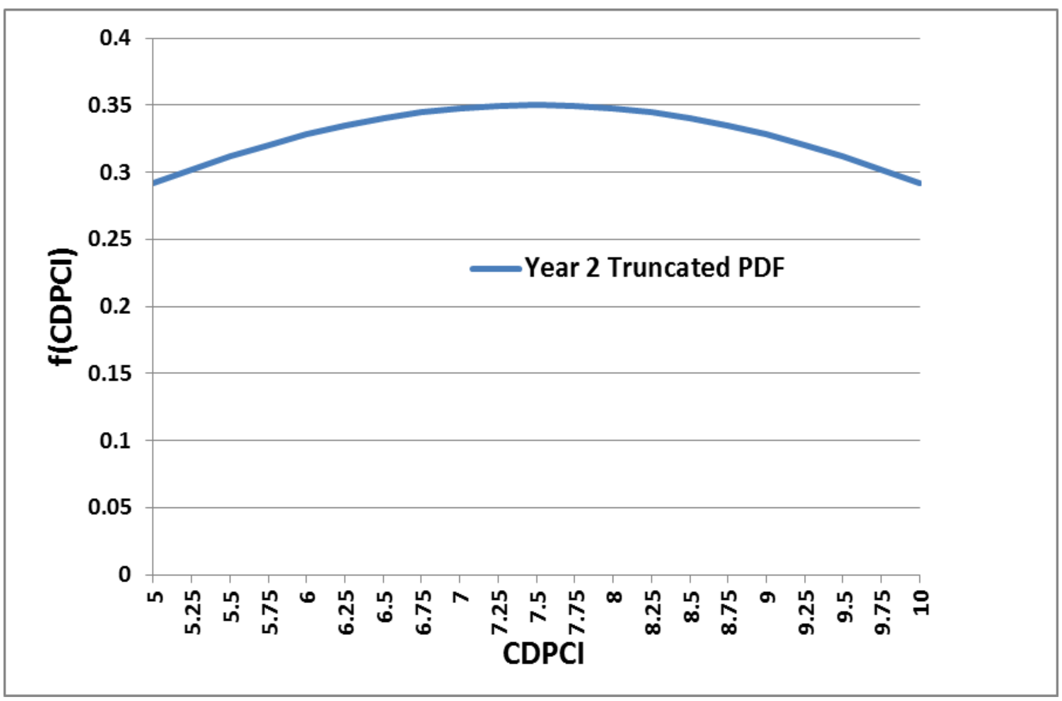

Figure C.3 Truncated PDF of Medium CDPCI Points Year 2

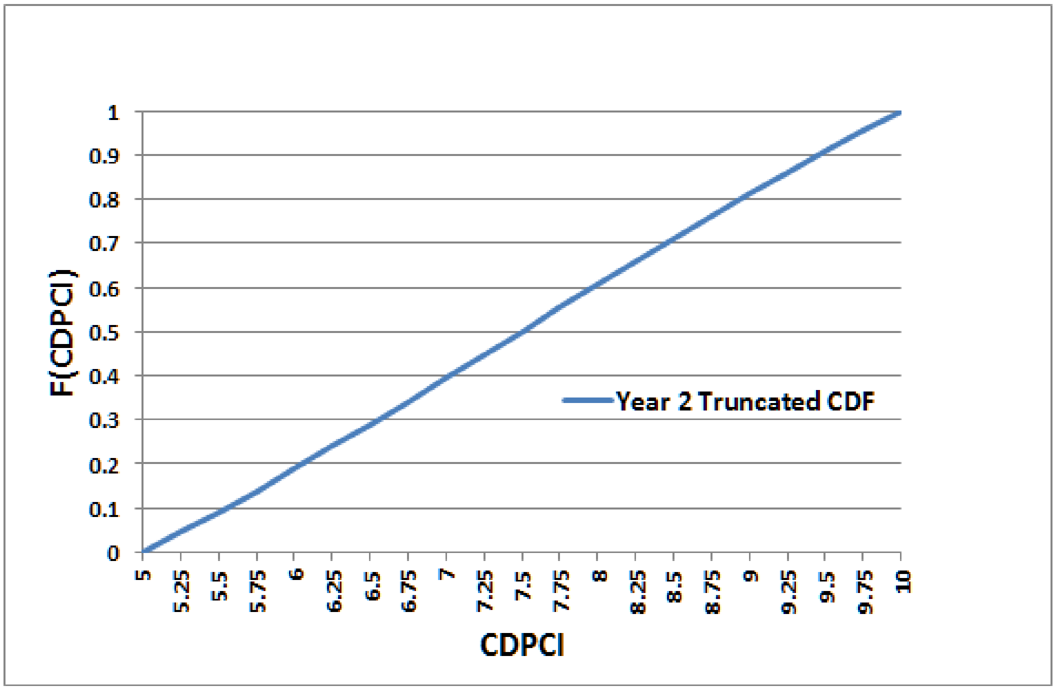

Figure C.4 Truncated CDF of Medium CDPCI Points Year 2

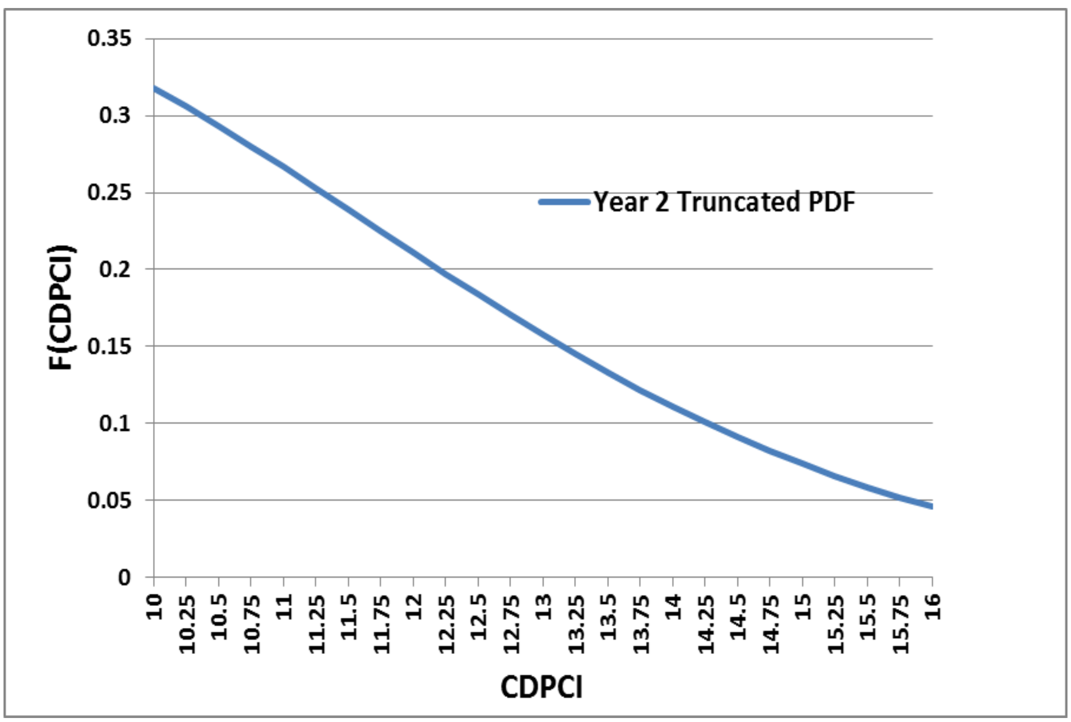

Figure C.5 Truncated PDF of High CDPCI Points Year 2

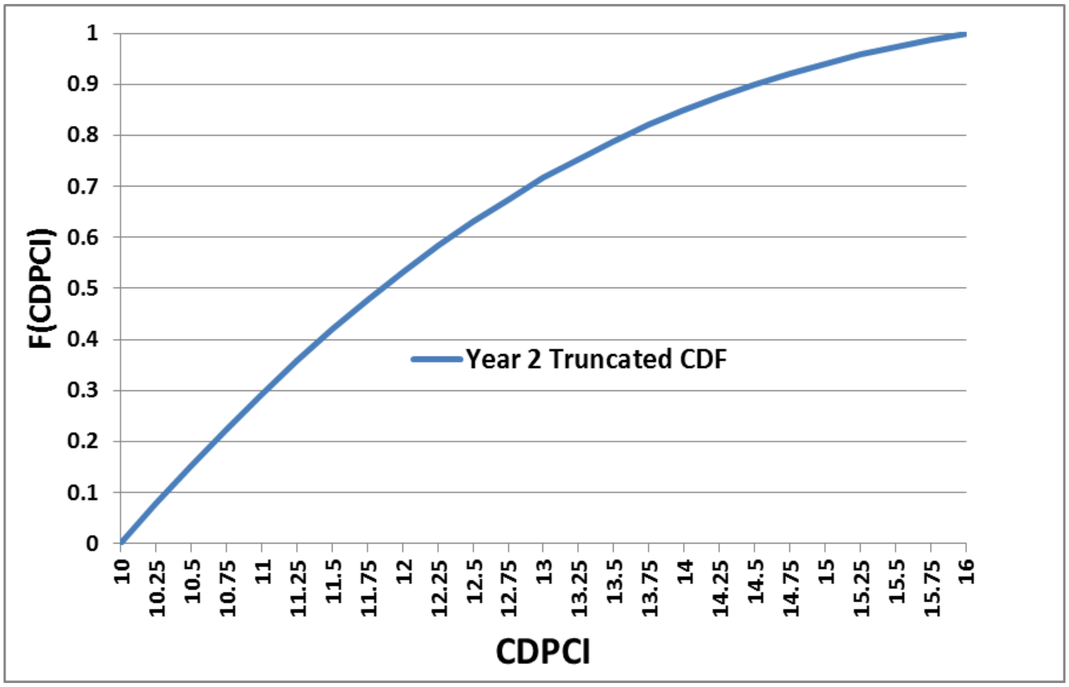

Figure C.6 Truncated CDF of High CDPCI Points Year 2

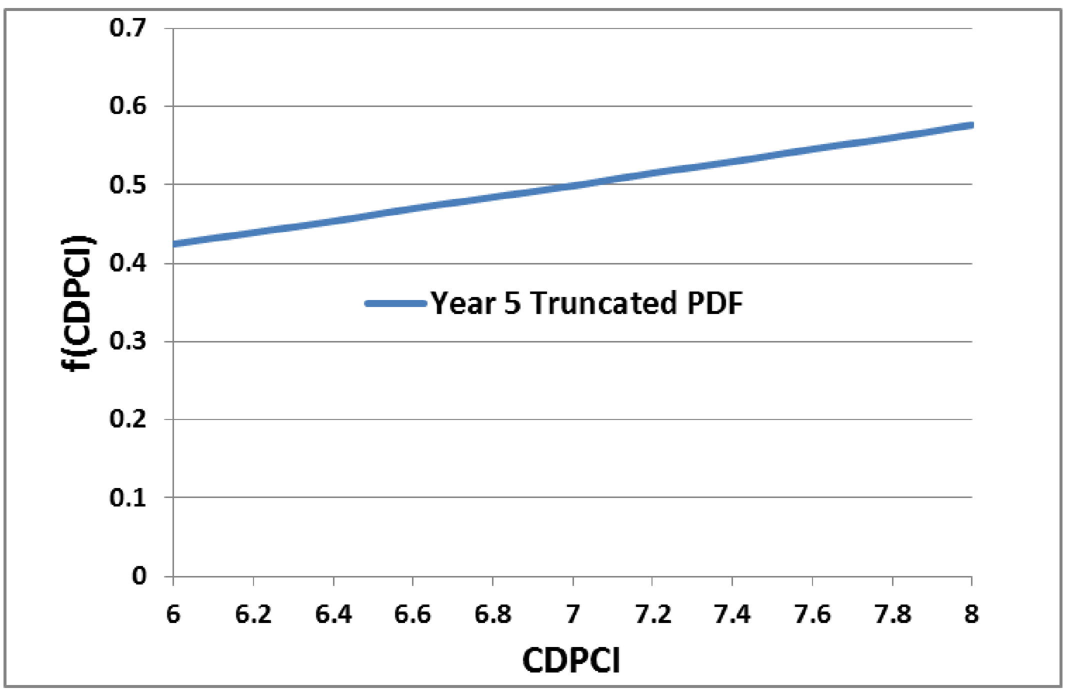

Figure C.7 Truncated PDF of Low CDPCI Points Year 5

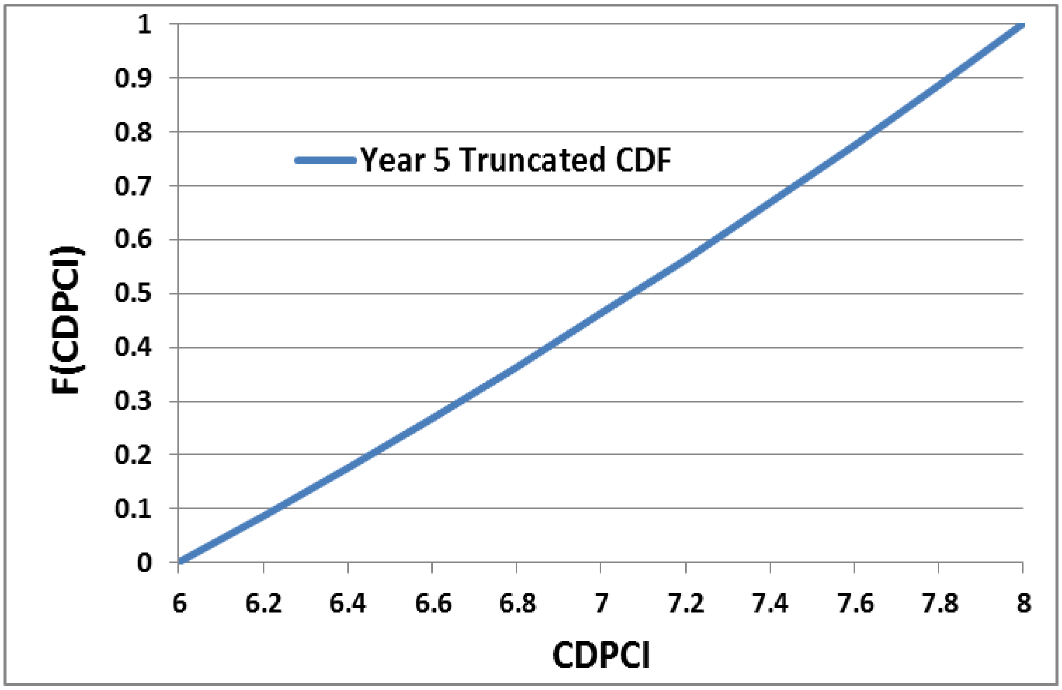

Figure C.8 Truncated CDF of Low CDPCI Points Year 5

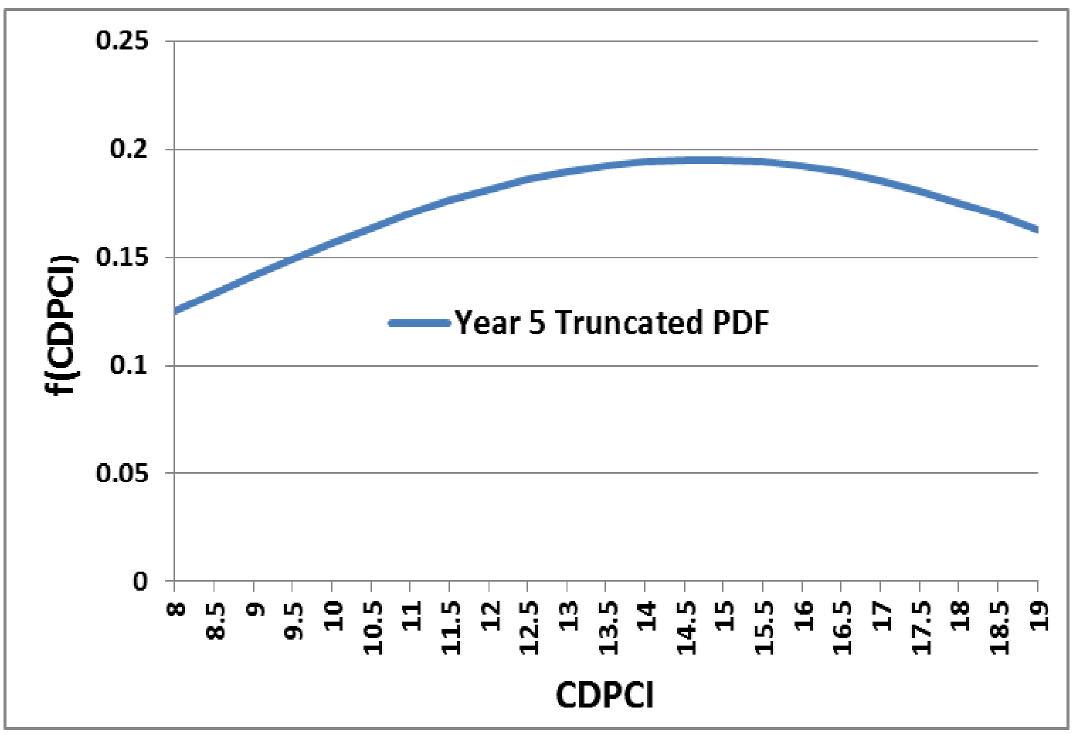

Figure C.9 Truncated PDF of Medium CDPCI Points Year 5

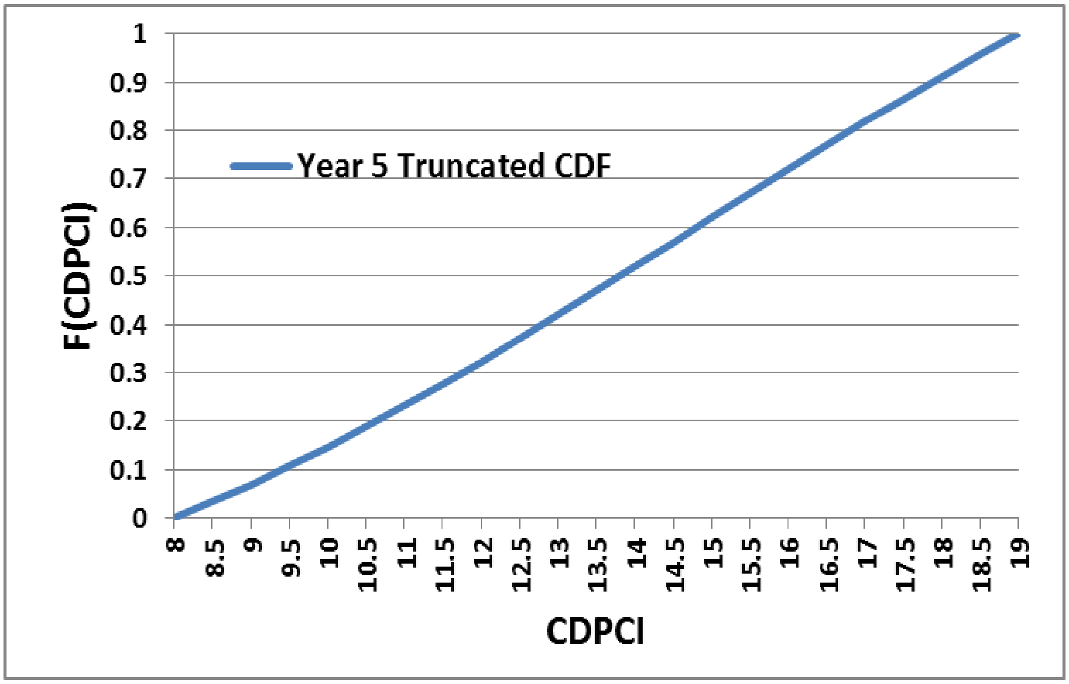

Figure C.10 Truncated CDF of Medium CDPCI Points Year 5

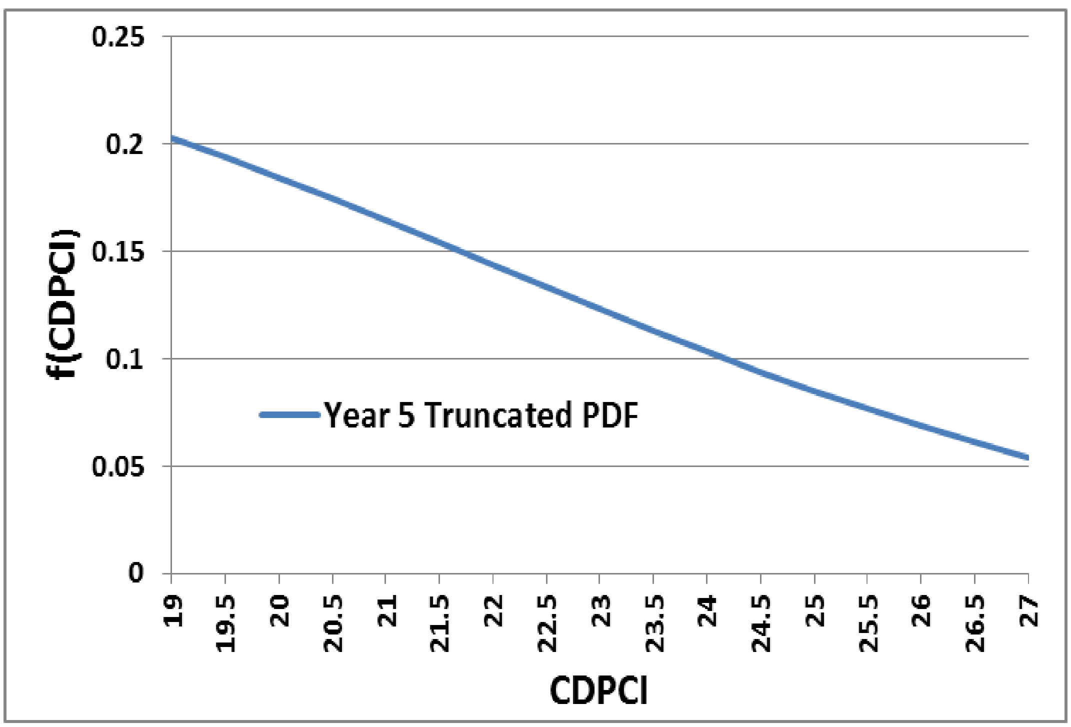

Figure C.11 Truncated PDF of High CDPCI Points Year 5

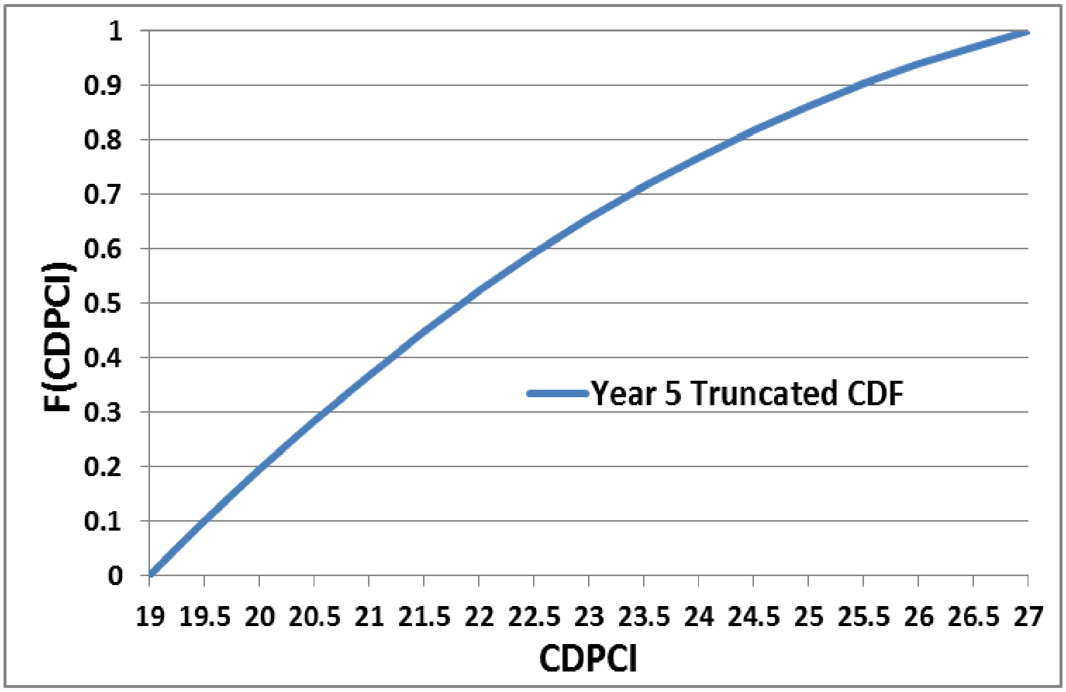

Figure C.12 Truncated CDF of High CDPCI Points Year 5

Examples of arterial AC random annual cumulative deterioration in PCI points histogram with fitted truncated normal probability density function of years 2 and 5 for low, medium, and high deterioration bands are shown in Figures C.13 trough C.18.

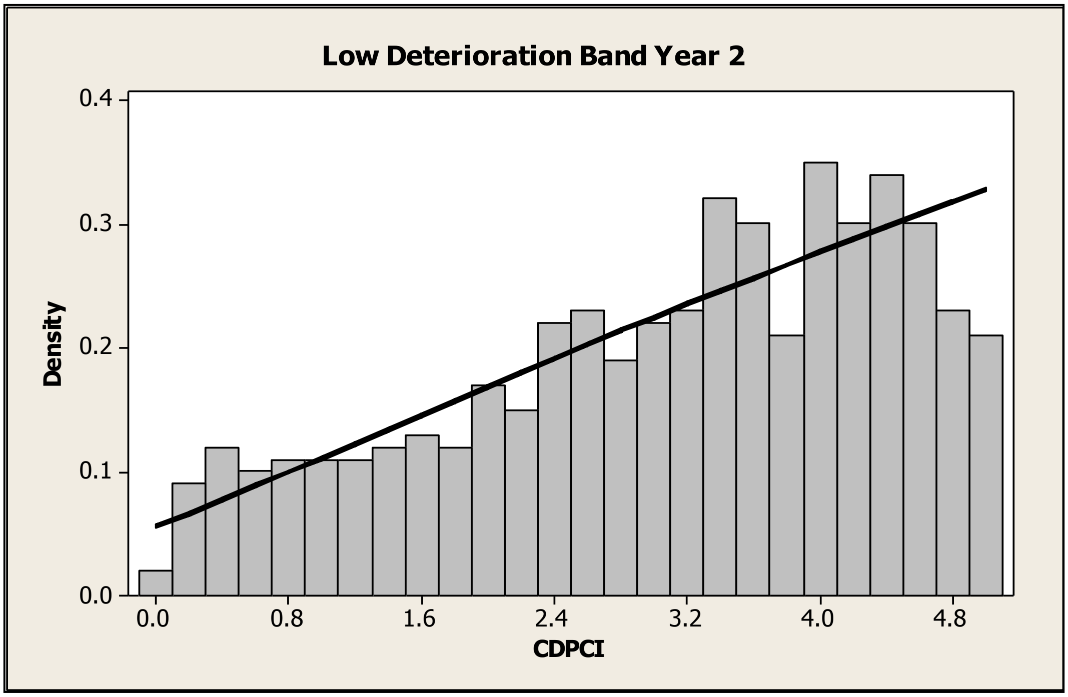

Figure C.13 Low CDPCI Points Year 2

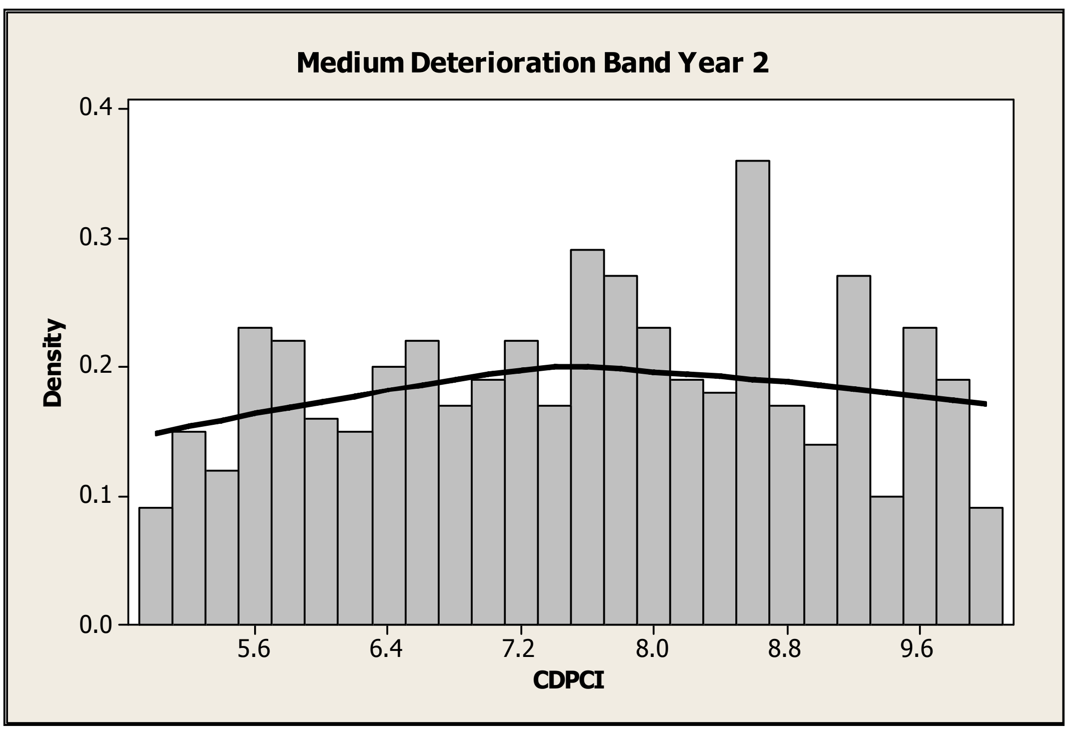

Figure C.14 Medium CDPCI Points Year 2

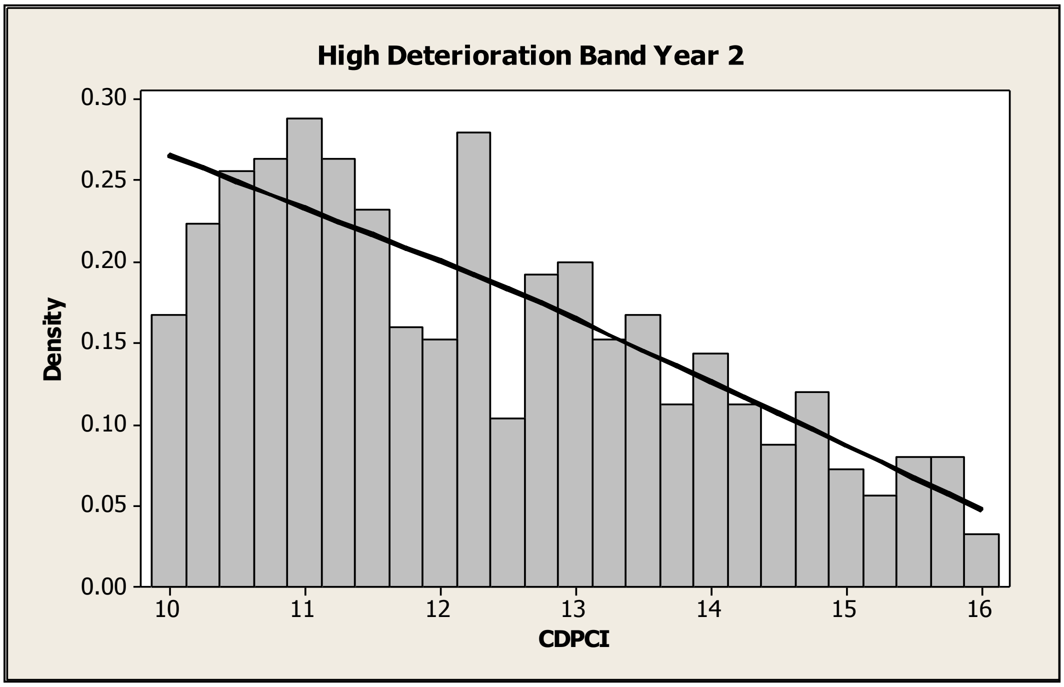

Figure C.15 High CDPCI Points Year 2

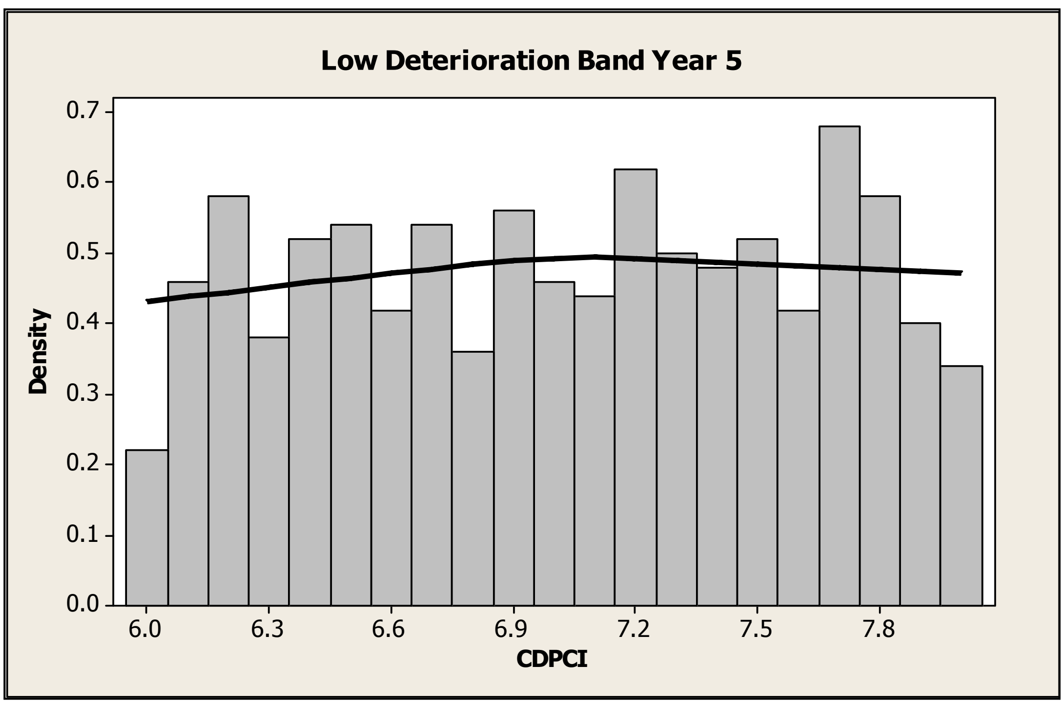

Figure C.16 Low CDPCI Points Year 5

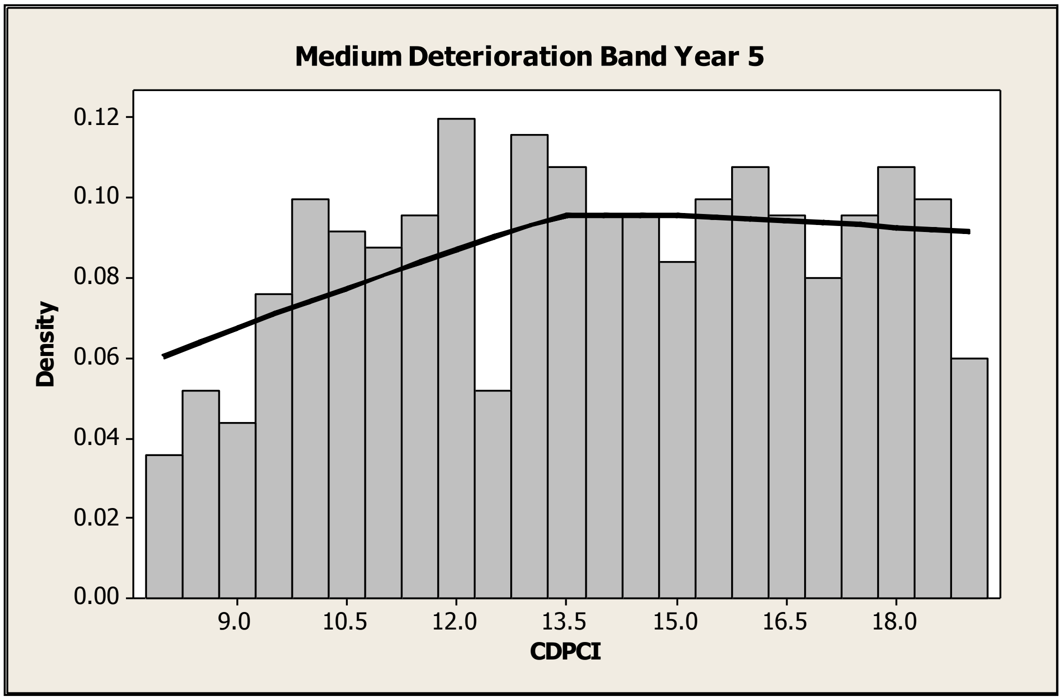

Figure C.17 Medium CDPCI Points Year 5

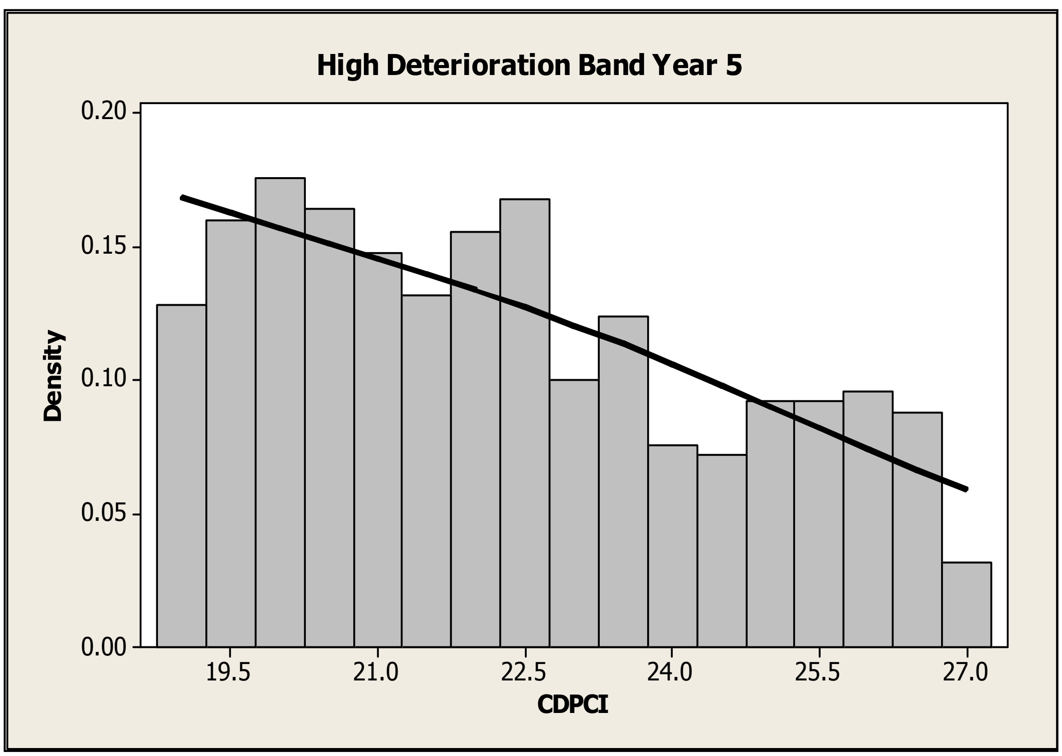

Figure C.18 High CDPCI Points Year 5

Appendix D. Probabilistic Pavement Performance-Based Scenario Reports

Needs analysis reports for a 20 year period from a 15 sections arterial streets network paved with AC, used in Chapter 5 for case study 3 conducted using low PPPBS deterioration band are shown in Tables D.1 through D.5, needs analysis conducted using medium PPPBS deterioration band are shown in Tables D.6 through D.12, and needs analysis conducted using high PPPBS deterioration band are shown in Tables D.13 through D.19.

Table D.1 Arterial AC Section 1Projected PCI and Budget Needs for Low Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
Low Deterioration Band			
Inspected PCI = 94		Age = 5 Years	
Year	PCI Treated	Treatment	Cost
2010	97	Seal Coat (S)	$ 3,288.89
2011	96	Do Nothing	$ -
2012	95	Crack Seal (C)	$ 12.52
2013	93	Do Nothing	$ -
2014	92	Crack Seal (C)	$ 19.36
2015	95	Seal Coat (S)	$ 3,812.72
2016	94	Do Nothing	$ -
2017	92	Do Nothing	$ -
2018	91	Do Nothing	$ -
2019	89	Do Nothing	$ -
2020	88	Do Nothing	$ -
2021	87	Do Nothing	$ -
2022	85	Do Nothing	$ -
2023	84	Do Nothing	$ -
2024	83	Do Nothing	$ -
2025	81	Do Nothing	$ -
2026	100	Mill and Thick Overlay	$ 44,575.18
2027	98	Do Nothing	$ -
2028	97	Crack Seal (C)	$ -
2029	96	Crack Seal (C)	$ -
		Total Cost	$51,708.67

Table D.2 Arterial AC Section 2 Projected PCI and Budget Needs for Low Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
Low Deterioration Band			
Inspected PCI = 89		Age = 6 Years	
Year	PCI Treated	Treatment	Cost
2010	95	Seal Coat (S)	$ 3,288.89
2011	92	Do Nothing	$ -
2012	91	Crack Seal (C)	$ 19.19
2013	89	Do Nothing	$ -
2014	89	Crack Seal (C)	$ 27.44
2015	93	Seal Coat (S)	$ 3,812.72
2016	92	Do Nothing	$ -
2017	91	Do Nothing	$ -
2018	89	Do Nothing	$ -
2019	88	Do Nothing	$ -
2020	86	Do Nothing	$ -
2021	85	Do Nothing	$ -
2022	84	Do Nothing	$ -
2023	82	Do Nothing	$ -
2024	81	Do Nothing	$ -
2025	80	Do Nothing	$ -
2026	78	Do Nothing	$ -
2027	77	Do Nothing	$ -
2028	76	Do Nothing	$ -
2029	75	Do Nothing	$ -
		Total Cost	$ 7,148.24

Table D.3 Arterial AC Section 3 Projected PCI and Budget Needs for Low Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
Low Deterioration Band			
Inspected PCI = 86		Age = 9 Years	
Year	PCI Treated	Treatment	Cost
2010	92	Seal Coat (S)	$3,288.89
2011	91	Do Nothing	$ -
2012	90	Crack Seal (C)	$ 22.71
2013	88	Do Nothing	$ -
2014	88	Crack Seal (C)	$ 29.65
2015	93	Seal Coat (S)	$3,812.72
2016	91	Do Nothing	$ -
2017	90	Do Nothing	$ -
2018	89	Do Nothing	$ -
2019	88	Do Nothing	$ -
2020	86	Do Nothing	$ -
2021	85	Do Nothing	$ -
2022	84	Do Nothing	$ -
2023	82	Do Nothing	$ -
2024	81	Do Nothing	$ -
2025	80	Do Nothing	$ -
2026	79	Do Nothing	$ -
2027	77	Do Nothing	$ -
2028	76	Do Nothing	$ -
2029	75	Do Nothing	$ -
		Total Cost	$7,153.97

Table D.4 Arterial AC Section 4 Projected PCI and Budget Needs for Low Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
Low Deterioration Band			
Inspected PCI = 83		Age = 10 Years	
Year	PCI Treated	Treatment	Cost
2010	90	Seal Coat (S)	$ 3,288.89
2011	88	Do Nothing	$ -
2012	88	Crack Seal (C)	$ 27.42
2013	87	Do Nothing	$ -
2014	87	Crack Seal (C)	$ 33.11
2015	92	Seal Coat (S)	$ 3,812.72
2016	91	Do Nothing	$ -
2017	90	Do Nothing	$ -
2018	88	Do Nothing	$ -
2019	87	Do Nothing	$ -
2020	85	Do Nothing	$ -
2021	84	Do Nothing	$ -
2022	82	Do Nothing	$ -
2023	81	Do Nothing	$ -
2024	80	Do Nothing	$ -
2025	79	Do Nothing	$ -
2026	77	Do Nothing	$ -
2027	76	Do Nothing	$ -
2028	75	Do Nothing	$ -
2029	74	Do Nothing	$ -
		Total Cost	$7,162.14

Table D.5 Arterial AC Section 5 Projected PCI and Budget Needs for Low Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
Low Deterioration Band			
Inspected PCI = 75		Age = 18 Years	
Year	PCI Treated	Treatment	Cost
2010	83	Seal Coat (S)	$ 3,288.89
2011	82	Do Nothing	$ -
2012	83	Crack Seal (C)	$ 44.02
2013	81	Do Nothing	$ -
2014	82	Crack Seal (C)	$ 49.38
2015	88	Seal Coat (S)	$ 3,812.72
2016	87	Do Nothing	$ -
2017	86	Do Nothing	$ -
2018	84	Do Nothing	$ -
2019	83	Do Nothing	$ -
2020	82	Do Nothing	$ -
2021	81	Do Nothing	$ -
2022	80	Do Nothing	$ -
2023	78	Do Nothing	$ -
2024	77	Do Nothing	$ -
2025	76	Do Nothing	$ -
2026	75	Do Nothing	$ -
2027	74	Do Nothing	$ -
2028	72	Do Nothing	$ -
2029	100	Mill and Thick Overlay	$ 48,708.50
		Total Cost	$ 55,903.52

Table D.6 Arterial AC Section 6 Projected PCI and Budget Needs for Medium Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
Medium Deterioration Band			
Inspected PCI = 77		Age = 10 Years	
Year	PCI Treated	Treatment	Cost
2010	85	Seal Coat (S)	$ 3,288.89
2011	83	Do Nothing	$ -
2012	82	Crack Seal (C)	$ 45.97
2013	80	Do Nothing	$ -
2014	81	Crack Seal (C)	$ 52.34
2015	87	Seal Coat (S)	$ 3,812.72
2016	85	Do Nothing	$ -
2017	83	Do Nothing	$ -
2018	81	Do Nothing	$ -
2019	79	Do Nothing	$ -
2020	77	Do Nothing	$ -
2021	75	Do Nothing	$ -
2022	73	Do Nothing	$ -
2023	72	Do Nothing	$ -
2024	79	Single Chip Seal	$ 5,478.94
2025	77	Do Nothing	$ -
2026	75	Do Nothing	$ -
2027	74	Do Nothing	$ -
2028	72	Do Nothing	$ -
2029	100	Mill and Thick Overlay	$ 48,708.50
		Total Cost	$ 61,387.36

Table D.7 Arterial AC Section 6 Projected PCI and Budget Needs for Medium Deterioratio PPPBS (Case Study 3)

Needs Projected PCI			
Medium Deterioration Band			
Inspected PCI = 77		Age = 10 Years	
Year	PCI Treated	Treatment	Cost
2010	85	Seal Coat (S)	$ 3,288.89
2011	83	Do Nothing	$ -
2012	82	Crack Seal (C)	$ 46.28
2013	80	Do Nothing	$ -
2014	81	Crack Seal (C)	$ 53.62
2015	86	Seal Coat (S)	$ 3,812.72
2016	84	Do Nothing	$ -
2017	82	Do Nothing	$ -
2018	81	Do Nothing	$ -
2019	78	Do Nothing	$ -
2020	77	Do Nothing	$ -
2021	75	Do Nothing	$ -
2022	73	Do Nothing	$ -
2023	71	Do Nothing	$ -
2024	100	Mill and Thick Overlay	$ 42,016.38
2025	98	Do Nothing	$ -
2026	96	Crack Seal (C)	$ -
2027	94	Crack Seal (C)	$ -
2028	93	Crack Seal (C)	$ -
2029	91	Crack Seal (C)	$ -
		Total Cost	$ 49,217.90

Table D.8 Arterial AC Section 7 Projected PCI and Budget Needs for Medium Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
Medium Deterioration Band			
Inspected PCI = 70		Age = 14 Years	
Year	PCI Treated	Treatment	Cost
2010	79	Single Chip Seal	$ 3,622.22
2011	77	Do Nothing	$ -
2012	77	Crack Seal (C)	$ 60.24
2013	76	Do Nothing	$ -
2014	76	Crack Seal (C)	$ 66.70
2015	83	Seal Coat (S)	$ 3,812.72
2016	81	Do Nothing	$ -
2017	80	Do Nothing	$ -
2018	78	Do Nothing	$ -
2019	76	Do Nothing	$ -
2020	74	Do Nothing	$ -
2021	73	Do Nothing	$ -
2022	71	Do Nothing	$ -
2023	100	Mill and Thick Overlay	$ 40,792.60
2024	98	Do Nothing	$ -
2025	96	Crack Seal (C)	$ -
2026	94	Crack Seal (C)	$ -
2027	92	Crack Seal (C)	$ -
2028	91	Crack Seal (C)	$ -
2029	90	Crack Seal (C)	$ -
		Total Cost	$48,354.49

Table D.9 Arterial AC Section 8 Projected PCI and Budget Needs for Medium Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
Medium Deterioration Band			
Inspected PCI = 68		Age = 16 Years	
Year	PCI Treated	Treatment	Cost
2010	100	Thin AC Overlay (1.5)	$10,155.56
2011	98	Do Nothing	$ -
2012	96	Crack Seal (C)	$ -
2013	94	Crack Seal (C)	$ -
2014	93	Crack Seal (C)	$ -
2015	91	Crack Seal (C)	$ -
2016	90	Crack Seal (C)	$ -
2017	89	Crack Seal (C)	$ 6.33
2018	93	Seal Coat (S)	$ 2,688.37
2019	91	Do Nothing	$ -
2020	89	Crack Seal (C)	$ 1.01
2021	87	Do Nothing	$ -
2022	87	Crack Seal (C)	$ 28.34
2023	91	Seal Coat (S)	$ 3,116.55
2024	89	Do Nothing	$ -
2025	87	Do Nothing	$ -
2026	85	Do Nothing	$ -
2027	83	Do Nothing	$ -
2028	81	Do Nothing	$ -
2029	79	Do Nothing	$ -
		Total Cost	$15,996.17

Table D.10 Arterial AC Section 9 Projected PCI and Budget Needs for Medium Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
Medium Deterioration Band			
Inspected PCI = 54		Age = 19 Years	
Year	PCI Treated	Treatment	Cost
2010	52	Do Nothing	$ -
2011	100	Thick AC Overlay (2.5)	$ 24,559.78
2012	98	Do Nothing	$ -
2013	96	Crack Seal (C)	$ -
2014	94	Crack Seal (C)	$ -
2015	92	Crack Seal (C)	$ -
2016	91	Crack Seal (C)	$ -
2017	90	Crack Seal (C)	$ -
2018	88	Crack Seal (C)	$ 10.06
2019	93	Seal Coat (S)	$ 2,769.02
2020	91	Do Nothing	$ -
2021	90	Crack Seal (C)	$ -
2022	88	Crack Seal (C)	$ 12.33
2023	86	Do Nothing	$ -
2024	91	Seal Coat (S)	$ 3,210.05
2025	89	Do Nothing	$ -
2026	87	Do Nothing	$ -
2027	85	Do Nothing	$ -
2028	83	Do Nothing	$ -
2029	81	Do Nothing	$ -
		Total Cost	$ 30,561.24

Table D.11 Arterial AC Section 9 Projected PCI and Budget Needs for Medium Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
Medium Deterioration Band			
Inspected PCI = 54		Age = 19 Years	
Year	PCI Treated	Treatment	Cost
2010	52	Do Nothing	$ -
2011	50	Do Nothing	$ -
2012	100	Thick AC Overlay (2.5)	$ 25,296.57
2013	98	Do Nothing	$ -
2014	96	Crack Seal (C)	$ -
2015	94	Crack Seal (C)	$ -
2016	92	Crack Seal (C)	$ -
2017	91	Crack Seal (C)	$ -
2018	90	Crack Seal (C)	$ -
2019	89	Crack Seal (C)	$ 8.46
2020	93	Seal Coat (S)	$ 2,852.09
2021	90	Do Nothing	$ -
2022	89	Crack Seal (C)	$ 3.59
2023	87	Do Nothing	$ -
2024	86	Crack Seal (C)	$ 32.01
2025	91	Seal Coat (S)	$ 3,306.35
2026	89	Do Nothing	$ -
2027	87	Do Nothing	$ -
2028	85	Do Nothing	$ -
2029	83	Do Nothing	$ -
		Total Cost	$ 31,499.07

Table D.12 Arterial AC Section 10 Projected PCI and Budget Needs for Medium Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
Medium Deterioration Band			
Inspected PCI = 68		Age = 18 Years	
Year	PCI Treated	Treatment	Cost
2010	100	Thin AC Overlay (1.5)	$10,155.56
2011	98	Do Nothing	$ -
2012	96	Crack Seal (C)	$ -
2013	94	Crack Seal (C)	$ -
2014	93	Crack Seal (C)	$ -
2015	91	Crack Seal (C)	$ -
2016	90	Crack Seal (C)	$ -
2017	89	Crack Seal (C)	$ 6.35
2018	93	Seal Coat (S)	$ 2,688.37
2019	91	Do Nothing	$ -
2020	90	Crack Seal (C)	$ -
2021	89	Crack Seal (C)	$ 10.04
2022	87	Do Nothing	$ -
2023	91	Seal Coat (S)	$ 3,116.55
2024	89	Do Nothing	$ -
2025	87	Do Nothing	$ -
2026	85	Do Nothing	$ -
2027	83	Do Nothing	$ -
2028	81	Do Nothing	$ -
2029	79	Do Nothing	$ -
		Total Cost	$14,332

Table D.13 Arterial AC Section 11 Projected PCI and Budget Needs for High Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
High Deterioration Band			
Inspected PCI = 88		Age = 2 Years	
Year	PCI Treated	Treatment	Cost
2010	94	Seal Coat (S)	$ 3,288.89
2011	88	Do Nothing	$ -
2012	84	Crack Seal (C)	$ 40.86
2013	78	Do Nothing	$ -
2014	76	Crack Seal (C)	$ 68.28
2015	81	Seal Coat (S)	$ 3,812.72
2016	77	Do Nothing	$ -
2017	74	Do Nothing	$ -
2018	71	Do Nothing	$ -
2019	76	Single Chip Seal	$ 4,726.18
2020	73	Do Nothing	$ -
2021	71	Do Nothing	$ -
2022	100	Mill and Thick Overlay	$ 39,604.47
2023	97	Do Nothing	$ -
2024	94	Crack Seal (C)	$ -
2025	92	Crack Seal (C)	$ -
2026	90	Crack Seal (C)	$ -
2027	88	Crack Seal (C)	$ 14.77
2028	92	Seal Coat (S)	$ 3,612.94
2029	90	Do Nothing	$ 89.82
		Total Cost	$ 55,258.94

Table D.14 Arterial AC Section 12 Projected PCI and Budget Needs for High Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
High Deterioration Band			
Inspected PCI = 67		Age = 10 Years	
Year	PCI Treated	Treatment	Cost
2010	76	Single Chip Seal	$ 3,622.22
2011	74	Do Nothing	$ -
2012	73	Crack Seal (C)	$ 71.11
2013	71	Do Nothing	$ -
2014	77	Single Chip Seal	$ 4,076.84
2015	75	Do Nothing	$ -
2016	72	Do Nothing	$ -
2017	100	Mill and Thick Overlay	$ 34,163.16
2018	97	Do Nothing	$ -
2019	95	Crack Seal (C)	$ -
2020	93	Crack Seal (C)	$ -
2021	90	Crack Seal (C)	$ -
2022	89	Crack Seal (C)	$ 7.97
2023	93	Seal Coat (S)	$ 3,116.55
2024	90	Do Nothing	$ -
2025	88	Crack Seal (C)	$ 11.81
2026	86	Do Nothing	$ -
2027	85	Crack Seal (C)	$ 50.28
2028	90	Seal Coat (S)	$ 3,612.94
2029	87	Do Nothing	$ -
		Total Cost	$ 48,732.89

Table D.15 Arterial AC Section 12 Projected PCI and Budget Needs for High Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
High Deterioration Band			
Inspected PCI = 67		Age = 10 Years	
Year	PCI Treated	Treatment	Cost
2010	76	Single Chip Seal	$ 3,622.22
2011	74	Do Nothing	$ -
2012	73	Crack Seal (C)	$ 71.11
2013	79	Single Chip Seal	$ 3,958.10
2014	79	Crack Seal (C)	$ 59.37
2015	75	Do Nothing	$ -
2016	73	Do Nothing	$ -
2017	79	Single Chip Seal	$ 4,454.88
2018	76	Do Nothing	$ -
2019	73	Do Nothing	$ -
2020	79	Single Chip Seal	$ 4,867.96
2021	76	Do Nothing	$ -
2022	73	Do Nothing	$ -
2023	70	Do Nothing	$ -
2024	100	Mill and Thick Overlay	$ 42,016.38
2025	98	Do Nothing	$ -
2026	95	Do Nothing	$ -
2027	93	Do Nothing	$ -
2028	90	Do Nothing	$ -
2029	87	Do Nothing	$ -
		Total Cost	$ 59,050.02

Table D.16 Arterial AC Section 13 Projected PCI and Budget Needs for High Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
High Deterioration Band			
Inspected PCI = 56		Age = 12 Years	
Year	PCI Treated	Treatment	Cost
2010	56	Do Nothing	$ -
2011	52	Do Nothing	$ -
2012	50	Do Nothing	$ -
2013	100	Thick AC Overlay (2.5)	$ 26,055.47
2014	97	Do Nothing	$ -
2015	94	Crack Seal (C)	$ -
2016	92	Crack Seal (C)	$ -
2017	90	Crack Seal (C)	$ -
2018	88	Crack Seal (C)	$ 9.42
2019	92	Seal Coat (S)	$ 2,769.02
2020	90	Do Nothing	$ -
2021	88	Crack Seal (C)	$ 15.37
2022	86	Do Nothing	$ -
2023	85	Crack Seal (C)	$ 45.27
2024	89	Seal Coat (S)	$ 3,210.05
2025	87	Do Nothing	$ -
2026	84	Do Nothing	$ -
2027	82	Do Nothing	$ -
2028	79	Do Nothing	$ -
2029	76	Do Nothing	$ -
		Total Cost	$ 32,104.60

Table D.17 Arterial AC Section 14 Projected PCI and Budget Needs for High Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
High Deterioration Band			
Inspected PCI = 74		Age = 12 Years	
Year	PCI Treated	Treatment	Cost
2010	83	Seal Coat (S)	$ 3,288.89
2011	80	Do Nothing	$ -
2012	80	Crack Seal (C)	$ 52.04
2013	77	Do Nothing	$ -
2014	77	Crack Seal (C)	$ 64.75
2015	83	Seal Coat (S)	$ 3,812.72
2016	80	Do Nothing	$ -
2017	77	Do Nothing	$ -
2018	73	Do Nothing	$ -
2019	71	Do Nothing	$ -
2020	78	Single Chip Seal	$ 4,867.96
2021	75	Do Nothing	$ -
2022	73	Do Nothing	$ -
2023	71	Do Nothing	$ -
2024	78	Single Chip Seal	$ 5,478.94
2025	75	Do Nothing	$ -
2026	73	Do Nothing	$ -
2027	79	Single Chip Seal	$ 5,986.98
2028	76	Do Nothing	$ -
2029	73	Do Nothing	$ -
		Total Cost	$ 23,552.29

Table D.18 Arterial AC Section 14 Projected PCI and Budget Needs for High Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
High Deterioration Band			
Inspected PCI = 74		Age = 12 Years	
Year	PCI Treated	Treatment	Cost
2010	83	Seal Coat (S)	$ 3,288.89
2011	80	Do Nothing	$ -
2012	80	Crack Seal (C)	$ 53.42
2013	77	Do Nothing	$ -
2014	76	Crack Seal (C)	$ 66.85
2015	82	Seal Coat (S)	$ 3,812.72
2016	79	Do Nothing	$ -
2017	76	Do Nothing	$ -
2018	73	Do Nothing	$ -
2019	71	Do Nothing	$ -
2020	78	Single Chip Seal	$ 4,867.96
2021	76	Do Nothing	$ -
2022	73	Do Nothing	$ -
2023	71	Do Nothing	$ -
2024	77	Single Chip Seal	$ 5,478.94
2025	75	Do Nothing	$ -
2026	73	Do Nothing	$ -
2027	70	Do Nothing	$ -
2028	100	Mill and Thick Overlay	$ 47,289.81
2029	98	Do Nothing	$ -
		Total Cost	$ 64,858.59

Table D.19 Arterial AC Section 15 Projected PCI and Budget Needs for High Deterioration PPPBS (Case Study 3)

Needs Projected PCI			
High Deterioration Band			
Inspected PCI = 55		Age = 16 Years	
Year	PCI Treated	Treatment	Cost
2010	55	Do Nothing	$ -
2011	52	Do Nothing	$ -
2012	100	Thick AC Overlay (2.5)	$ 25,296.57
2013	97	Do Nothing	$ -
2014	95	Crack Seal (C)	$ -
2015	93	Crack Seal (C)	$ -
2016	91	Crack Seal (C)	$ -
2017	89	Crack Seal (C)	$ 2.38
2018	93	Seal Coat (S)	$ 2,688.37
2019	90	Do Nothing	$ -
2020	88	Crack Seal (C)	$ 15.14
2021	85	Do Nothing	$ -
2022	84	Crack Seal (C)	$ 46.79
2023	89	Seal Coat (S)	$ 3,116.55
2024	87	Do Nothing	$ -
2025	84	Do Nothing	$ -
2026	81	Do Nothing	$ -
2027	78	Do Nothing	$ -
2028	76	Do Nothing	$ -
2029	73	Do Nothing	$ -
		Total Cost	$ 31,165.80

Vita

Rafael Arturo Ramirez received his Bachelor of Science in Civil Engineering from Universidad Nacional Autonoma de Mexico in 1970. He then received his Master of Science degree in Construction Management from Instituto Tecnologico de la Construccion in 2002. Rafael Arturo Ramirez joined the doctoral program in Civil Engineering at The University of Texas at El Paso in fall 2008.

Rafael Ramirez has worked in the construction industry in Mexico since 1968 up to 2000, when he became a full time professor at Universidad Autonoma de Ciudad Juarez (UACJ). He is returning to teach and conduct research at UACJ after obtaining his Ph.D. degree. He is also a member of the American Society of Civil Engineers, Mexico Chapter.

While pursuing his degree, Rafael Ramirez worked as a research assistant in the Center for Transportation Infrastructure Systems (CTIS) at the University of Texas at El Paso. Rafael Ramirez presented his research at international conferences including the 9th National Conference on Transportation Asset Management, Congreso Internacional de Investigacion Academia Journals, and graduate school presentations at UTEP.

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