A Two-Phase Maintenance and Rehabilitation Framework for Pavement Assets under Performance Based Contracts

by

Zaid Alyami

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Traditional Canadian pavement construction contracts provide detailed specifications for the work that needs to be carried out. This is the case for both maintenance and rehabilitation contracts. However, for many road agencies around the world, this traditional way of contracting had shortcomings. These agencies have been proactive in changing their contracts to maintain the road networks while reducing the cost. The challenge of maintaining the road networks to the highest possible condition while investing the minimal amount of money has promoted innovative contracting approaches. Furthermore, road agencies have increased the private sector involvement through warranty contracts. According to road agencies around the world, there has been a movement over the last two decades towards Performance Based Contracts (PBCs), a long term warranty contract.

In PBCs, the client agency specifies certain clearly defined minimal performance measures to be met or exceeded during the contract period and payments are explicitly linked to the contractor successfully meeting or exceeding those performance measures. Therefore, the PBC maintenance and rehabilitation selection differs significantly from that of traditional asset management contracts and more complex due to the pavement deterioration process and probability of failure to achieve the specified level of service for various performance measures along the contract period.

This thesis involves the development of a novel framework that facilitates the selection of maintenance and rehabilitation activities for pavement assets under PBCs. The framework consists of two phases. Phase-One, called the Initial Program, uses historical data, performance modeling, and optimization to establish and select the maintenance and rehabilitation program for the bidding stage. Phase-Two, called Project Asset Management, is implemented after the contract is awarded. This phase uses the contract performance monitoring data and the cost estimate from Phase-One as a baseline budget to update and validate the established program through performance modeling and optimization. A case study using data from the Ministry of Transportation Ontario (MTO) second generation Pavement Management System (PMS2) is used to illustrate the framework.

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Last but not least, I owe an eternal debt of gratitude and appreciation to my family for the unconditional love, support, encouragement and patience. Special thanks to my lifelong mentors and ever-loving parents; I owe the two of you the world.

Dedication

I dedicate this thesis to my father, my mother and to my family.

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Chapter 1

Introduction

1.1 Background

Canada has approximately 900,000 km of roads with the national highway system composing of 38,000 km of important provincial and national highways (Alberta 2010). In Canada, about 90 % of goods are transported via trucks (Transport Canada 2004); therefore, the Canadian economy is dependent on good pavement infrastructure. It is estimated that the road infrastructure in Canada has an asset value between $120 billion to $160 billion (Transport Canada 2004). However, with reduced budget and increasing traffic loading, maintaining the roads and pavement infrastructure is of critical importance (TAC 2012).

Traditionally, agencies specify their maintenance and rehabilitation contracts by means and methods to be performed and the sequence of the job (Piñero and Jesus 2004). However, according to road agencies around the world, this traditional methodology has shortcomings to achieve the agencies main goal to maintain the road networks at acceptable level of service while reducing the cost (Piñero and Jesus 2004). Therefore, the challenge of maintaining the road networks at the highest possible condition while investing the minimum amount of money will always keep transportation agencies searching for innovative approaches (Juan Carlos Piñero 2003). As a result, road agencies have increased private sector involvement (Queiroz 1999) through warranty contracts. According to road agencies around the world, there has been a movement over the last two decades towards Performance Based Contracts (PBCs), a long term warranty contract (Giglio, J M., Ankner, W. D. 1998; Juan Carlos Piñero 2003; Manion and Tighe 2007; Queiroz 1999).

In traditional method-based contracts, the owner agency specifies techniques, materials, methods, quantities, along with the time period for the contract. In contrast, in PBC, the client agency specifies minimum performance measures to be met or exceeded along the contract period. PBC is a type of contract in which payments are explicitly linked to the contractor successfully meeting or exceeding certain clearly defined minimum performance indicators (World Bank 2005).

The development of PBC started in the late 1980s to early 1990's. British Columbia, Canada, was first province to contract a PBC in 1988. British Columbia was followed by Argentina, Uruguay, Brazil, Australia, New Zealand, and United States of America (Zietlow 2005). This approach has been successfully used in several highway maintenance and rehabilitation projects. In addition, there is a movement towards implementing this contract model in new construction projects.

The main aspect of PBC is that contractors are paid based on the end result achieved not on following the specified method of performing the work. Therefore, the contractor is paid based on how well they meet the specified performance goals. Payments are made in instalments, usually monthly. Incentives and penalties can be introduced and consist of increases or decreases of a payment due to exceeding or not meeting the specified performance goal (NCHRP 2009). Consequently, the PBC define success in terms of how well the contractor meets the performance goals. The intent of PBC is to encourage contractor innovation and improve quality by encouraging value engineering and improved efficiency (Segal et al. 2003).

PBC can cover one asset or multiple assets (Anastasopoulos et al. 2010). The complexity of PBC can range from a "simple" to a "comprehensive" contract depending on the number of assets included in the contract. A simple PBC can be a contract for a single activity such as maintaining the signs, while on the other hand, a comprehensive contract include all assets along a highway corridor, such as signs, pavement, bridges, etc. (World Bank 2005).

1.2 Problem Statement

PBC differs from the traditional asset management as the performance criteria is determined and modeled based on various number of performance measures, while in traditional asset management an overall performance index is normally used. Therefore, performance modeling in the PBC is a more complex task. Moreover, pavement deterioration follows a stochastic behavior, and the deterioration process and the improvement due to maintenance and rehabilitation activities varies based on many factors such as environment, loading, and data used for the modeling, which result in a risk to the contractor in such contract models.

The risk of failure could be a result of the contractor error in (i) predicting deterioration of contracted assets; (ii) determining appropriate design, specifications and materials; (iii) planning needed maintenance interventions; and (iv) estimating quantities. Therefore, there is a need to develop a framework to facilitate the selection of an effective maintenance and rehabilitation program that takes into account those possible causes of risk.

1.3 Research Objective and Scope

The objective of this research is to develop a framework that facilitates the selection of maintenance and rehabilitation activities for pavement assets under PBCs. The framework consists of two phases. Phase-One, called Initial Program, uses historical data, performance modeling, and optimization to establish and select the maintenance and rehabilitation program for the bidding stage. Phase-Two, called Project Asset Management, is implemented after the contract is awarded. This phase uses the contract performance monitoring data and the cost estimate from Phase-One as a baseline budget to update and validate the established program through performance modeling and optimization. A case study using data from the Ministry of Transportation Ontario (MTO) second generation Pavement Management System (PMS2) is used to illustrate the framework.

The framework is beneficial to contractors as it helps mitigate the risk of failure to meet the specified level of service during the contract period. In addition, due to the continuous monitoring and optimization of the maintenance and rehabilitation program, a cost saving may be achieved resulting in more profit and higher project quality. On the other hand, agencies may use the framework to establish a cost baseline and a general idea during contractors' bid evaluation process. Also, agencies can benefit from the framework in evaluating the benefits of using the PBC model in comparison to the traditional model.

1.4 Thesis Organization

This thesis consists of six chapters, and the contents of each chapter are explained as follows: Chapter One provides an introduction to the research thesis, the objective and scope.

Chapter Two provides a literature review highlighting the concept of performance based contracts, different performance modeling background, and maintenance and rehabilitation programing and optimization.

Chapter Three introduces the proposed framework illustrating in details each step while providing examples.

Chapter Four describes how the framework could be implemented to a case study. The case study developed for an MTO highway section under a performance based contract.

Chapter Five evaluates the framework by applying a sensitivity analysis of different variables in the contract model and the framework including the specified level of service and maintenance and rehabilitation activities deterioration rates.

Chapter Six summarizes the main conclusions and recommendations of the thesis.

Chapter 2
Literature Review

2.1 Performance Based Contracts Overview

Performance-based contracts (PBC) differ significantly from the traditional method-based contracts. In traditional method-based contracts, the owner agency specifies techniques, materials, methods, quantities, along with the time period at which the work is to be performed. The payment to the contractor is based on the amount of inputs such as material quantity, number of working hours, etc. In contrast, in PBC, the client agency does not specify any methods, material, or techniques; however, specifies minimum performance measures to be met or exceeded along the contract period. PBC is a type of contract in which payments are explicitly linked to the contractor successfully meeting or exceeding certain clearly defined minimum performance measures (World Bank 2005).

One main feature of the PBC is that contractors are paid based on the end result achieved not on following the specified method of performing the work. Therefore, the contractor is paid based on how well they meet the specified performance measures. For example, the contractor is not paid for the number of potholes patched; instead, the contractor is paid for the compliance of the specified performance requirement of no potholes remaining (i.e. 100 % potholes patched). Payments are made in instalments, usually monthly (World Bank 2005). Incentives and penalties maybe introduced and consist of increase or decrease of a payment due to exceeding or falling short on achieving the specified performance measure (NCHRP 2009).

PBC can cover one asset or multiple assets (Anastasopoulos et al. 2010). The complexity of PBC can range from a “simple” to a “comprehensive” contract depending on the number of assets included in the contract. A simple PBC can be a contract for a single activity such as maintaining the signs, on the other hand, a comprehensive contract include all assets along a highway corridor, such as signs, pavement, bridges, etc. (World Bank 2005). Since pavement maintenance (such as resurfacing, etc.) is periodic, the contract period ranges from 3-10 years and up to 30 years in some cases.

A PBC is referred to by different terminology in different countries and within states and provinces (NCHRP 2009; Pakkala et al. 2007). For the purpose of this research, the term "Performance Based Contract" will be used. Some examples of terminologies include:

- Performance-Based Maintenance Contract
- Performance Contract
- Total Maintenance Contract
- Performance-Specified Maintenance Contract
- Asset Management Contract
- Contract for Rehabilitation and Maintenance
- Managing Agent Contract
- Area Maintenance Contract
- Asset Management Contracts
- Asset Maintenance Contracts
- Performance Specified Maintenance Contracts (PSMC)
- Long-Term Maintenance Contracts
- Long-Term Performance Contracts
- Managing Agent Contracts (MAC)
- Term Maintenance Contracts
- Term Network Contracts
- Maintenance By Contract
- Performance Contracting
- Total Maintenance Contracting
- Alliance Contracting

The theory behind this contracting scheme is based on the following two facts (Piñero and Jesus 2004): (1) "Industry" might know cheaper and better processes, so the agency should specify only the desired result or outcome (what) and let the competing bidders choose the processes (how to), and (2) Contractors can work more efficiently when they have maximum freedom to choose the manner in which they will perform the contract.

Because the PBC define the success of a contractor in terms of how well they meet the performance goals alone, they spark contractor innovation and improve quality which in turn creates opportunities for value engineering and improved efficiencies (Segal et al. 2003). Agencies who have implemented performance based contracts claim cost saving between 10-50%, Table 2.1, reduction in house work force, improved level of service, and greater user satisfactory (Anastasopoulos et al. 2010; Liautaud 2001; Queiroz 1999; Zietlow 2005). Moreover, some of the advantages found in the literature (NCHRP 2009) include:

- Potential reduction in costs
- Improved level of service (could cost more)
- The transfer of risk to the contractor
- More innovation
- More integrated services
- Enhanced asset management
- Ability to reap the benefits of partnering
- Building a new industry
- Achieving economies of scale

Table 2.1: Cost Saving by Country for Using PBC over Conventional (World Bank 2005)

Country	Cost Savings
Norway	About 20%–40%
Sweden	About 30%
Finland	About 30%–35%
Holland	About 30%–40%
Estonia	20%–40%
England	10% minimum
Australia	10%–40%
New Zealand	About 20%–30%
United States	10%–15%
Ontario, Canada	About 10%
Alberta, Canada	About 20%
British Columbia, Canada	Some, but might be on the order of 10%

The development of PBC started in late 1980s to early 1990s. British Columbia, Canada, was the first province to contract a PBC in 1988 (Zietlow 2005) followed by Alberta and Ontario, Canada. Australia launched its first PBC in 1995 which involved maintenance of urban roads in Sydney followed by New South Wales, Tasmania, and Southern and Western Australia (Zietlow 2005). In 1998 a PBC was introduced in New Zealand to maintain 405 km of national roads (Zietlow 2005). PBCs were introduced in the USA in 1996 in the State of Virginia followed by Alaska, Florida, Oklahoma, Texas, and North Carolina. In addition, Washington, D.C., has started applying PBC approaches to maintain highways, bridges, tunnels, rest areas, and urban streets (FHWA 2005). Argentina introduced PBCs in 1995, which now covers about 44% of its national network (Liautaud 2001). Uruguay started its first PBC contract in the mid-nineties followed by other Latin American countries including Brazil, Chile, Colombia, Ecuador, Guatemala, Mexico and Peru (World Bank 2005; Zietlow 2005).

Gradually, PBC trends spread to other developed and developing countries in Europe, Africa and Asia. Some examples include United Kingdom, Sweden, Finland, Netherlands, Norway, France, Estonia, Serbia and Montenegro, South Africa, Zambia, Chad, the Philippines, etc. (World Bank 2005). Figure 2.1 and 2.2 (Anastasopoulos et al. 2010) illustrate a map of PBCs implemented worldwide and in the United States., respectively.

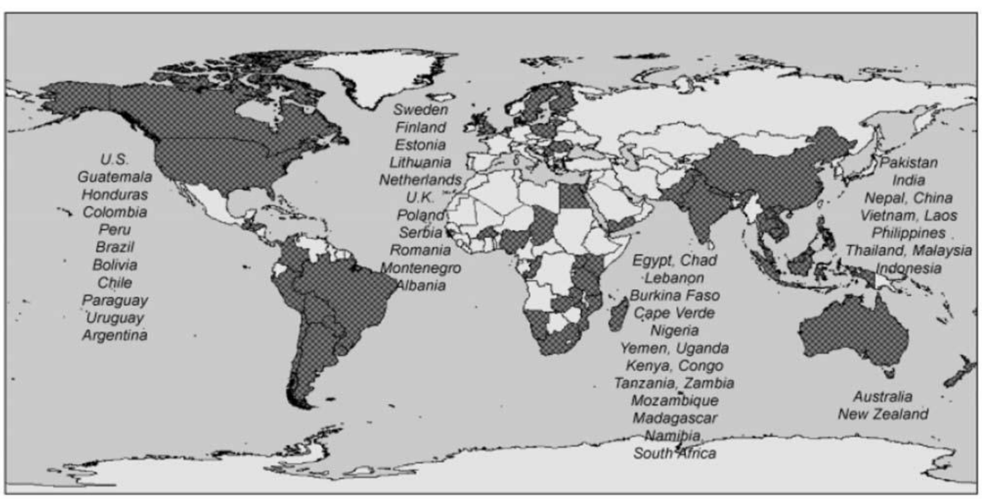

Figure 2.1: PBCs implemented Worldwide (Anastasopoulos et al. 2010)

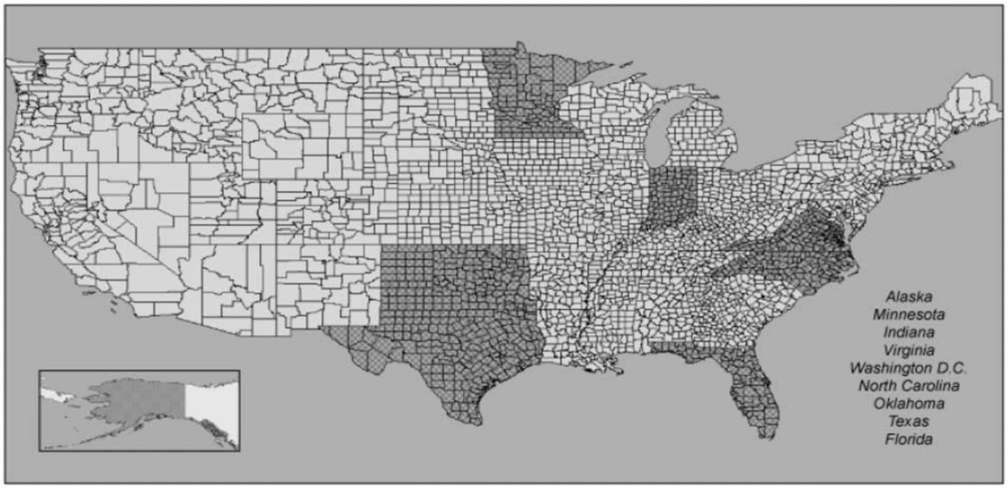

Figure 2.2: PBCs implemented in the US (Anastasopoulos et al. 2010)

2.2 Performance Measures

The basis of a PBC is to define performance measures and performance level of service (LOS) that are expected to be achieved by the contractor under the PBC. Performance measures and LOS are perhaps the most critical elements of performance contracting (FHWA 2002). The performance measures have to be clearly defined and objectively measurable in order to avoid ambiguity and risk disputes (Zietlow 2005). Moreover, experts argue the benefit of using a few key performance measures instead of many because of the associated simplicity and manageability of those performance measures (NCHRP 2009). It is therefore important that the owner agency properly identify which physical attributes, performance measures, of the road network are required and the associated level of service to be achieved (Manion and Tighe 2007).

Performance measures are a set of defined outcome-based conditions (for example roughness) that an agency uses to evaluate the success of the contractor. Performance goals are the minimum acceptable levels to be achieved for each performance measure (for example an IRI of 2 m/km) (SAIC 2006). For this contract model to be successfully used, agencies must carefully identify the performance measure and goals to be achieved for projects under this contract.

Lichiello in his Guidebook for Performance Measurement has defined the performance measurement as “the specific representation of a capacity, process, or outcome deemed relevant to the assessment of performance. A performance measure is quantifiable and can be documented.” (Lichiello and Turnock 2002). For a performance measure to be effective, the following questions should be considered (SAIC 2006):

- Is the performance measure specific?
- Is the performance measure measurable?
- Is the performance measure achievable?
- Is the performance measure results- oriented?
- Is the performance measure timely?
- Does the measurement meet with the agency’s objectives and desires?
- Has the performance been measured before?
- Dose the measurement conflict with the agency’s standard specifications?
- Does the measurement aim to improve performance?

In an investigation commissioned by Land Transport New Zealand to study the effectiveness of their current key performance measures (Kadar and Henning 2007), it was noted that an adequate PBC is based on the following essential requirements and/or assumptions:

- The performance requirements are consistent with the policies and objectives of the community and with those of the owner.
- Policies can be expressed with the help of measurable parameters, i.e. qualitative policies can be translated into quantitative measures or parameters.
- The relationship between quantitative measures and future performance can be modelled reliably. Deterioration models for local conditions are available and are satisfactorily calibrated.
- The input parameters for the performance models can be measured satisfactorily and accurately at a cost commensurate with the asset value.

- The funding level of the asset management activities is consistent with the desired outcome and asset value.

Different agencies have different performance measures and performance goals. Under its International Technology Exchange Program, the United States Federal Highway Administration (FHWA) conducted a study of the European practice of PBC. The study presented a summary of the performance measures used in Europe as well as some of the US states. Table 2.2 and 2.3 present some of the identified performance measures (FHWA 2002). It is noted that the scan was conducted in 2003, and there might have been further development to the identified performance measures in the host countries.

Table 2.2: Performance Measures of Some American States (FHWA 2002)

Performance Measure	AL	CA	CO	FL	IN	ME	MI	MO	OH	WI
Alligator Cracking	X	X	X	X		X	X			X
Bleeding/ Flushing	X	X				X	X		X	X
Block Cracking	X	X				X	X			X
Delamination									X	
Disintegrated Areas	X		X	X		X	X			X
Edge Cracking	X	X	X	X				X	X	X
Edge Ravelling										X
Longitudinal Cracking	X	X	X	X	X			X	X	X
Longitudinal Distortion	X									X
Patching						X	X		X	X
Potholes	X		X	X		X	X	X		
Ride Quality	X		X	X	X		X			
Rutting	X	X	X	X	X	X	X	X	X	X
Scabbing	X									
Shoving/ Slippage Area	X		X	X		X				
Skid Resistance	X				X					
Spalling								X		
Surface Ravelling	X	X	X					X	X	X
Transverse Cracking	X	X	X	X	X	X	X	X		X

Note: AL Alabama, CA: California, CO: Colorado, FL Florida, IN Indiana, ME Main, MI Michigan, MO Missouri, OH Ohio, WI Wisconsin

Table 2.3: Performance Measures of some European Countries (FHWA 2002)

Performance Measure	Spain	Germany	Denmark	Sweden	UK
Deterioration (Longitudinal. Transverse and alligator cracking, and potholing	X	X	X	X	X
Durability (Ravelling, joints)	X	X	X	X	X
Friction	X	X	X		X
International Roughness Index	X		X	X	
Transverse profile and drainage of surface water			X		X
Rutting			X	X	X
Instability/ Structural	X		X		X
Crossfall			X	X	
Texture					X

Performance LOS is the targeted level or value to be achieved by contractor for the performance measure. Agencies must take care when developing the performance goals such that the goal is not too high, resulting in high cost, nor too low, resulting in poor quality (Pakkala 2002).

There are different methods suggested by NCHRP Synthesis 389 “Performance Based Contracting for Maintenance” to establish the level of service or goals including the following (NCHRP 2009):

- Base performance goal to that achieved by the In-house staff
- Examine the literature, procurement document and contracting information on performance goals of other agencies; compare to other goals adapted by other provinces, states, and countries
- Conduct benchmarking studies
- Set a scale from 0-100 for each performance measure and set the goal at 80

Regardless of the method used to establish the performance measure and goal, it is important that they are addressed with the contractors in early stages of the contract acquisition, that ensure the measures and goals are realistic and agreeable by potential bidders (NCHRP 2009).

Table 2.4 presents the performance measures and goals for a project in British Columbia. Another example is shown in Table 2.5 for the performance measures and goals specified by some Latin American Countries.

Table 2.4: Performance Measures and LOS for A Trans-Canada Highway Project (NCHRP 2009)

Performance Measure	Performance LOS
Roughness	IRI of 2.28
Rutting mm	Rut depth 20 mm
Surface Distress SDI Index	SDI of 7.9
Potholes	Repaired within 48 hours

Table 2.5: Performance Measures and LOS for Different Latin American Countries (Zietlow 2005)

Performance Measure	Performance LOS
Potholes	No potholes
Roughness (asphalt)	IRI < 2.0 (Argentina), IRI < 2.8 (Uruguay)
Roughness(bituminous)	IRI < 2.9 (Argentina), IRI < 3.4 (Uruguay)
Rutting	< 12mm (Argentina), < 10mm (Uruguay, Chile)
Cracks	Sealed

2.3 Warranty

As indicated earlier in this chapter, one of the greatest advantages to implementing a PBC model is allowing the contractor the freedom to implement innovative material, processes, etc. In some cases, the innovation may result in some undesirable consequences (Ozbek 2004). In order to avoid or mitigate the risk of the undesirable consequences, the concept of warranty is implemented. Warranty is a form of PBC that has been popularly used in in the recent years (Queiroz 1999). During the warranty period, the contractor is responsible for the post-construction risk in addition to that assumed during the construction process. The contractor has to ensure that the constructed infrastructure provides the level of service specified in the contract by the agency within the warranty period (Panthi 2009).

A warranty is defined as a contract that guarantees the integrity of a product and assigns responsibility for the repair or replacement of defects to the Warrantor (Contractor) (FHWA 2003). A warranty is used to specify the desired performance characteristics of a particular product over a specified period of time and to define who is responsible for the product (FHWA 2011). Warranty is classified and defined into four types of warranty specifications, including *prepaid maintenance warranties, workmanship warranties, materials and workmanship warranties, and performance warranties,* (Aschenbrener and DeDios 2001) as follows:

1. The ***prepaid maintenance warranty*** is a typical arrangement where the owner specifies the design, materials to be used, and prescriptive workmanship process. The contractors' responsibilities include the development of an estimate to maintain the pavement in accordance with the owner's construction requirements.

2. The ***workmanship warranty*** requires the contractor to correct any future defects that might arise from poor workmanship. As the owner is responsible for the design, the contractor does not carry any responsibility for defects that are a result of an inadequate design.

3. *A* ***materials and workmanship warranty*** requires the contractor to correct any future defects that result of either defective materials or poor workmanship. The owner is responsible for any future defects related to an inadequate design.

4. A ***performance warranty*** assigns full responsibility for the pavement performance to the contractor during the warranty period as the contractor prepares the design.

Furthermore, FHWA (FHWA 2011) defines **performance warranty** into short term and long term performance warranty.

5***. Short-Term Performance Warranty***

The warranty period for short-term performance warranties generally ranges from 5 years to 10 years depending on the pavement type and the design of the project. These warranties include specific agency pavement performance criteria to be achieved. Project specifications for short-term warranties include the minimum material and construction requirements acceptable to the agency.

Typically for short-term warranties, the agency is responsible for the structural design requirements of the pavement and the contractor is responsible for the mixture design. The agency is responsible for the evaluation of the pavement over the warranty period. Final acceptance of short-term warranty projects is not until the specified warranty period has been completed.

6***. Long-Term Performance Warranty***

The warranty period for long-term performance warranties generally ranges from 10 years to 20 years. For long-term warranties, the contractor has additional responsibility to meet the minimum materials, structural, and mixture design requirements for the pavement. The contractor's Quality Control Plan (QCP) and procedures are used to address the construction details. The agency is responsible for the evaluation of the pavement over the warranty period. Final acceptance of long-term warranties is not until the specified warranty period has been completed.

2.4 Warranty Period

The warranty period is the pre-specified time for the duration of the warranty. It varies based on contract type and the warranty type. Table 2.6 provides an overview of warranty periods for different types of contracts for various European countries. In the United States, warranty types and periods vary for different states. Table 2.7 provides different states' warranty periods, warranty types and specification types (FHWA 2003). General definitions of Traditional Contracts, Design Build and Design Build Operate Finance are provided herein for reference.

Traditional Contract: In traditional contracts, the owner agency specifies techniques, materials, methods, quantities, along with the time period for the contract. Traditional contracts are unit or work order oriented where contractors are paid for the amount of work they do not on the quality of work that is provided (World Bank 2005).

Design Build Contracts: Design build contract is a delivery method whereby the design and construction is under one contract. One contractor, or a team, is responsible for a project in it entity. In design build contracts, the risk is shifted to the private sector since it owns the design details and responsible for all errors and omissions (FHWA 2003).

Design Build Operate Finance (DBOF) Contracts: Design build operate finance is a delivery method in which the contractor, or team, is responsible for completing the design, construction, maintenance, and the finance of the project until the end of the project period (Pakkala 2002).

Table 2.6: Warranty Periods for Various Contracts of Various Countries (FHWA 2003)

Country	Type of Contract	Warranty Period (Years)
Canada (Ontario)	Traditional Design Build Minimum Oversight Pavement with Warranty	1 5 2,3 7
Spain	Traditional Design Build Operate Finance (DBOF)	1 30
Germany	Performance Based Contract	20
Denmark	Performance Based Contract	10
Sweden	Performance Based Contract	5-8
United Kingdom	Traditional Design-Build DBOF	2 5 30

Table 2.7: United States Warranty Types and Periods (FHWA 2003)

State	Warranty Period (Years)	Warranty Type	Specification Type
Minnesota	2	Materials and workmanship	Method
Colorado	3	Materials and workmanship	Method
Florida	3	Materials and workmanship	Method
Illinois	5	Materials and workmanship	Method
Indiana	5	Materials and workmanship	Method
Michigan	5	Materials and workmanship	Method
Ohio	7	Materials and workmanship	Method
Wisconsin	5	Short-term performance	End-Result
Florida (Design-Build)	5	Short-term performance	End-Result
Minnesota (Design-Build)	5	Short-term performance	End-Result
Michigan (Performance)	7	Short-term performance	End-Result

2.5 Performance Monitoring

In PBC, contractors are paid based on the end result achieved not on following the specified method of performing the work. In other words, the contractor is paid based on how well they meet the specified performance measures (NCHRP 2009). Thus, performance monitoring is a major factor in the success of PBC model (Segal et al. 2003). In addition, data collection, or performance monitoring, requires time, effort, money to collect, store, retrieve, and use (World Bank 2006). Therefore, a monitoring system should be carefully developed and implemented for projects under PBCs.

There are different approaches to monitor and evaluate the contract performance measures. One approach is the agency being responsible for monitoring the performance measures periodically. In addition to periodic monitoring, the agency may wish to use a random, unannounced inspection of performance measures (NCHRP 2009).

Another approach, the monitoring could be performed by the contractor. In this case, the agency requires the contractor to present periodic (monthly, annually etc.) reports of the performance measure. The agency also may assure that the monitoring and evaluation of performance is done properly by joining the contractor during data collection as well as scheduling random quality assurance evaluations.

Finally, the monitoring could be performed by an independent third party, which may result in added cost (NCHRP 2009).

2.6 Risk in Performance Based Contracts

In traditional contracting, the agencies prescribe the specifications, materials, construction methods, etc. With this contract method, the contractor is limited to the risk of defining all requirements for the project and eliminating the unknown conditions. Then, the public agency assumes the risk of any failure in the specifications, plans, designs, unexpected or additional work, etc. (Moynihan et al. 2009)

Risk should be the responsibility of the party that can manage it best as acknowledged in the literature (Amos 2004; Queiroz 1999). As mentioned earlier in this chapter, the contractor is free to make the decisions of “what to do”, “when” and “how” as long as the specified performance measures LOSs are achieved. With that, the contractor bares the entire risk of any failure or shortcomings of its decisions (World Bank 2005). The risk of failure could be a result of the contractor error in (i) predicting deterioration of contracted assets; (ii) determining appropriate design, specifications and materials; (iii) planning needed maintenance interventions; and (iv) estimating quantities.

Also, the following types of risks, among others, are identified in the National Cooperative Highway Research Program (NCHRP) synthesis 386 "Performance Based Contracting for Maintenance" (NCHRP 2009):

- Poor quality of construction
- Unexpectedly severe weather
- Unanticipated environmental problems
- Emergencies
- Unanticipated legislative change
- Unexpected traffic growth
- A short-term focus that fails to minimize long-term life-cycle costs
- Difficulty in acquiring the resources needed to perform the work (e.g., subcontractors)
- The possibility of having to correct problems covered under a warranty

As shown in Figure 2.3, as the highway agencies move from traditional contracting to different forms of contracting, its risk decreases while the contractor's risk increases (Queiroz 1999). However, it is worth noting that the allocation of risks in PBC varies from country to country (Segal et al. 2003). The following are some examples:

- In Virginia, USA, the contractor assumes the risk for unpredictable costs, including inflation, escalating material prices, accidents, etc.
- In Argentina PBCs allow for reimbursement of cost overruns in certain circumstances, such as those beyond the control of the contractor (earthquakes, hurricanes and pavement material shortages). The government uses the contractor's

schedule of input prices submitted in the bid as a baseline for overruns estimates. The risk of excessive cost overruns is contained by a 25% cushion on these prices.

- In British Columbia, Canada, and Estonia PBC include an annual price adjustment process that takes into consideration changes in prices indices for labor and fuel.

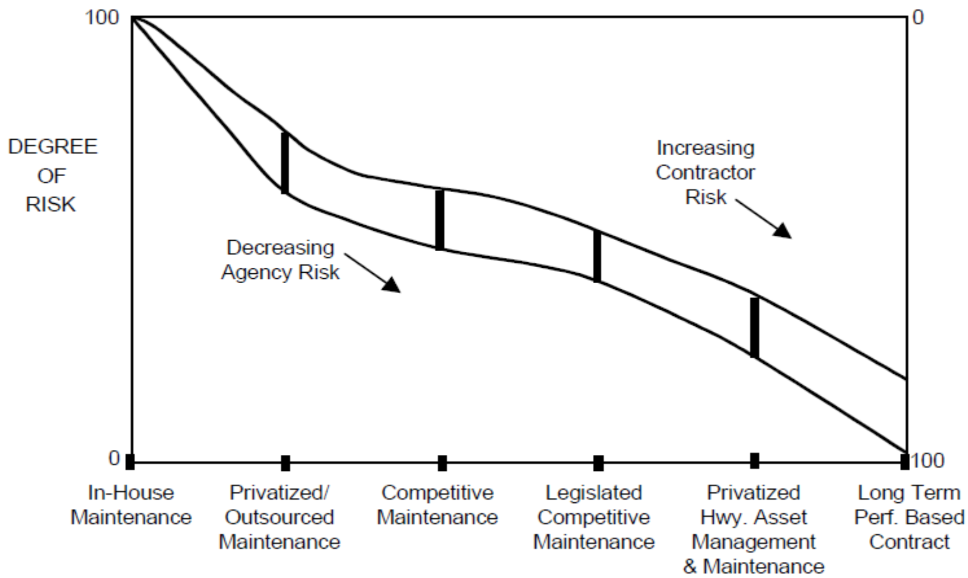

Figure 2.3: Distribution of Risks with Different Contract Approaches (Haas et al. 2001)

2.7 Performance Modeling

Performance modeling is identified to be a high risk area in PBC if not performed properly (Panthi 2009). Therefore, performance modeling is very crucial in terms of establishing the appropriate maintenance activity, and the appropriate time of application to maintain the LOS specified for different performance measures. Figure 2.4 illustrates how performance modeling is used to predict future deterioration of pavement, expected improvements due to application of maintenance or rehabilitation activity and determining the “need year” of application.

Performance modeling is used to predict performance and deterioration of pavements as a function of time, and therefore, predict pavement life. Various types of distress, such as roughness, rutting, cracking, etc., or indexes based on combinations of such distresses, can be used as input for these models (FHWA 2002a).

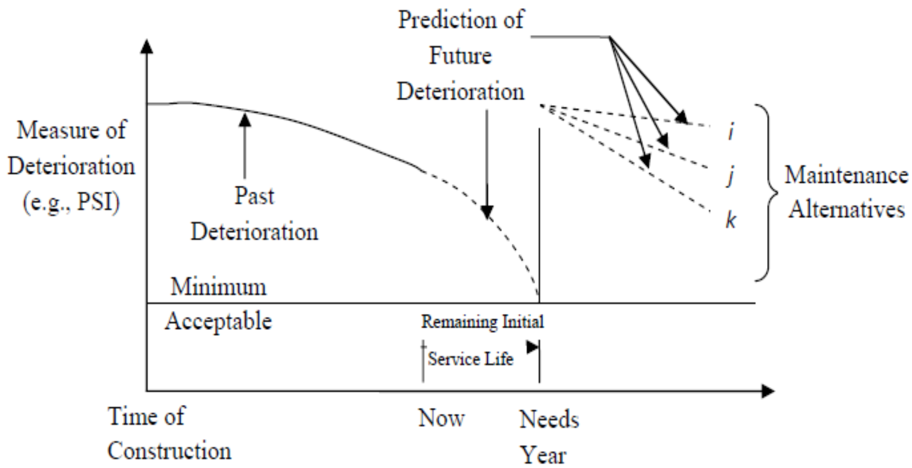

Figure 2.4: Deterioration Modeling and Impact of Maintenance or Rehabilitation Activities on Pavement (FHWA 2002a)

There are various deterioration model proposed in the literature. Based on modeling approach, performance modeling is classified into four groups (Haas et al. 1994; TAC 1997): Mechanistic, Empirical, Mechanistic-Empirical, and Subjective. Table 2.8 summarizes the four types.

Table 2.8: Deterioration Modeling Approaches (Adopted from (Haas et al. 1994; TAC 1997))

Modeling Approach	Description
Mechanistic	Based on some primary response behavior such as stress, strain, etc.
Empirical	Using regression, where the dependent variable of observed or measured structural or functional deterioration is related to one or more independent variables like subgrade strength, axle load applications, pavement layers thicknesses and properties, environmental factors, and their interaction.
Mechanistic-Empirical	Where measured structural or functional deterioration, such as distress or roughness, is related to a response parameter through a transfer function or regression equations
Subjective	Or probabilistic, where experience is “captured” in a formalized or structure way, using semi-Monrovian transition process models, or Bayesian, for example, to develop deterioration prediction models

Deterioration models can be generally classified to two groups according to the techniques they use, including: Deterministic and Probabilistic. (FHWA 2002a; Haas et al. 1994; Li 1997; Li 2005; Mahoney 1990; Morcous 2002; Moynihan et al. 2009). For the deterministic models, a condition is predicted as a precise value on the basis of mathematical function of observed conditions (Robinson and McDonald 1991) and the future condition of a pavement section is predicted as the exact serviceability value or pavement condition index with the past information of the pavement (Durango 2002). On the other hand, the probabilistic models predict the performance of a pavement by giving the probability with which the pavement would fall into a particular condition state (Durango 2002). Most deterministic models in the literature are classified to be mechanistic or empirical and they include primary response, structural performance, functional performance, and damage models (FHWA 2002a; Mahoney 1990). Probabilistic model examples include survival curves and Markov process models are shown in Table 2.9.

Table 2.9: Types of Performance Models (FHWA 2002)

Deterministic Models				**Probabilistic Models**		
Primary Response	Structural	Functional	Damage	Survivor Curve	Transition Process Models	
• Deflection • Stress • Strain • Etc.	• Distress • Pavement Condition	• PSI • Safety • Etc.	• Load Equivalent		Markov	Semi-Markov

Deterministic models are developed using regression, empirical, and combined mechanistic-empirical methods. The selection of a mathematical form to be used for the pavement performance models must fit the observed data and the regression-statistical analysis (Li 1997). A common features among different types of deterministic models is that they are al1 based on a large number of long term observed field data and processed through regression analysis (Li 1997).

On the other hand, most probabilistic models are developed to characterize the uncertain behavior of pavement deterioration processes (Li 2005; Panthi 2009). The Markov model has proved an effective performance modeling tool among various researchers (Butt et al. 1987; Haas et al. 1994; Li 1997; Madanat et al. 1995). The Markov model is commonly used due to its ability to capture the probabilistic behavior of pavement and the time dependent uncertainty deterioration process as well as for different maintenance and rehabilitation activities (Panthi 2009). The model is based on the change of a pavement from a given state to another over a period of time. The Markov model is classified, according to different assumptions, as homogeneous and non-homogeneous. Homogenous Markov model assumes that variables (such as load, traffic, environment, etc.) are constant throughout the analysis period (Li 1997). On the other hand, non-homogenous Markov model considers the rate of change incurred at each different stage. Markov chain models are developed using time-based (estimate the probability of time needed to transition from one state to another) or state-based models (estimate the probability of transition from one state to another in a predetermined period of time). Figure 2.5 illustrate the classification of the Markov model. Further illustration on Markov model is presented in a following chapter. The different types of models along with advantages and disadvantages are presented in Table 2.10.

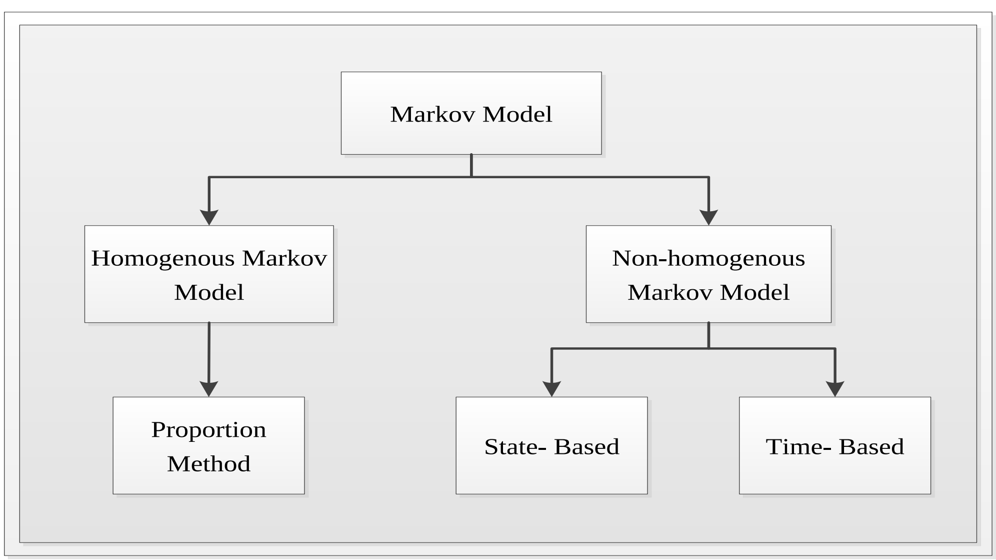

Figure 2.5: Classification of Markov Model

Table 2.10: Advantages and Disadvantages of different Models (Panthi 2009)

Model	Advantages	Disadvantages
Regression	• Microcomputer software packages are now widely available for analysis which makes modeling easy and less time consuming • These models can be easily installed in a PMS • Models take less time and storage to run	• Needs large database for a better model. • Works only within the range of input data • Faulty data sometimes get mixed up and induces poor prediction. Needs data censorship • Selection of proper form is difficult and time taking
Survivor Curve	• Comparatively easy to develop • It is simpler as it gives only the probability of failure corresponding to pavement age	• Considerable error may be expected if small group of units are used
Markov	• Provides a convenient way to incorporate data feedback • reflects performance trends regardless of non- trends	• No ready made software is available • Past performance has no influence • It does not provide guidance on physical factors which contribute to change • Needs large computer storage and time
Semi-Markov	• Can be developed solely on subjective inputs • Needs much less field data • Provides a convenient way to incorporate data feedback • Past performance can be used	• No ready made software is available • Needs large computer storage
Mechanistic	• Prediction is based on cause and- effect relationship, hence gives the best result	• Needs maximum computer power, storage and time • Uses large number of variables (e.g. material properties, environment conditions, geometric elements, loading characteristics etc.) • Predicts only basic material • responses

Model	Advantages	Disadvantages
Mechanistic- empirical	• Primarily based on cause- and- effect relationship, hence its prediction is better • Easy to work with the final empirical model • Needs less computer power and time	• Depends on field data for the development of empirical model • Does not lend itself to subjective inputs • Works within a fixed domain of independent variable • Generally works with large number of input variables (material properties, environment conditions, geometric elements, etc.) which are often not available in a PMS
Bayesian	• Can be developed from past experience and limited field data • Simpler than Markov and • Semi-Markov models • Can be suitably enhanced using feedback data	• May not consider mechanistic behavior • Improper judgment can lead to erroneous model

2.8 Selection of Maintenance and Rehabilitation and Optimization

Selection of maintenance and rehabilitation alternatives can be based on engineering judgment, local experience or agencies policies (TAC 1997). In pavement management systems, priority programing involves four steps: Integrating information, identification of needs, priority analysis, and output reports. Various priority programming methods are established ranging from simple to more complex mathematical programming (Haas et al. 1994). Table 2.11 indicates the different classes of methods and some advantages and disadvantages.

The analysis of the feasibility of different rehabilitation and maintenance activities involves three major elements:

- Selection of alternatives that are feasible which depends on various factors such as the condition, geometric constrains, type of pavement, etc.
- Prediction of deterioration of the feasible treatments
- Identifying associated cost, or cost benefit analysis, cost effectiveness, etc.

Deterioration modeling as a means of studying the feasibility of different maintenance and rehabilitation activities gained some attention among agencies and researchers (Haas et al. 1994; Li 2005; Panthi 2009; TAC 1997).

Optimization is a branch of mathematics concerned with finding the optimum alternative to complex problems in accordance with established objectives and constraints (Thompson 1994). The optimization method is used to select alternatives to satisfy a specific objective function that is subject to certain constrains. The formulation of these models varies from optimization and dynamic optimization (Haas et al. 1994).

Table 2.11: Classes of Priority Programming Methods (Haas et al. 1994)

Class of Method	Advantages and Disadvantages
Simple subjective ranking of projects based on judgment	Quick, simple; subject to bias and inconsistency; may be far from optimal
Ranking based on parameters, such as serviceability, deflection, etc.	Simple and easy to use; maybe far from optimal
Ranking based on parameters with economic analysis	Reasonably simple; should be closer to optimal
Optimization by mathematical programming model for year-by-year basis	Less simple; maybe close to optimal, effects of timing is not considered
Near optimization using heuristic and marginal cost-effectiveness	Reasonably simple; can be used in a microcomputer environment, close to optimal results
Comprehensive optimization by mathematical programming model taking into account the effects	Most complex; can give optimal program (max. of benefits)

2.9 Summary and Conclusions

PBC differ significantly from the traditional method-based contracts. The main aspect of the PBC is that contractors are paid based on the end result achieved not on following the specified method of performing the work. Therefore, the contractor is paid based on how well they meet the specified performance measures. Because of that, PBC encourages contractor innovation and quality which in turn creates opportunities for value engineering and improved efficiencies. Agencies that have implemented performance based contracts claim cost saving between 10-50%.

In the PBC, performance modeling is a very complex task. Moreover, pavement deterioration follows a stochastic behavior, and the deterioration process and the improvement due to maintenance and rehabilitation activities varies based on many factors such as environment, loading, and data used for the modeling, which result in a risk to the contractor in such a contract model.

The risk of failure could be a result of the contractor error in (i) predicting deterioration of contracted assets; (ii) determining appropriate design, specifications and materials; (iii) planning needed maintenance interventions; and (iv) estimating quantities. Therefore, there is a need to develop a framework to facilitate the selection of an effective maintenance and rehabilitation program that takes into account those possible causes of risk.

Chapter 3
Two-Phase Maintenance and Rehabilitation Framework

3.1 Introduction

In long term warranty contracts, such as PBC, the development of maintenance and rehabilitation activities is a complex task. Performance modeling is very crucial to establish appropriate and effective maintenance activity that maintains the specified performance measures' LOS for the intended period. On the other hand, pavement deterioration follows a stochastic behavior, and the deterioration process and the improvement due to maintenance and rehabilitation activities varies based on many factors such as environment, loading, and the data used for the modeling, which result in a risk to the contractor in such contract models. The risk of failure in achieving specified level of services could be a result of the contractor error in (i) predicting deterioration of contracted assets; (ii) determining appropriate design, specifications and materials; (iii) planning needed maintenance interventions; and (iv) estimating quantities.

This chapter provides an overview of the proposed two-phase maintenance and rehabilitation framework. The framework consists of two phases and the implementation process of the two phases of the framework is illustrated in Figure 3.1. Phase-One of the framework is named Initial Program, while Phase-Two is named Project Asset Management Phase.

The Initial Program phase uses historical data, performance modeling, and optimization to establish and select the maintenance and rehabilitation program for the bidding stage. On the other hand, the Project Asset Management phase is implemented after the contract is awarded. This phase uses the contract performance monitoring data and the cost estimate from Phase-One as a baseline budget to update and validate the established program through performance modeling and optimization. Explanation of each phase and its components is presented in the following sections.

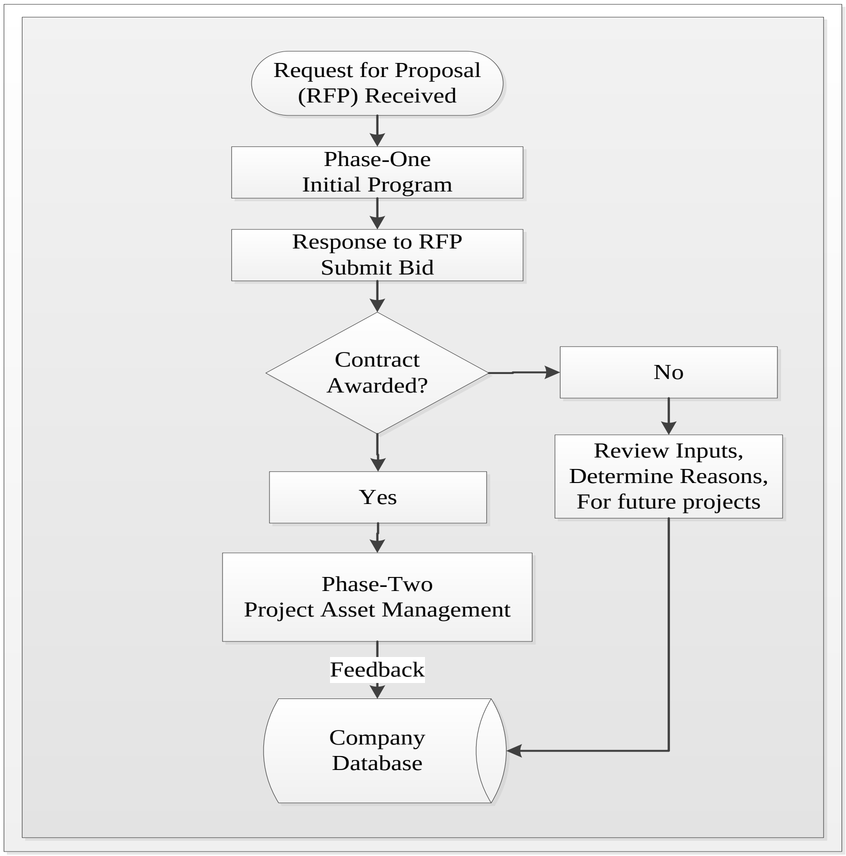

Figure 3.1: Two-Phase Framework Overview

3.2 Phase-One: Initial Program

Phase-One, the Initial Program, is intended to develop a maintenance and rehabilitation program for the bidding stage, which ultimately results in an estimate of the overall cost of the project. Figure 3.2 shows the overview of the framework. The inputs of the framework include the contract performance specifications, contract warranty and period, maintenance and rehabilitation deterioration models, resultant improvements and costs, and the pavement data. Pavement data includes the current performance condition, historical performance, pavement information such as traffic, thickness, material, etc. The inputs are fed to an optimization model that results in a prioritized maintenance and rehabilitation program. Each of the framework components are discussed in the following sections. This phase is beneficial to the contractor to establish the optimum maintenance and rehabilitation program with the lowest cost to maintain the specified performance measures level of service along the contract period. In addition, during the bidding stage, agencies shall prepare preliminary estimates for asset to be contracted out under a PBC (World Bank 2005). The objective is to obtain a benchmark price for the contract against which bids will be compared during the bids evaluation process (World Bank 2005). This phase can be used by agencies to achieve this objective.

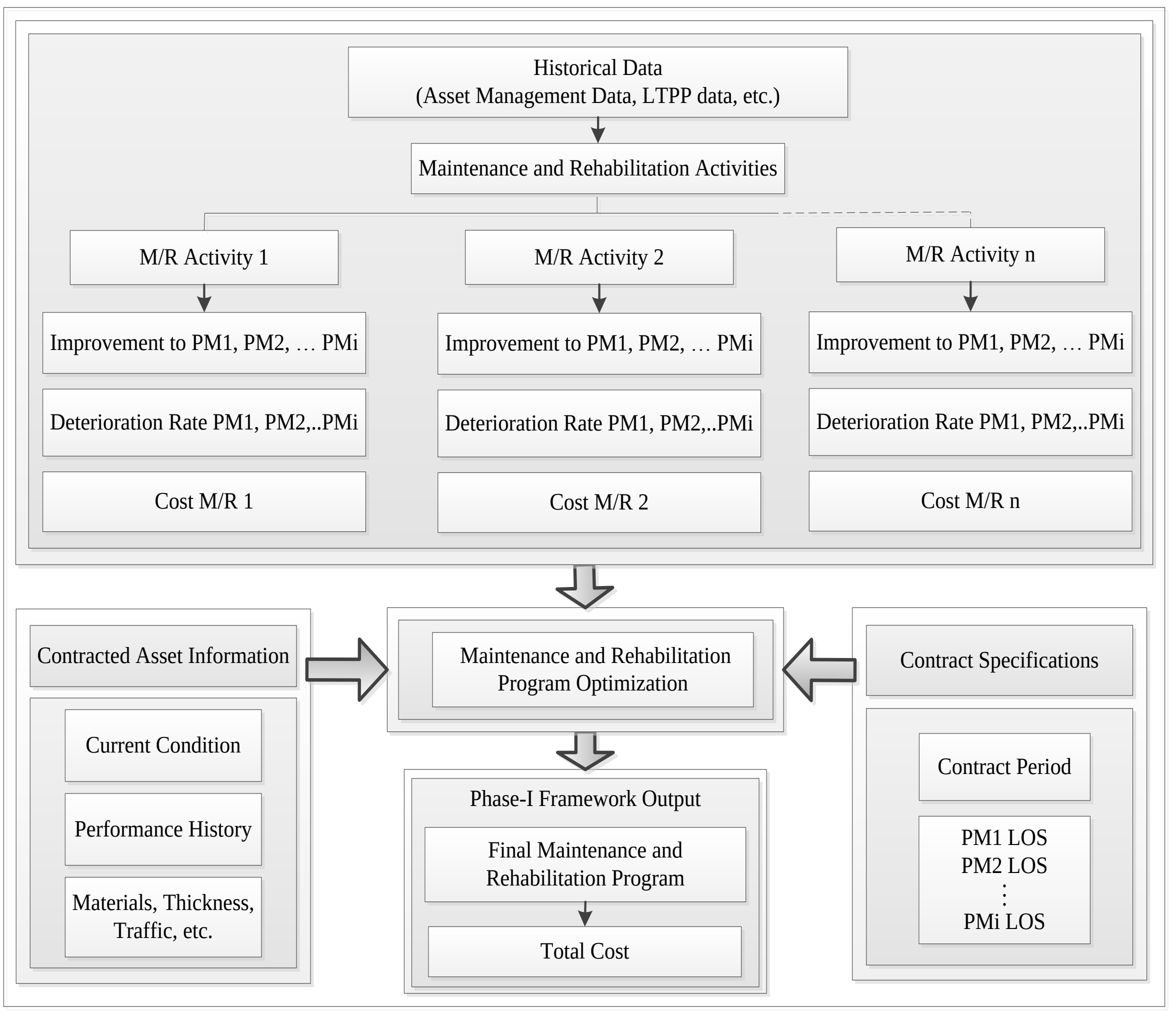

Figure 3.2: Initial Program Framework

3.2.1 Initial Program Inputs

3.2.1.1 Contract Specifications

As mentioned earlier, PBCs differ significantly from traditional method-based contracts. In PBCs, the client agency specifies minimum performance measures to be met or exceeded along the contract period. As such, the development of maintenance and rehabilitation programs is subject to the specified performance measures and the associated level of service as well as the contract period.

3.2.1.2 Pavement Data

The pavement data component is very important in developing an effective maintenance and rehabilitation program for many reasons. First, identifying appropriate maintenance and rehabilitation alternatives rely on pavement information such as thickness, current condition, traffic, etc. The pavement data should include the following:

- Pavement current condition
- Pavement historical performance
- Pavement material
- Pavement thickness
- Soil type
- Traffic information
- Pavement geometry
- Environmental Data
- Construction and maintenance history

Good quality pavement data is important for identifying feasible maintenance and rehabilitation activities and also in establishing deterioration rates and improvements of these activities. Further illustration of the needs of such data is discussed in the deterioration modeling section.

3.2.1.3 Maintenance and Rehabilitation Activities

To evaluate feasible maintenance and rehabilitation alternatives and the impact on the pavement performance, deterioration modeling is needed. As indicated earlier, performance modeling is very crucial in terms of establishing the appropriate maintenance activity, and the appropriate time of application to maintain the LOS specified for different performance measures.

To construct deterioration models and the associated improvements, pavement data as noted earlier is needed. The data source can be a challenge; however, most agencies have a pavement management system in place with a wide range of data. For example, the Ministry of Transportation Ontario (MTO) implements a pavement management system that was developed in 1985 (Kazmierowski et al. 2001). In addition, some countries maintain pavement performance data base program, such as Long Term Pavement Performance (LTPP) program developed by Federal Highway Administration (FHWA), which is an excellent source of data for pavements in Canada and USA (LTPP 2012).

It is imperative to obtain the necessary data to construct accurate deterioration models. To do so, homogenous sections with the same characteristics, such as material, thickness range, soil type, traffic, and weather condition are to be identified and the performance of such sections is analyzed. Also, the performance of various maintenance and rehabilitation treatments applied to these homogenous sections can be evaluated. An example of establishing maintenance and rehabilitation alternatives and associated deterioration rate is shown in Table 3.1. In this example, using the MTO PMS2, pavement sections with the same influence factors including pavement type, soil type, traffic range, and environmental conditions were analyzed. Deterioration models of the overall performance condition index (a function of various performance measures) for various alternatives were modeled using the Regression model as shown in the Table 3.1. However, for PBC, the performance modeling will be applicable for the various specified performance measures, such as roughness, rutting, cracking, etc.

Table 3.1: Deterioration Modeling Example (Hamdi et al. 2012)

No.	Treatment	Model	R^2
1	Hot Mix Overlay 1 Lift (45mm)	PCI=0.062*Age^2-3.39*Age+91.86	0.81
3	Mill and Hot Mix Overlay 1 Lift (45mm)	PCI= -0.032*Age^2-1.173*Age+83.35	0.62
5	Full Depth Reclamation (FDR) and Hot Mix Overlay 2 Lift (45 mm)	PCI= -0.023*Age^2-1.686*Age+94.27	0.72

Where: PCI =Pavement Condition Index (0-100); Age= Age of Pavement (years)

In addition, when a maintenance or rehabilitation activity is applied to a pavement section, the pavement condition is improved as a result, depending on the activity applied. Since the purpose of developing a maintenance and rehabilitation program is to maintain the pavement asset at a specified LOS for various performance measures, the improvement of each performance measure due to the application of a maintenance or a rehabilitation activity is important and should be determined.

3.2.2 Initial Program Process

3.2.2.1 Maintenance and Rehabilitation Program Development and Optimization

In traditional asset management, budget constraints dictate establishing priority programming of various maintenance and rehabilitation activities. In other words, with the available budget, the managers and engineers determine how much work can be carried out. Different methods were established to develop priority programs as discussed earlier in section 2.8 of this thesis. However, to establish a maintenance and rehabilitation program for a pavement asset under PBC, the question is different: How much will it cost to maintain the specified performance measures levels of service for the period of the contract.

To successfully develop the program and also increase the probability of wining the bid of the potential contract, another objective is added to the latter question. The objective is to minimize the total cost required to maintain the specified LOS over the contract period. To set up the optimization problem, an objective function is constructed by summing the total present worth of the applied maintenance and rehabilitation activities (TMRC) applied throughout the contract period (Equation 3.1).

$$\text{Minimize TMRC} = \sum_{i=1}^{n} \sum_{y=0}^{Y} X_{iy} \times C_{iy} \qquad \text{Equation 3.1}$$

Such that;

$$X_{iy} = \begin{cases} 1 & \text{if treatment (i) is applied at year (y)} \\ 0 & \text{Otherwise} \end{cases}$$

Where X_{iy} = Maintenance or Rehabilitation activity i (of "n" total activities) applied at year y (of the Y years of the contract period), C_{iy} =Present worth cost of maintenance or rehabilitation activity i applied at year y (of the Y years of the contract period).

In addition to the objective function, the optimization model should accounts for the constraint of the contract specified performance measures' LOS. In other words, the performance of each specified performance measure should satisfy the specified performance measures' LOS:

$$P_{jiy} \geq PM_j \text{ for all } PM_j \in \{PM_1, PM_2, \ldots, PM_j\} \qquad \text{Equation 3.2}$$

P_{ji} = Performance condition of Performance Measure (PM) j at year y as a result of latest maintenance or rehabilitation activity i applied, PM_j= specified level of service (LOS) of Performance Measure j.

Once the objective function, constraints, and variables are defined, the optimization model is formulated and the optimization method is determined.

3.2.3 Initial Program Output

For a pavement asset under PBC, utilizing the proposed Initial Program framework will result in a maintenance and rehabilitation program with the associated costs, which is then used in the final bid. Figure 3.3 shows a conceptual output of the Initial Program phase presenting a summary of the maintenance and rehabilitation program along with performance models for hypothetical performance measures A, and B.

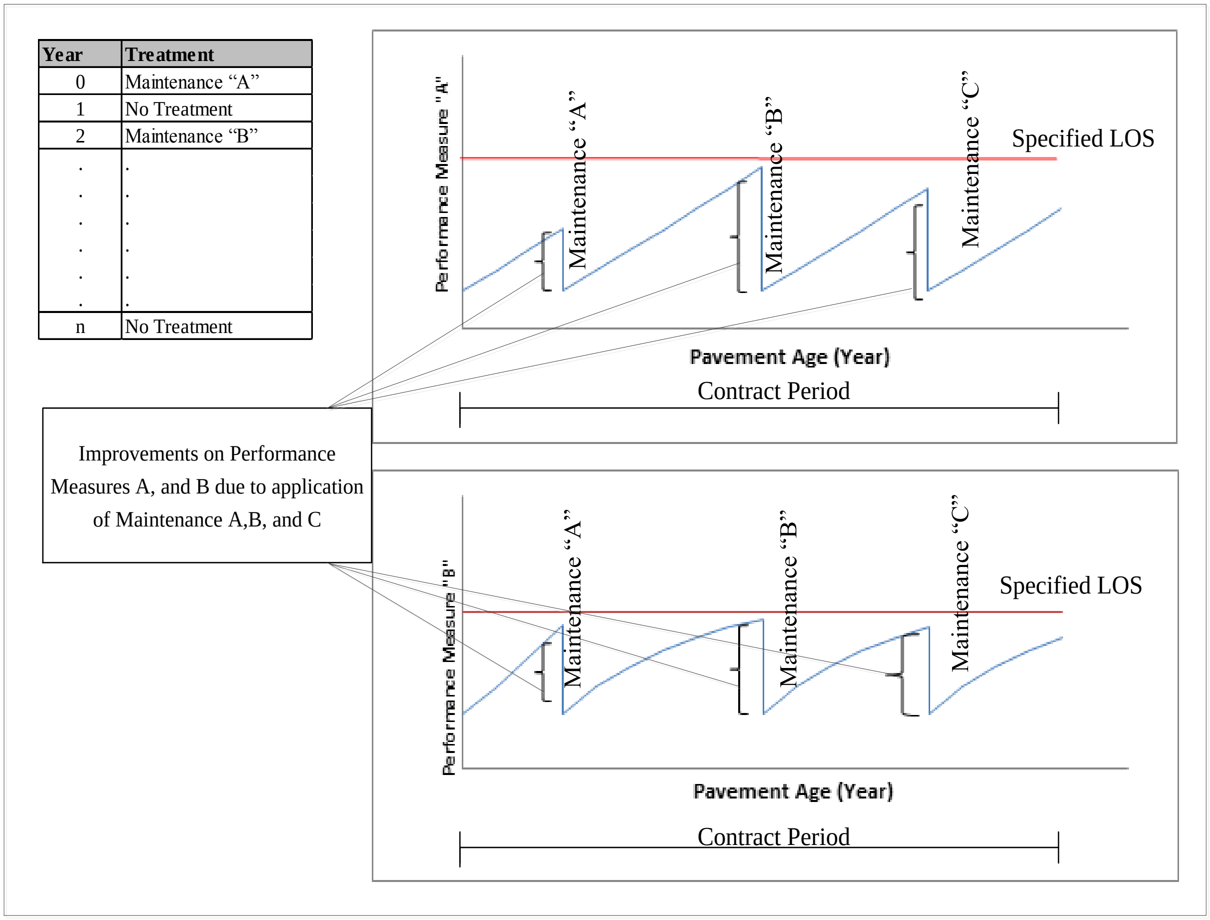

Figure 3.3: Initial Program Output Example

3.3 Phase-Two: Project Asset Management

PBC tenure typically ranges from 3-10 years and could be extended to 30 years due to the nature of periodic maintenance and rehabilitation (McCullouch et al. 2009). In addition, pavement deterioration follows a stochastic behavior, and the deterioration process and the improvement due to maintenance and rehabilitation activities varies based on many factors such as environment, traffic loading, material properties, and data used for the modeling, which result in a risk to the contractor in such contract models. Phase-Two, Project Asset Management, is developed to validate the deterioration models using the real time data from the monitoring process, and to re-optimize the maintenance and rehabilitation program with the constraint of “new budget”. The budget constraint is the remaining of the total cost estimated from the Initial Program phase. Figure 3.4 shows the overview of the framework. Explanation of the framework components is presented in the following sub-sections.

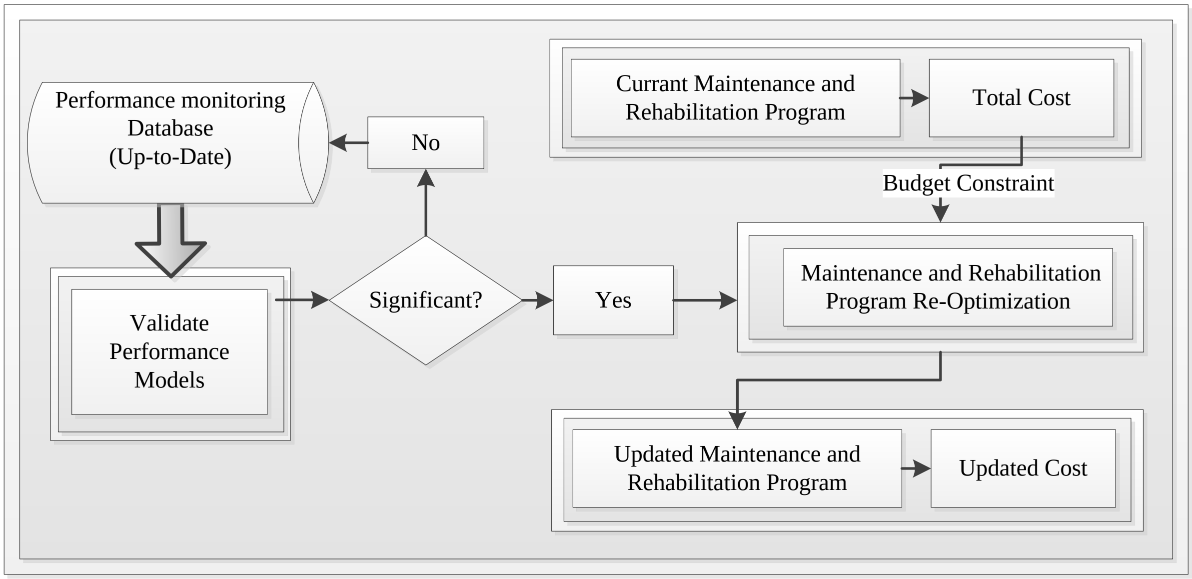

Figure 3.4: Project Asset Management Overview

The idea of this framework is similar to the concept of implementing a Pavement Management System (PMS) where agencies have a set budget, and determined needs to be prioritized. However, in this case, the contractor has a set budget from that submitted in the bid, and the constraints of meeting the specified level of services of various performance measures over the remaining of the contract period. The significance of this phase is to mitigate the contractor risk of failing to meet the specified performance measures level of service along the contract period by validating the deterioration models using the performance monitoring data and optimization. In addition, the Project Asset Management phase may result in contractor cost saving due to re-optimization of the maintenance and rehabilitation program using the performance monitoring data and continuous validation of deterioration models.

3.3.1 Project Asset Management Input

3.3.1.1 Budget

The cost submitted in the bid, based on the results from the Initial Program phase, is set as the budget available for the Project Asset Management phase of the framework. The budget is used as a constraint in the optimization process similar to that presented in the Initial Program phase. Since this framework is implemented at various points of the contract life cycle, at which some maintenance and rehabilitation work may have been performed, the budget constraint is defined as the amount of money remaining to date of the total cost submitted.

3.3.1.2 Performance Monitoring Data

In PBCs, the contractors receive payments based on meeting the specified performance measures level of service (NCHRP 2009). As such, performance monitoring is a major component of the contract. The performance monitoring is done periodically, and performed by the contractor, the agency, or a third party (NCHRP 2009). The performance data collected are checked against the specified level of services as basis of payment to the contractor.

The performance data is a good indicator of the improvement and the deterioration rate of the pavement due to the application of maintenance or rehabilitation activity. The data can be used to validate the deterioration models established in Initial Program phase framework. If the data obtained shows a significant difference to that of the deterioration models constructed using historical data, validation of deterioration model is to be is performed.

3.3.2 Project Asset Management Process

3.3.2.1 Performance Model Validation

The effectiveness of maintenance or rehabilitation activity depends on the accuracy of the deterioration model to predict the improvement and future performance. If the historical data is not sufficient or accurate, the planned maintenance or rehabilitation activity could be far from optimal (Durango and Madanat 2002). In addition, Performance deterioration is of stochastic nature, and uncertainty is present (Madanat et al. 1995).

Based on the deterioration model obtained from the historical data and the performance monitoring data, three scenarios are possible. The performance model is accurate, the performance model underestimates the deterioration rate or it overestimates the deterioration rate. Figure 3.5 illustrate the possible scenarios.

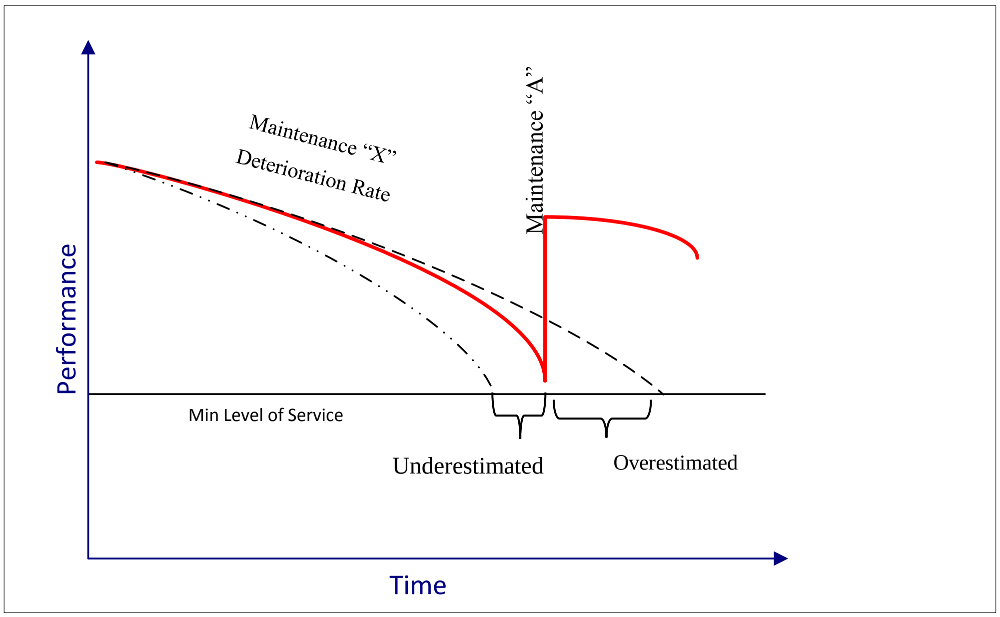

Figure 3.5: Performance Model Variation Scenarios

3.3.2.2 Maintenance and Rehabilitation Program Re-optimization

As a result of the variation of the actual performance compared to that of the predicted from the deterioration models, re-optimization of the program may be necessary. In the case of over estimating the deterioration rate, maintenance or a rehabilitation activity may be scheduled earlier than needed. Therefore, adjustment of the maintenance and rehabilitation program may result in a cost saving and ultimately higher profit to the contractor. Alternatively, underestimating the deterioration rate may subject the contractor to a risk of reaching the specified level of service earlier than anticipated. Therefore, re-programing of the scheduled maintenance or rehabilitation activity is obligatory to avoid any penalties.

The re-optimization is a challenging process due to many reasons. First, the nature of PBC dictates that all performance measures' deterioration models are evaluated as the payment is made as a result of compliance on meeting all the specified performance measures' LOS. In addition, the cost estimate submitted as a result of "Initial Program" framework is fixed. Therefore, the objective now is to maintain the specified performance measures' LOS for the remaining period of the contract with the remaining "budget" up to date. Therefore, the constructed objective function is as follows:

$$\text{Minimize TMRC}=\sum_{i=1}^{n}\sum_{y=m}^{Y} X_{iy}\times C_{iy} \qquad \text{Equation 3.3}$$

Such that;

$$X_{iy}=\begin{cases}1 & \text{if treatment (i) is applied at year (y)}\\ 0 & \text{Otherwise}\end{cases}$$

Where X_{iy} = Maintenance or Rehabilitation activity i (of "n" total activities) applied at year y (of the Y years of the contract period), C_{iy} =Present worth cost of maintenance or rehabilitation activity i applied at year y (of the Y years of the contract period), m= the year at which the re-optimization is applied.

In addition to the objective function, the optimization model should accounts for the constraint of the contract specified performance measures' LOS similar to that presented in Equation 3.2. Moreover, the optimization model should count for the constraint of the remaining budget to date from that submitted in the bid as follows:

$$\sum_{i=1}^{n}\sum_{y=m}^{Y} X_{iy}\times C_{iy} \leq \text{Remaining budget to date} \qquad \text{Equation 3.4}$$

3.3.3 Project Asset Management Output

After a given set of periodic performance monitoring data that shows a significant difference to that of predicted using historical data, the Project Asset Management phase is followed and a new maintenance and rehabilitation program is generated as an output. The output of the project Asset Management phase is similar to that of the Initial Program phase. However, the maintenance and rehabilitation program starts at some point during the contract period. At this point, a re-optimization would be necessary. The Project Asset Management phase is applied at every performance monitoring data cycle. Therefore, different outputs maybe generated throughout the life cycle of the project. Figure 3.8 shows a potential conceptual output of the framework.

Year	Treatment	Re-optimized
0	Maintenance “X”	Maintenance “X”
1	No Treatment	No Treatment
2	Maintenance “A”	No Treatment
3	No Treatment	Maintenance “A”
.	.	.
.	.	.
.	.	.
.	.	.
.	.	.
n	No Treatment	No Treatment

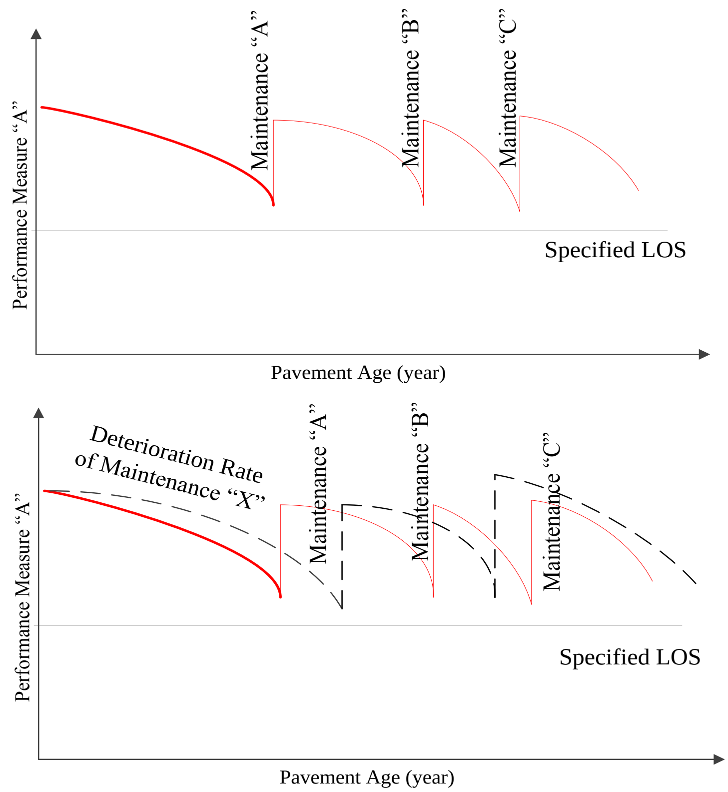

Figure 3.6: Project Asset Management Output Example

As shown in Figure 3.8, the solid line indicates the performance curve for performance measure “A” of the maintenance program; however, the dashed line shows the re-optimized program due to adjustment to the deterioration rate of maintenance “X”.

3.4 Summary and Conclusions

The proposed framework consists of two phases. Phase-One named Initial Program uses historical data, performance modeling, and optimization to establish and select the maintenance and rehabilitation program for the bidding stage. The significance of this phase is for the contractor to establish the optimum maintenance and rehabilitation program with the lowest case to maintain the specified performance measures along the contract period which increases the chances of winning the bid. This phase also can be used by agencies to establish preliminary cost estimate for benchmarking purposes prior to contract awarding.

Phase-Two, Project Asset Management, is implemented after the contract is awarded. This phase uses the contract performance monitoring data and the cost estimate from Phase-One as a baseline budget to update and validate the established program through performance modeling and optimization. The significance of the phase is to mitigate the contractor risk of failing to meet the specified performance measures level of service along the contract period by validating the deterioration models using the performance monitoring data and optimization. In addition, the Project Asset Management phase may result in contractor cost saving due to re-optimization of the maintenance and rehabilitation program using the performance monitoring data.

Chapter 4

Implementation of Framework Case Study: Highway 7

4.1 Introduction

In order to demonstrate the application of the proposed framework, a hypothetical case study of Highway 7 is developed. The case study uses data from the MTO PMS2. The performance measures selected for this case study include roughness and rutting as they are widely used in PBCs as illustrated in Chapter 2 of this thesis. In addition, sufficient data is available for the selected performance measures in the PMS2. The specification on the performance measures were developed based on typical values found in the literature. Although the case study was developed for two performance measures, the framework can be extended to any number of performance measures and level of services. Maintenance and rehabilitation activities and their associated deterioration rates were developed using PMS2 data. Estimates of cost of these maintenance and rehabilitation activities were obtained from MTO for the purpose of this study. A discount rate of 5% was chosen.

4.2 Project Description

Highway 7 is located between Kitchener and Guelph in the province of Ontario. It is a total length of approximately ten km as shown in Figure 4.1. Highway 7 is a typical two-lane rural highway with signalized and unsignalized intersections. The land use adjacent to the highway ranges from commercial and industrial within the urban border to mainly agricultural with some commercial land uses along the rural section.

This highway was chosen for this case study as it represents typical two-lane highways in Ontario, and in Canada in general. In addition, the highway is heavily trafficked which results in higher probability of deterioration and as a result in higher need for maintenance and rehabilitation.

A PBC period of ten years or more has proven to be effective for sustained preservation of pavement network (Haas et al. 2008). Therefore, a contract period of ten years is chosen for this case study.

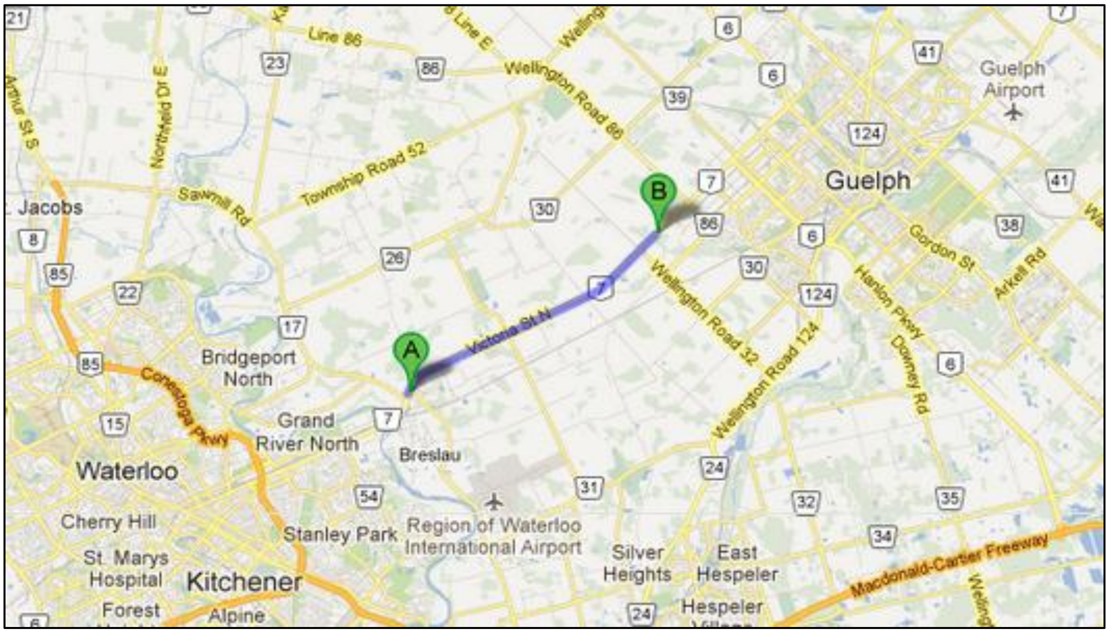

Figure 4.1: Highway 7 Site View (Google Maps 2012)

For the purpose of this case study, roughness and rutting are selected as specified performance measures. Roughness and rutting are widely used in PBCs and the PMS2 contains the historical data for these performance measures. Although only two performance measures are used in this case study, the framework can be extended for any number of performance measures. Based on the literature review presented in Chapter 2, the performance specifications identified for this case study are presented in Table 4.1

Table 4.1: Performance Specification

Performance Measure	Specification
Roughness (IRI)	< 2 m/km
Rutting	< 12 mm

Using MTO PMS2 data, highway 7 performance history was evaluated. The highway roughness and rutting performance are shown in Figure 4.2 and Figure 4.3, respectively.

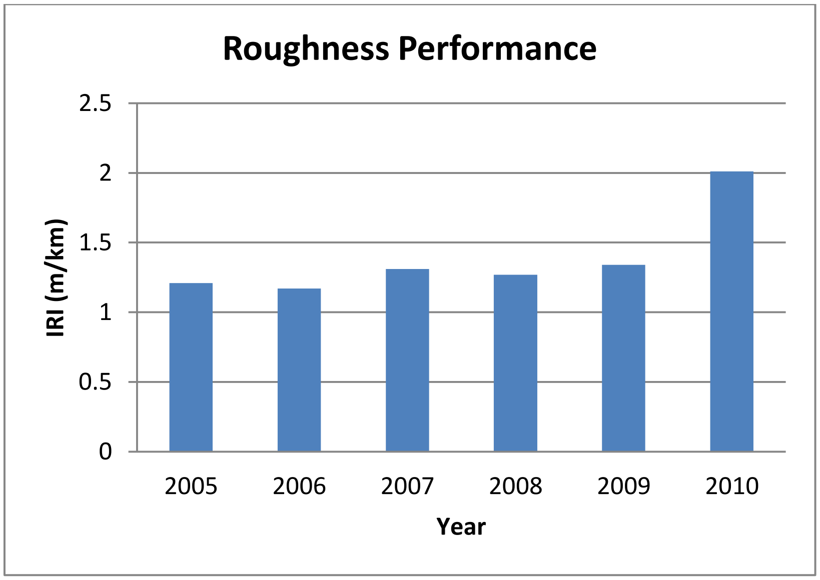

Figure 4.2: Highway 7 Roughness Historical Performance

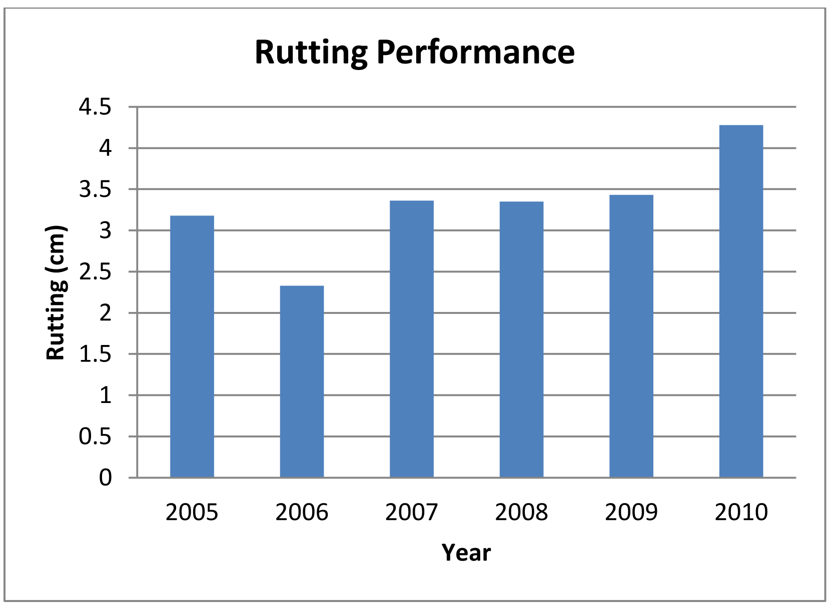

Figure 4.3: Highway 7 Rutting Historical Performance

As noted from Figures, the roughness and rutting values are relatively high. Due to the high traffic volume and the location of this highway connecting the two cities as well as the high roughness and rutting condition, this highway is a good candidate for this study.

Roughness is defined as “the deviation of a surface from a true planar surface with characteristics dimensions that affect vehicle dynamics and ride quality” (TAC 2012). Roughness measurements can be used to measure the serviceability of the pavement and directly relate to the vehicle operating cost (TAC 2012). The quality indicator generally used for ride quality is the International Roughness Index (IRI). Roughness is the direct interaction between pavement, vehicle, and road users and therefore a very important performance measure.

Rutting is defined as longitudinal depression, which can take the form of a single rut or double ruts, left in the wheel tracks after repeated load applications. It results from densification and permanent deformation under load, combined with displacement of pavement materials. Deep ruts are often accompanied by longitudinal cracking in the wheel tracks (MTO 1989). Rutting can pose a safety concern and ride discomfort as it affects the handling characteristics of a vehicle (TAC 2012). Rutting therefore is a key performance measure to be employed for PBC.

Rutting is measured by profilers that use a sensor that records the elevation of the sensor elevation relative to the pavement surface. There are four technologies used to estimate the rut depths including Ultrasonic, Point Lasers, Scanning Lasers, and Optical Imaging (World Bank 2006).

4.3 MTO Pavement Management System

The MTO’s PMS2 obtained for this study contains data collected from 1990 to 2010. The data base includes 870 sections with data classified as historical data and survey data. The historical data includes: Climatic Zone (Northern and Southern), Equivalent Thickness, Subgrade Soil Type, Pavement Type as well as the maintenance and rehabilitation activities applied throughout pavement life cycle. On the other hand, survey data includes: Annual Average Daily Traffic (AADT), Truck Percentage, Equivalent Single Axel Load (ESALs), Roughness (IRI m/km), Rutting (cm), Pavement Condition Index (PCI), and Distress Manifestation Index (DMI). Table 4.2 shows a sample of the PMS2 data used in this study.

Table 4.2: PMS2 Sample Data

func_ class	Sec #	year	IRI	rut_ depth	Esals	length	Year r/m	r/m act	subgrad e	Pave type	enviro n	surfthi ck
FWY	1	2003	1.18	5.31	938155	4.428	1996	114	Sandy si	AC	SO	123
FWY	1	2002	1.23	4.27	976979	4.428	1996	114	Sandy si	AC	SO	123
FWY	1	1999	1.08	0	982315	4.428	1996	114	Sandy si	AC	SO	123
FWY	1	2000	1.17	0	1013832	4.428	1996	114	Sandy si	AC	SO	123
.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.
FWY	41	2010	0.72	6.26	2204256	7.329	2004	112	Sandy si	AC	SO	92
FWY	41	2009	0.72	6.08	2204256	7.329	2004	112	Sandy si	AC	SO	92
FWY	41	2008	0.72	6.25	2273735	7.329	2004	112	Sandy si	AC	SO	92
FWY	41	2007	0.85	3.69	2567628	7.329	2004	112	Sandy si	AC	SO	92

Where: func_class= Function Class, Sec# =Section Number, year= year of data collection, Esals= Equivelant Single Axel Load, year r/m= year of application of maintenance or rehabilitation activity, pave type= Pavement Type, envi= Environmental Zone, surfthick= Surface Thickness

4.4 Development of Maintenance and Rehabilitation Deterioration Models

Performance modeling is very crucial in terms of establishing the appropriate maintenance activity, and the appropriate time of application to maintain the specified level of services for different performance measures. As discussed earlier, performance models are classified as deterministic or probabilistic. Probabilistic models predict the performance of a pavement by giving the probability with which the pavement would fall into a particular condition state (Durango 2002). Probabilistic models are developed to characterize the uncertain behavior of pavement deterioration processes (Li 2005; Panthi 2009). The Markov model has proved to be an effective performance modeling tool among various researchers (Butt et al. 1987; Haas et al. 1994; Li 1997; Madanat et al. 1995; Tighe 1997). The Markov model is commonly used due to its ability to capture the probabilistic behavior of pavement and the time dependent uncertainty deterioration process as well as for different maintenance and rehabilitation activities (Panthi 2009). The model is based on the change of a pavement from a given state to another over a period of time. As such, Markov models are developed using Transition Probability Matrix (TPM). In order to develop the Markov models, the following steps are followed:

- Data screening and evaluation
- Identifying homogenous pavement section groups
- Developing TPM

4.4.1 Data Analysis

The pavement deterioration process is affected by many factors such as environment, loading, and material. To construct accurate deterioration models for maintenance and rehabilitation activities, homogeneous pavement sections should be identified. The MTO's PMS2 was evaluated to identify influence factors and develop homogeneous sections for the purpose of developing deterioration models of various maintenance and rehabilitation activities. The influence factors and the corresponding levels presented in Table 4.3 are identified.

Table 4.3: Pavement Deterioration Influence Factors and Corresponding Levels

Influence Factor	Corresponding Levels
Pavement Type	Asphalt Cement (AC) Portland Cement (PC) Composite (CO) Surface Treated (ST)
ESALs	Low (<50,000) Medium (50,000- 500,000) High (>500,000)
Subgrade Material	Sandy Silt Granular Lacustrine Clay Vared Clay
Climatic Zone	Southern Zone Northern Zone
Surface Thickness (mm)	Low (< 100 Medium (100-150) High (>150

Based on the influence factors and the corresponding levels presented in Table 4.3, homogenous sections are formed. An example of such sections is as follow: Pavement sections with AC pavement type on a sandy silt subgrade with ESAL value under 50,000 and surface thickness under 100 located in a southern climatic zone. The MTO PMS2 data base was utilized to obtain highway 7 characteristics as presented in Table 4.4.

Table 4.4: Highway 7 Pavement Characteristics

Pavement Type	Asphalt Pavement
ESALs	426419
Soil Type	Sandy Silt
Environmental Zone	Southern
Surface Thickness	125 mm
Roughness (m/km) (2010)	2.01
Rutting (cm) (2010)	4.28

Based on highway 7 pavement characteristics, sections with similar influence factors were obtained from PMS2 data for the analysis and modeling deterioration rates for maintenance and rehabilitation activities. Highway 7 falls in the pavement homogenous sections group with the influence factors presented in Table 4.5.

Table 4.5: Influence factors for Highway 7

Influence Factor	Corresponding Level	Total number of sections
Pavement Type	Asphalt Cement (AC)	248
ESALs	Medium (50,000- 500,000)	
Subgrade Material	Sandy Silt	
Climatic Zone	Southern Zone	
Surface Thickness (mm)	Medium (100-150)	

Four maintenance activities are identified for this study. Table 4.6 presents a summary of the maintenance activities as well as the number of pavement sections in the analysed pavement homogenous group that received one of the maintenance activities used in this case study, and the associated cost as provided by MTO (Li 2012). Each pavement section performance history for roughness and rutting since the maintenance activity was applied is used to construct the Markov deterioration models.

Table 4.6: Maintenance Activities and Cost

Activity Code	Activity Description	Cost $/m^2	Number of Sections
101	Hot Mix Overlay one lift (45mm)	19.49	17
103	Hot Mix Overlay two lifts (45 mm)	27.85	9
102	Mill + Hot Mix Overlay one lift (45 mm)	19.16	30
104	Mill +Hot mix overlay two lifts (45 mm)	28.94	72

4.4.2 Developing Transition Probability Matrix

The TPM is used to present the probability of pavement condition transitioning from one state to the other. For this study and based on the data analysis, pavement roughness conditions are presented in terms of five condition states, while rutting is divided into eight condition states as shown in Table 4.7. It is assumed that the pavement will transition by only one state condition each year. In other words, the pavement will either stay in its condition state in the following year, or it will move to the following state (Butt et al. 1987).

Table 4.7: State Condition Classification

State	1	2	3	4	5	6	7	8
Roughness (m/km)	0→ 1	1→2	2→3	3→4	>4	-	-	-
Rutting (cm)	0→ 1	1→2	2→3	3→4	4→5	5→6	6→7	>7

The TPM is presented in the form of a matrix of order *(n x n)* where in *(n)* is the number of condition states identified. The TPM is therefore in the following form:

Condition State at year t+1

Condition state at year t

$$
\begin{vmatrix}
P1 & 1-P1 & 0 & 0 & 0 \\
0 & P2 & 1-P2 & 0 & 0 \\
. & . & . & . & . \\
. & . & . & . & . \\
0 & 0 & 0 & Pi & 1-Pi \\
0 & 0 & 0 & 0 & 1
\end{vmatrix}
$$

Where Pi is the probability of staying in the same state while 1-Pi is the probability of transitioning to the following state in one year. The 1 value at the last row of matrix indicates a holding state where the pavement does not transition any further (Butt et al. 1987). To determine the probabilities the proportion method is used (Jiang et al. 1988; Ortiz-García et al. 2006). In this method, the probability is found as follows:

$$Pij = nij / n$$

Where,

Pij = the probability of a pavement section to transition from state I to state j

n_{ij} = number of pavement section transitioned from state j to state j in one year

n = Total number of section in state i

The state vector of pavement section at any given year t $[\widehat{Pt}]$ can be found by multiplying the initial state vector $[\widehat{P0}]$ by TPM to the power of t. (Butt et al. 1987). Thus:

$$[\widehat{Pt}] = [\widehat{P0}] \; x \; [TPM]^t$$

Where the initial state vector is the state vector at year t=0 and is assumed that the pavement will be in best state, Thus:

$$[\widehat{P0}] = [1 \;\; 0 \;\; 0 \;\; \ldots \; 0]$$

Once the state vector at any year t is determined, the Future State (FS) value can be determined by multiplying the state vector at year t by the state index vector [S], i.e. the state condition established in Table 4.7. Thus,

$$FSt = [\widehat{P0}] \; x \; [TPM]t \; x[S]$$

The procedure described above is used to establish the TPM for roughness and rutting for the four maintenance activities used in this study. The TPM are then used to predict the future conditions of pavement due to applying a given maintenance or rehabilitation activity. Table 4.8 presents the TPM developed for the various maintenance activities used in this study.

Table 4.8: TPM's for Maintenance Activities Used in Case Study

<table>
<tr><th>Treatment</th><th>Roughness TPM</th><th>Rutting TPM</th></tr>
<tr><td>Hot Mix Overlay one lift (45mm)</td><td>
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<tr><th></th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th></tr>
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<tr><td>5</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>1.00</td></tr>
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<tr><td>1</td><td>0.33</td><td>0.67</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>2</td><td>0.00</td><td>0.54</td><td>0.46</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>3</td><td>0.00</td><td>0.00</td><td>0.42</td><td>0.58</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>4</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.61</td><td>0.39</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
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<tr><td>6</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.61</td><td>0.39</td><td>0.00</td></tr>
<tr><td>7</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.50</td><td>0.50</td></tr>
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<tr><td>Hot Mix Overlay two lift (45mm)</td><td>
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<tr><td>3</td><td>0.00</td><td>0.00</td><td>0.67</td><td>0.33</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
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<tr><td>8</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>1.00</td></tr>
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<tr><td>Mill + Hot Mix Overlay one lift (45 mm)</td><td>
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<tr><td>7</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.82</td><td>0.18</td></tr>
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<tr><td>Mill +Hot mix overlay two lifts (mm)</td><td>
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<tr><td>4</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.82</td><td>0.18</td></tr>
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<tr><td>3</td><td>0.00</td><td>0.00</td><td>0.65</td><td>0.35</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>4</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.73</td><td>0.27</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>5</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.74</td><td>0.26</td><td>0.00</td><td>0.00</td></tr>
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As discussed in Chapter 3 of this thesis, each maintenance or rehabilitation activity applied results in an improvement of various performance measures' conditions. To establish the improvements resulting from each maintenance activity, the MTO PMS2 is analyzed. However, a review of the data showed that after applying a given maintenance or rehabilitation activity, it is usually reassigned a value of zero for roughness and rutting; however, that is not practical. Due to the limited information regarding the improvements of rutting and roughness due to applying the maintenance activities used in this case study, and as this case study is developed to illustrate the application of the framework, the improvements of these maintenance activities were assumed. Therefore, applying any of the maintenance activities used in this case study is assumed to reduce roughness to a value of 0.2 m/km and rutting to a value of 1mm.

4.5 Phase-One: Initial Program

Phase-One of the framework is implemented to develop the Initial Maintenance Program for the bidding stage of the project. As discussed in Chapter 3, the inputs in this phase include the following:

- Pavement Data
- Contract Specifications
- Maintenance and rehabilitation deterioration models

The objective of this phase is to develop a maintenance and rehabilitation program at the lowest cost while maintaining the contract specifications. In order to achieve this objective, an optimization model was proposed. The objective of the optimization function is to minimize the total cost needed to maintain roughness and rutting below the specified level of services along the contract period. The formulated optimization function to obtain the Initial Program of maintenance and rehabilitation follows the optimization model presented in section 3.2.

An excel worksheet is developed to apply the process of this framework. All inputs are formulated in the excel cells. Figure 4.4 presents the developed Excel sheet for implementing this framework. As shown in Figure 4.4, all inputs are formulated on the left side including maintenance activities and associated costs, the contract specifications and the contracted pavement information.

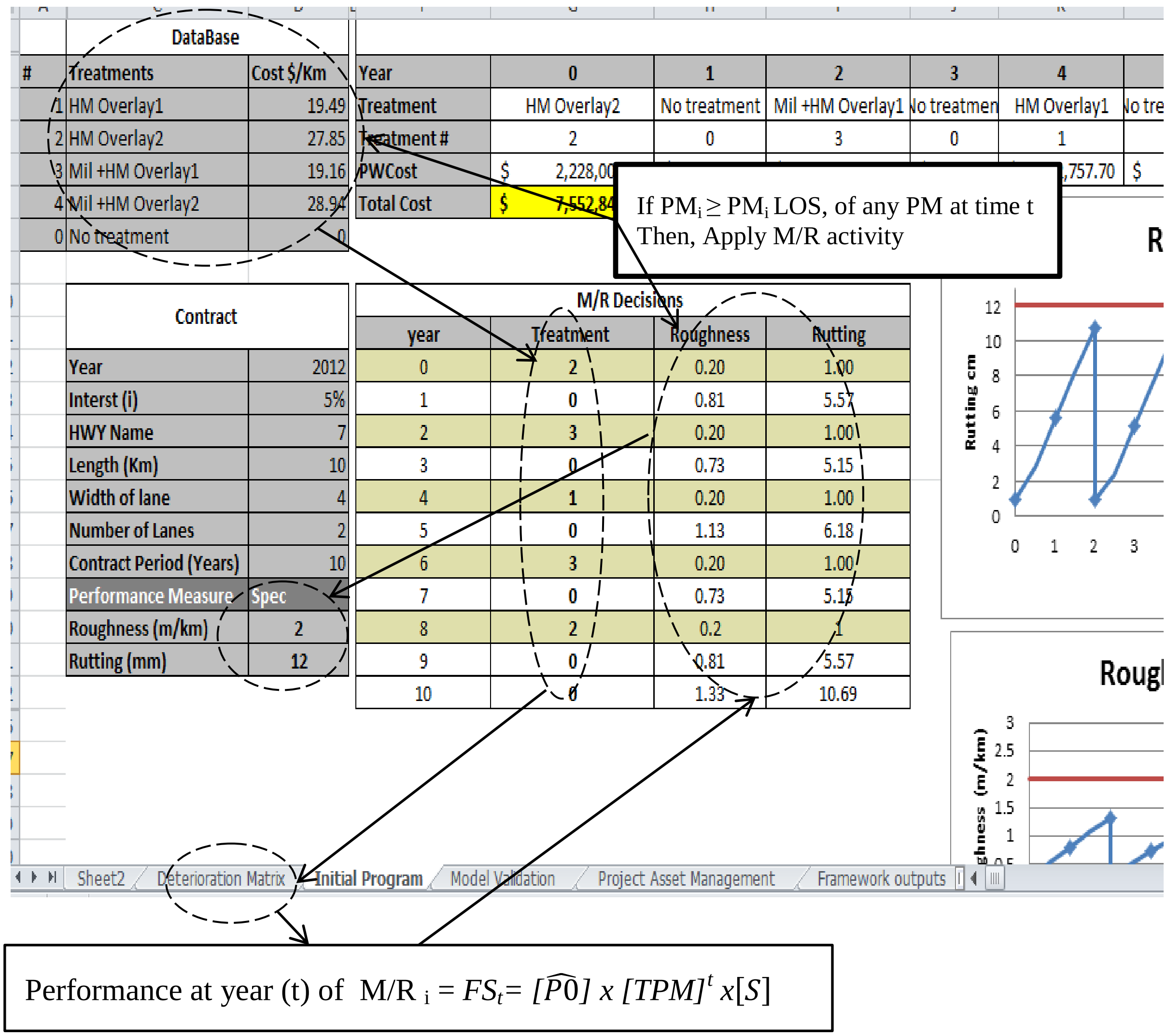

Figure 4.4: Snapshot of Excel Worksheet

The formulated excel functions for the maintenance and rehabilitation selection in the spreadsheet follow the logic presented in Figure 4.5. As shown, the worksheet is set up to select maintenance or rehabilitation activities and evaluates and monitors the deterioration process for each performance measure for the selected maintenance or rehabilitation activity every year. Once the specified LOS is reached, a maintenance or rehabilitation activity is to be selected. Once a maintenance or a rehabilitation activity is selected, it is logged in the data base with the corresponding year of application. The process is continued until the contract period is reached. The process of selection of the combination of maintenance and rehabilitation activities that will maintain the specified LOSs is repeated to arrive to the optimum maintenance and rehabilitation program.

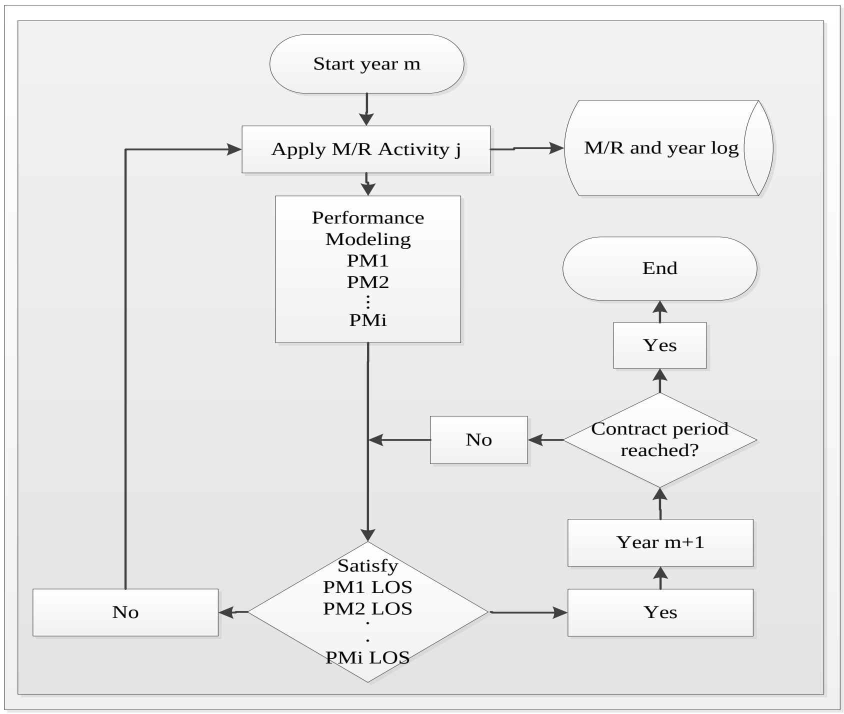

Figure 4.5: Flowchart of Selecting and Evaluating Maintenance or Rehabilitation Activities

To assist with the optimization process, Evolver software is utilized. Evolver is a genetic algorithm optimization add-in for Microsoft Excel (see palisade.com/Evolver). An illustrative screenshot of the developed excel worksheet and the use of Evlover is shown in Figure 4.6. As shown in Figure 4.6, the model definition box showing on the left corner allows for identifying the variables and the constraints to reach the objective function. The objective function shown in the figure is to minimize the total cost by changing the maintenance and rehabilitation activities applied at a given year while maintaining the performance measures constraints. The optimization model was run several times to assure the optimum Initial Program is developed. Table 4.9 presents the Initial Program developed as a result of implementing this phase.

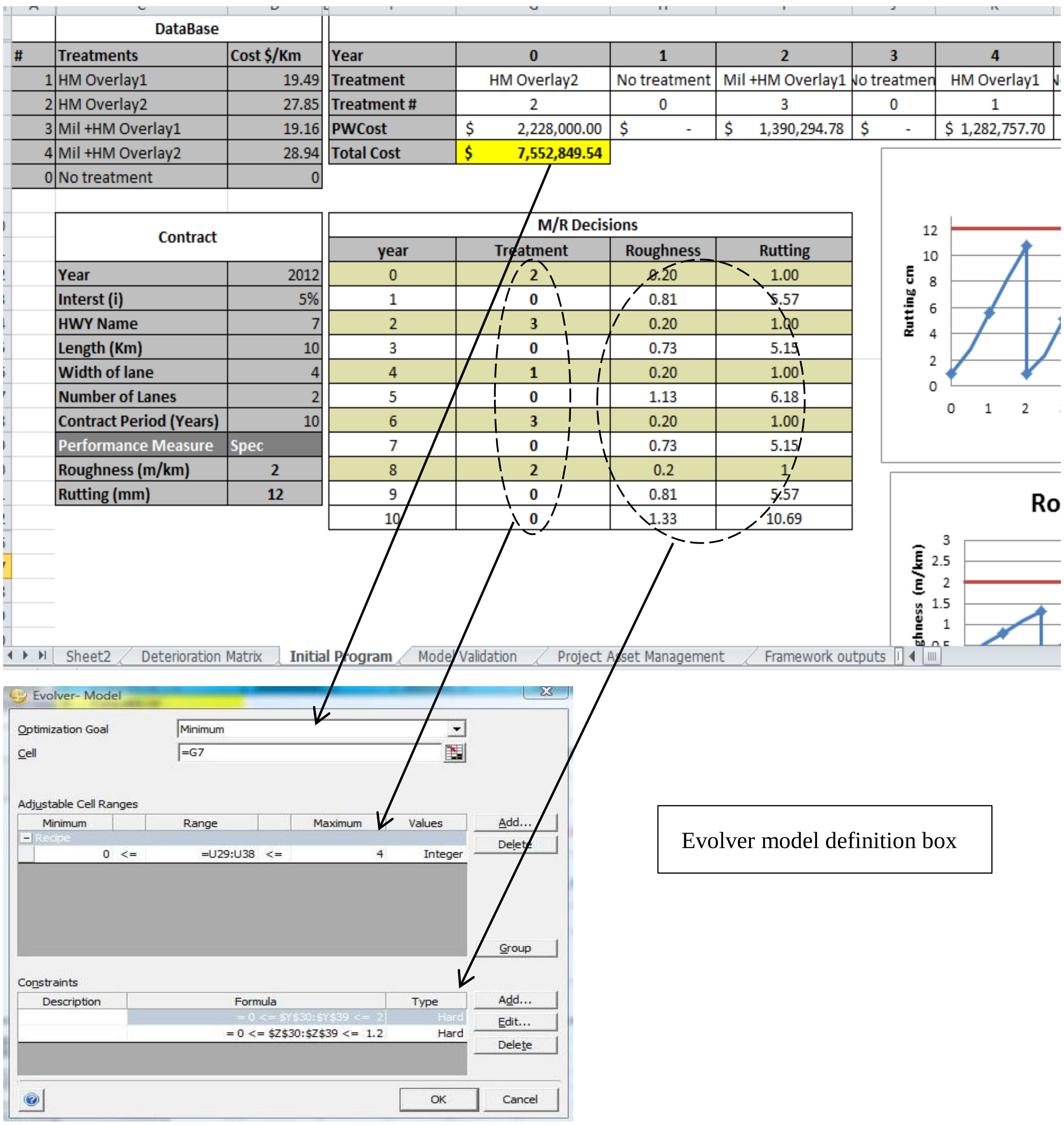

Figure 4.6: Snapshot of Excel Worksheet and Evolver Optimization

Table 4.9: Initial Program Output

Year	Treatment	Present Worth Cost
0	HM Overlay2	$ 2,228,000.00
1	No treatment	$ -
2	Mil +HM Overlay1	$ 1,390,294.78
3	No treatment	$ -
4	HM Overlay1	$ 1,282,757.70
5	No treatment	$ -
6	Mil +HM Overlay1	$ 1,143,798.96
7	No treatment	$ -
8	HM Overlay2	$ 1,507,998.10
9	No treatment	$ -
10	No treatment	$ -
Total Cost		**$ 7,552,849.54**

As shown in Table 4.9, the output provides a variation of maintenance activities applied at various years throughout the contract period. The present worth of each activity for the case study section is also presented. To total sum is the total expected cost for the maintenance program to be submitted in the bid.

Each applied maintenance impact the performance of pavement based on the deterioration models presented in section 4.4. Figure 4.7 and Figure 4.8 illustrate the performance models for roughness and rutting, respectively, over the contract period as a result of the proposed maintenance program. As shown in Figure 4.7 and Figure 4.8, rutting deterioration is faster than that of roughness in most cases; as a result the maintenance activities are applied before roughness LOS is reached. That is due to the contract dictating that all performance measures' LOS to be met and the maintenance activities applied in this case study result in improvements for both performance measures. As a result, the performance specifications for performance measures are maintained throughout the contract period even if the LOS is not reached.

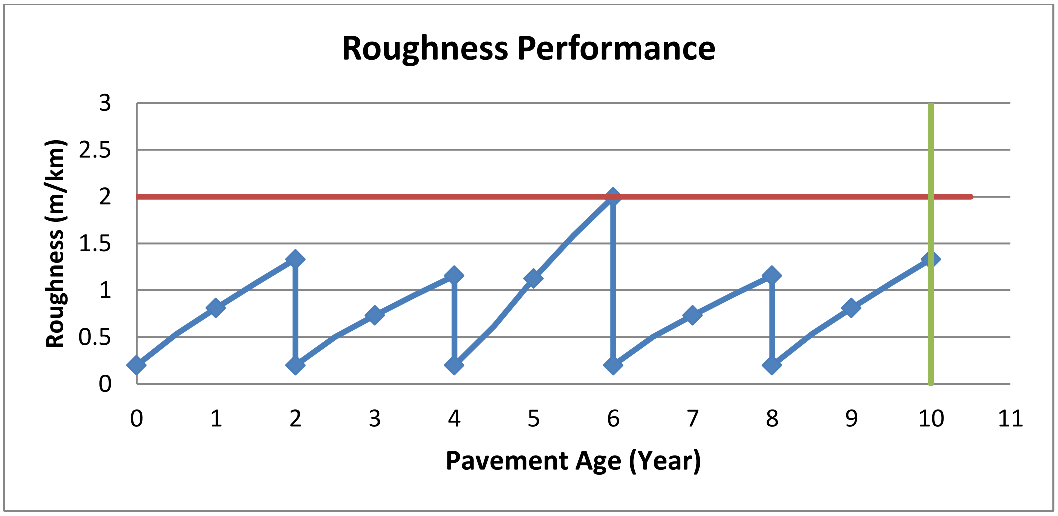

Figure 4.7: Roughness Performance over Contract Period

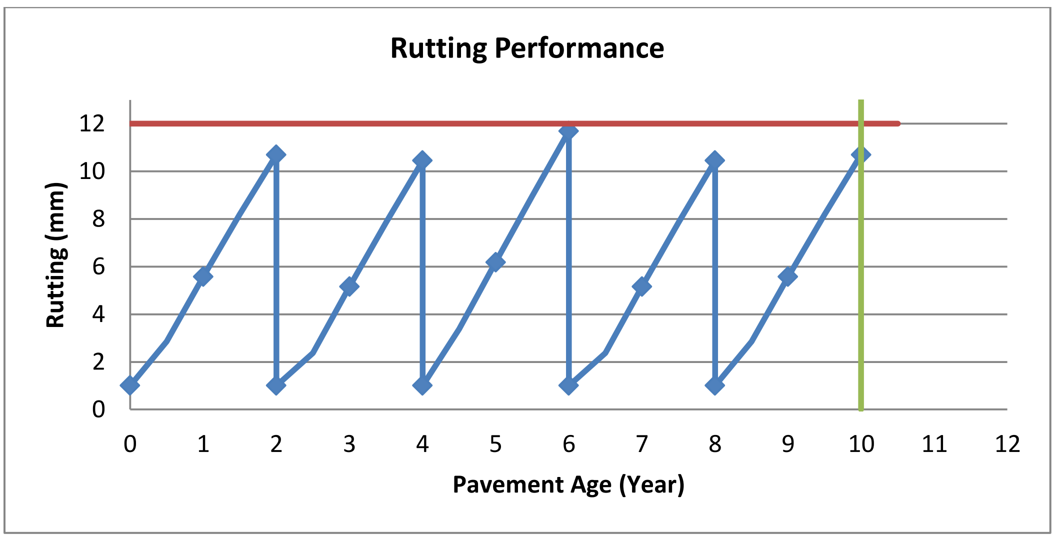

Figure 4.8: Rutting Performance over Contract Period

4.6 Phase-Two: Project Asset Management

As indicated earlier, pavement deterioration follows a stochastic behavior, and the deterioration process is subject to many factors such as loading, environment and the historical data used to develop deterioration rates. In addition, the effectiveness of maintenance and rehabilitation activities relays on the accuracy of the deterioration models used to predict future conditions. As illustrated in Chapter 3 of this thesis, three scenarios of the developed deterioration models are apparent. The predicted model is accurate, it over estimates the deterioration rate, or underestimates the deterioration rate for a given maintenance or rehabilitation activity. For the purpose of illustrating the framework in this case study, two scenarios are considered. Overestimated deterioration rate, and underestimated deterioration rates of maintenance activity (Hot mix overlay one lift 45 mm) applied at year 4 of the contract period.

The objective of Phase-Two, Project Asset Management, is to continuously validate the deterioration models using the performance monitoring data as well as re-optimizing the maintenance and rehabilitation program as needed subject to the constraint of the reaming budget obtained in the bidding stage. The inputs to this phase include:

- Budget (Remaining from the estimated cost submitted in the bid)
- Performance Monitoring Data
- All inputs from Phase-One

In order to achieve the objective of Project Asset Management phase, an optimization model was proposed. The objective of the optimization function is to maintain roughness and rutting performance below the specified level of services for the remaining of the contract period while constraint by the amount of money remaining to date of the cost estimate submitted.

4.6.1 Scenario One: Underestimated Deterioration Rate

In this hypothetical scenario, the deterioration rate used to predict the future condition was underestimated. In other words, the pavement is deteriorating at a higher rate and will reach the specified performance measure specification earlier than planned. Figure 4.9 and 4.10 show the predicted performance and the actual performance data for roughness and rutting, respectively.

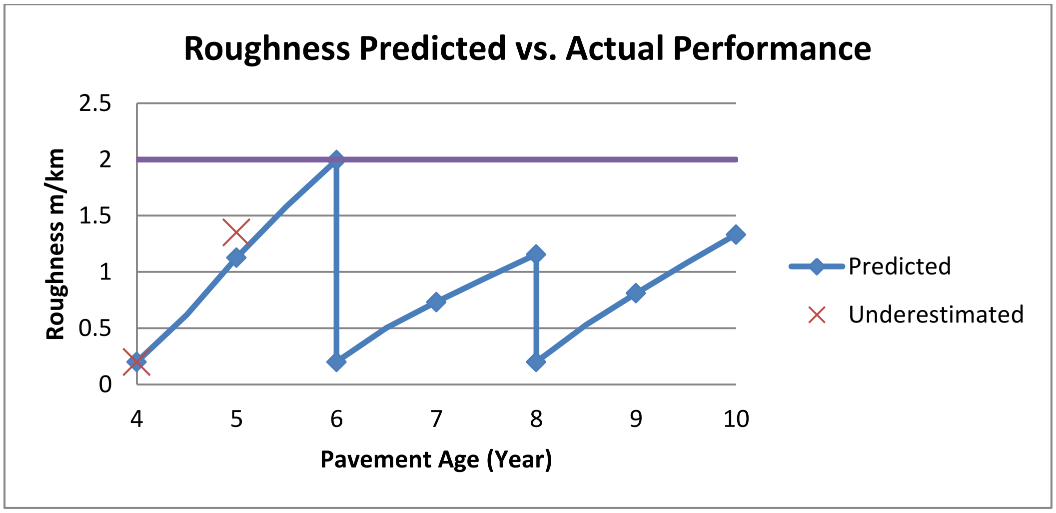

Figure 4.9: Roughness Predicted vs. Actual Performance - Underestimated Scenario

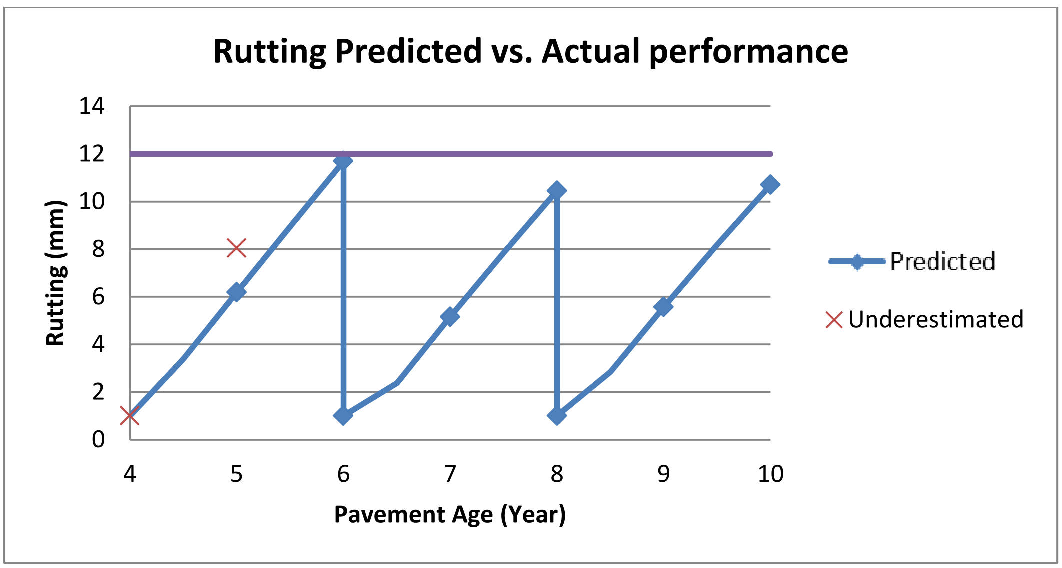

Figure 4.10: Rutting Predicted vs. Actual Performance – Underestimated Scenario

As shown in Figure 4.9 and Figure 4.10, the performance curve reaches the performance specification earlier than predicted. Therefore, a maintenance or rehabilitation activity needs to be applied to prevent penalties. However, that decision means a change in the planned maintenance and rehabilitation program which will result in encountering losses. As such, Phase-Two of the proposed framework is utilized to re-optimize and develop a maintenance and rehabilitation plan that will maintain the specified performance measures while staying within the remaining of the budget established from bidding stage. The optimization model developed follows the presented optimization model presented in section 3.3. Based on the performance data shown in Figure 4.9 and 4.10, the trend shows that the level of service could be reached sometime between year five and six. Therefore, to mitigate the risk, year 5 is selected as a starting point for the re-programing process.

An excel worksheet is developed to apply the process of this framework. All inputs are formulated in the excel cells. The formulated excel worksheet is similar to that developed for Phase-One of the framework. Figure 4.11 shows an illustrative screenshot of the developed excel worksheet and the use of Evlover.

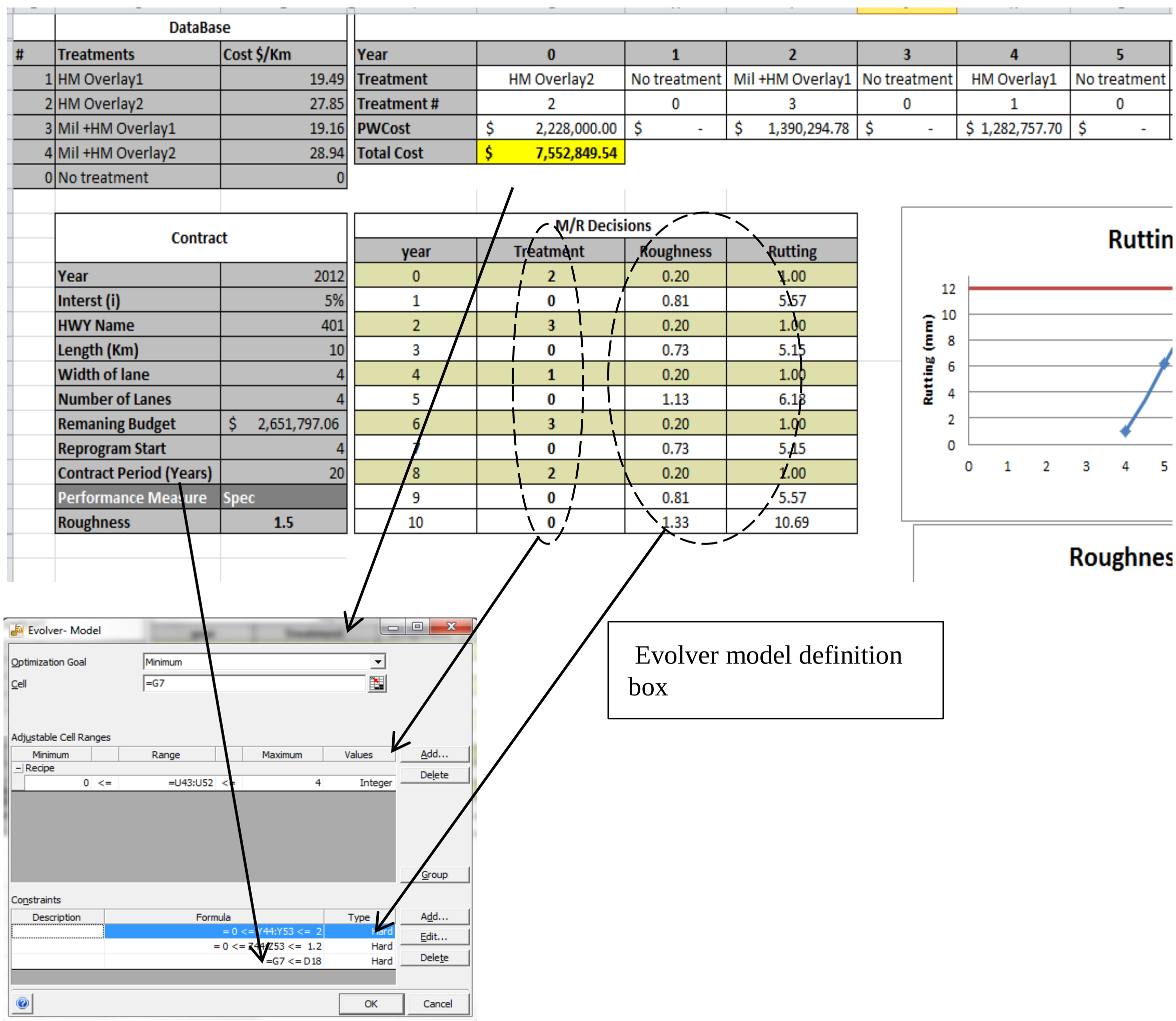

Figure 4.11: Project Asset Management Excel Worksheet Snapshot

As shown in Figure 4.11, the model definition box showing on the left corner allows for identifying the variables and the constraints to reach the objective function. The objective function shown in the figure is to minimize the total cost by changing the maintenance and rehabilitation activities applied at a given year while maintaining the performance measures constraints and the budget constraint. The optimization model was run several times to assure the optimum maintenance program is developed for the remaining of the contract period. Table 4.10 presents the maintenance program developed as a result of implementing Project Asset Management phase along with the output maintenance program developed from Initial Program phase.

Table 4.10: Project Asset Management Phase Output-Underestimated Scenario

	Initial Program Output		**Project Asset Management Output**	
Year	Treatment	Present Worth Cost	Treatment	Present Worth Cost
0	HM Overlay2	$ 2,228,000.00	HM Overlay2	$ 2,228,000.00
1	No treatment	$ -	No treatment	$ -
2	Mil +HM Overlay1	$ 1,390,294.78	Mil +HM Overlay1	$ 1,390,294.78
3	No treatment	$ -	No treatment	$ -
4	HM Overlay1	$ 1,282,757.70	HM Overlay1	$ 1,282,757.70
5	No treatment	$ -	Mil +HM Overlay1	$ 1,200,988.91
6	Mil +HM Overlay1	$ 1,143,798.96	No treatment	$ -
7	No treatment	$ -	Mil +HM Overlay1	$ 1,089,332.34
8	HM Overlay2	$ 1,507,998.10	No treatment	$ -
9	No treatment	$ -	Mil +HM Overlay1	$ 988,056.55
10	No treatment	$ -	No treatment	$ -
Total Cost		**$ 7,552,849.54**		**$ 8,179,430.28**

As shown in Table 4.10, the output maintenance program changes at year five of the contract period. It is noted that there is an increase in the total present worth of the maintenance program by 8% due to the underestimation of the deterioration rate.

Figure 4.12 and Figure 4.13 illustrate the performance models for roughness and rutting, respectively, over the contract period as a result of the modified maintenance program. As shown in Figure 4.12 and Figure 4.13, the performance specifications for performance measures are maintained throughout the contract period.

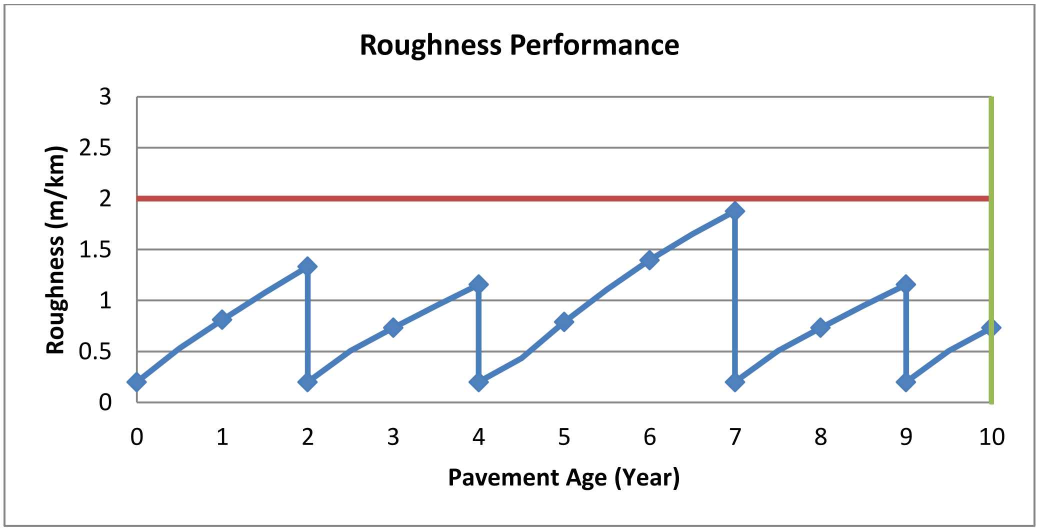

Figure 4.12: Roughness Performance over Contract Period - Underestimated Scenario

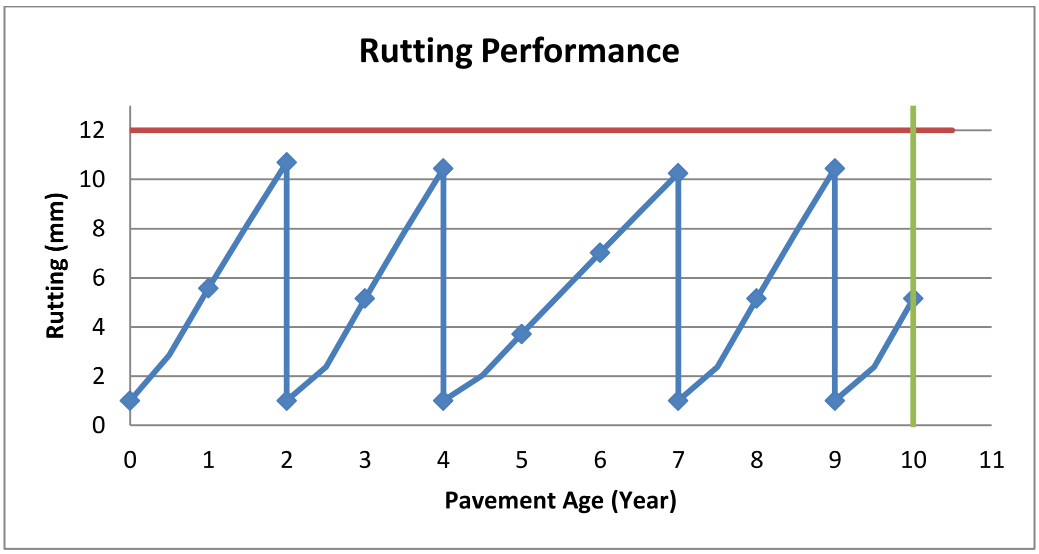

Figure 4.13: Rutting Performance over Contract Period - Underestimated Scenario

4.6.2 Scenario Two: Overestimated Deterioration Rate

In this hypothetical scenario, the deterioration rate used to predict the future condition was overestimated. In other words, the pavement is deterioration at a higher rate and will reach the specified performance measure specification earlier than planned. Figure 4.14 and 4.15

show the predicted performance and the actual performance data for roughness and rutting, respectively.

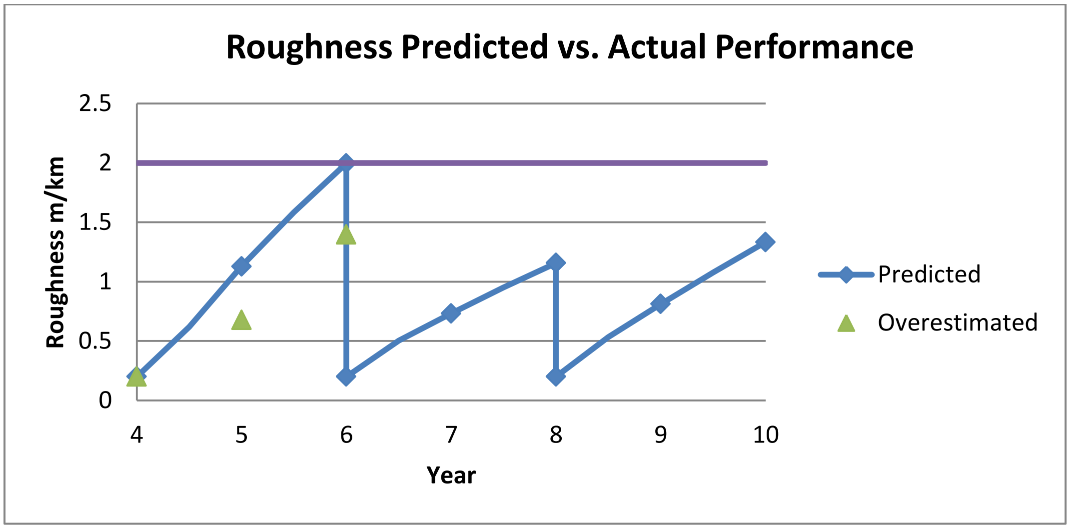

Figure 4.14: Roughens Predicted vs. Actual Performance – Overestimated Scenario

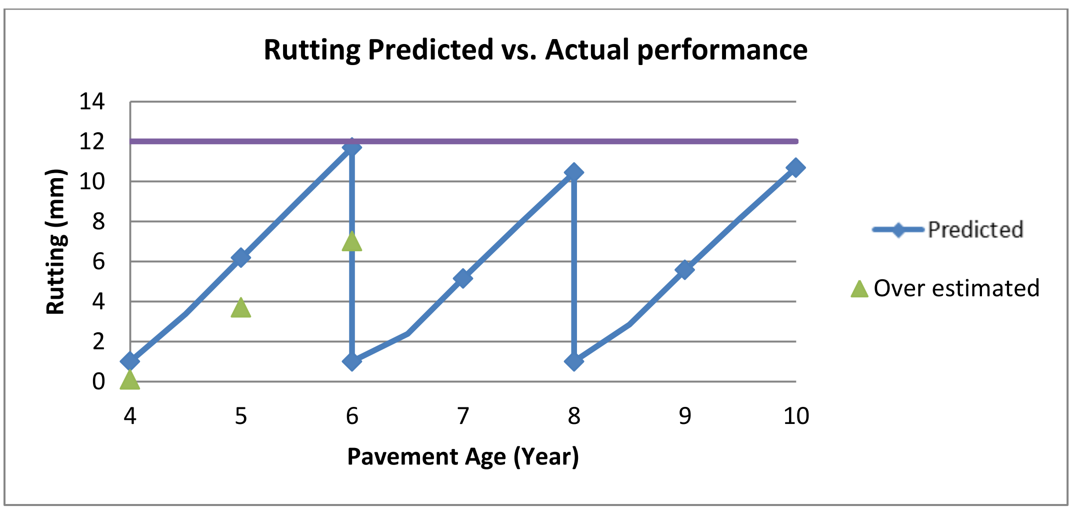

Figure 4.15: Rutting Predicted vs. Actual Performance- Overestimated Scenario

As can be seen in Figure 4.14 and Figure 4.15, the performance predicated using the deterioration models is over estimated. In other words, it was predicted that the specified level of service will be reached at year six; however, the performance monitoring data suggest that it is well below the specified level of service. In this case, if incentives are present, the contractor will benefit and the maintenance program should be maintained as planned. On the other hand, if no incentive is present, the contractor could benefit by delaying the planned maintenance and re-optimize the maintenance and rehabilitation program. Based on the performance monitoring data, the trends show that the specified level of service will be reached no earlier than year seven. Therefore, year seven is selected as the new optimization cycle. The process presented in the previous section is followed in this case and Table 4.11 presents the output.

Table 4.11: Project Asset Management Phase Output- Overestimated Scenario

	Initial Program Output		**Project Asset Management Output**	
Year	Treatment	Present Worth Cost	Treatment	Present Worth Cost
0	HM Overlay2	$ 2,228,000.00	HM Overlay2	$ 2,228,000.00
1	No treatment	$ -	No treatment	$ -
2	Mil +HM Overlay1	$ 1,390,294.78	Mil +HM Overlay1	$ 1,390,294.78
3	No treatment	$ -	No treatment	$ -
4	HM Overlay1	$ 1,282,757.70	HM Overlay1	$ 1,282,757.70
5	No treatment	$ -	No treatment	$ -
6	Mil +HM Overlay1	$ 1,143,798.96	No treatment	$ -
7	No treatment	$ -	Mil +HM Overlay1	$ 1,089,332.34
8	HM Overlay2	$ 1,507,998.10	No treatment	$ -
9	No treatment	$ -	Mil +HM Overlay1	$ 988,056.55
10	No treatment	$ -	No treatment	$ -
Total Cost		**$ 7,552,849.54**		**$ 6,978,441.37**

As shown in Table 4.11, the output maintenance program changes at year seven of the contract period. It is noted that there a saving in the total present worth of the maintenance program by 8%.

Figure 4.16 and Figure 4.17 illustrate the performance models for roughness and rutting, respectively, over the contract period as a result of the modified maintenance program. In addition, as seen in both figures, the performance specifications for performance measures are maintained throughout the contract period.

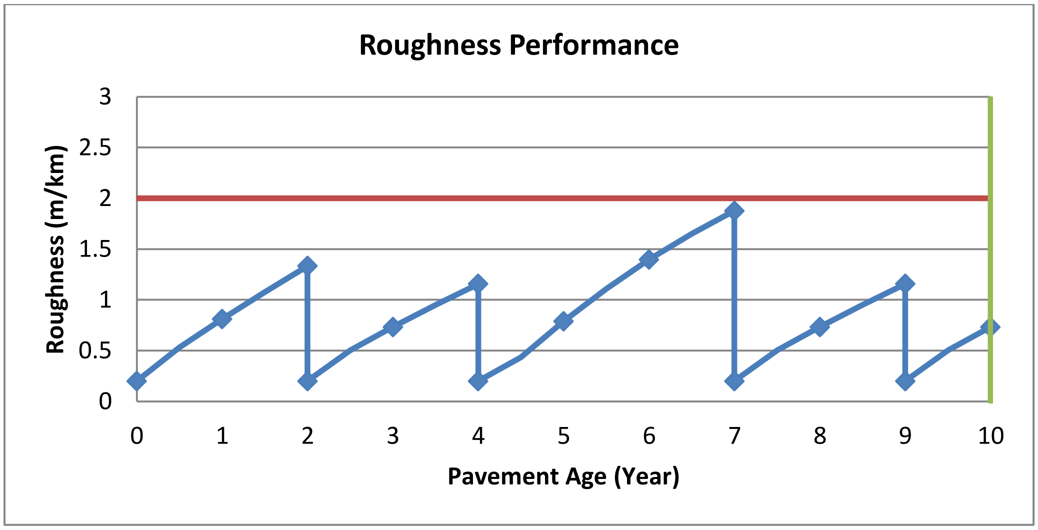

Figure 4.16: Roughness Performance over Contract Period - Overestimated Scenario

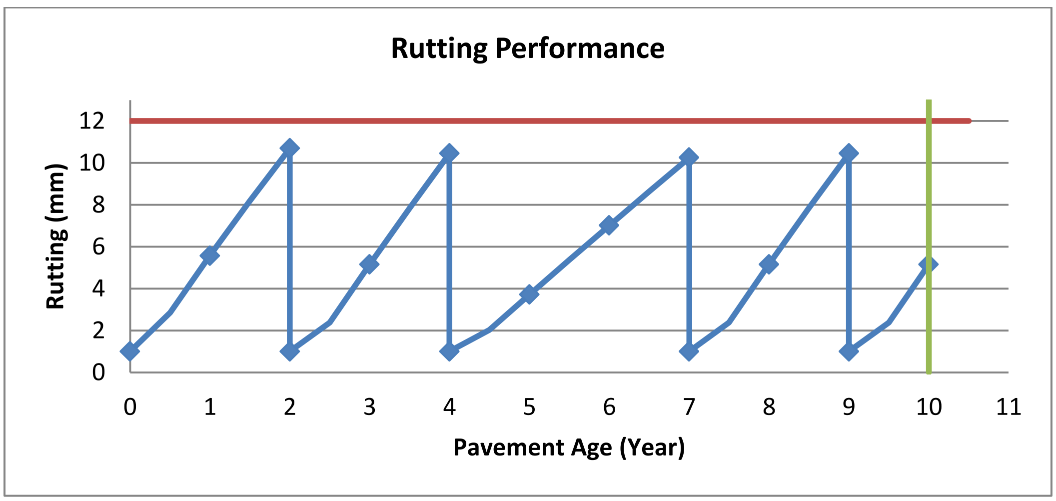

Figure 4.17: Rutting Performance over Contract Period - Overestimated Scenario

4.7 Conclusions

The two-phase maintenance and rehabilitation framework was illustrated in details in this chapter by applying it to a case study of Highway 7 located between Kitchener and Guelph Ontario. The highway was chosen for this case study as it represents typical two-lane highways in Ontario and in Canada in general. In addition, the highway is heavily trafficked which results in higher probability of deterioration and as a result in higher need for maintenance and rehabilitation.

The MTO's PMS2 data base was used to develop deterioration rates for applicable maintenance activities used in this study. The Markov model was used due to availability of sufficient data and the model ability to capture the probabilistic behavior of pavement and the time dependent uncertainty deterioration process as well as for different maintenance and rehabilitation activities. The cost of the maintenance activities used in this study was obtained from MTO. For the purpose of the case study, roughness and rutting are selected as specified performance measures. Roughness and rutting are widely used in PBCs and the PMS2 contains the historical data for these performance measures. Although only two performance measures are used in this case study, the framework can be extended for any number of performance measures.

Phase-One of, Initial Program, was used to develop the initial maintenance program used for the bidding stage. The optimization method was used to obtain a maintenance program that maintains the specified performance level of service with the lowest cost. To assist with the optimization process, Evolver software is utilized. Evolver is a genetic algorithm optimization add-in for Microsoft Excel.

To illustrate Phase-Two Project Asset Management, two scenarios were developed. Overestimated deterioration rate, and underestimated deterioration rates of maintenance activity (Hot mix overlay one lift 45 mm) applied at year 4 of the contract period. The implementation of the framework resulted in maintenance program that maintained the performance measures specified level of service over the contract period. In addition, the framework adapted for a variation in the predicted performance to the actual performance allowing for re-optimization and development of alternative maintenance program.

Chapter 5
Framework Sensitivity Analysis

5.1 Introduction

As illustrated in the previous chapters, the proposed framework resulted in an optimized maintenance and rehabilitation program based on various variables. The inputs include alternative maintenance and rehabilitation activities and the corresponding cost and deterioration rates. The deterioration rates are developed based on historical data using a given modeling method. Regardless of the modeling method, pavement deterioration is of stochastic nature and uncertainty is present (Madanat et al. 1995). In addition, the development and selection of maintenance and rehabilitation programs are subject to the specified performance measures' level of service.

Therefore, the proposed framework is evaluated for sensitivity to variability in the deterioration rates and the specified performance measures' level of services. The variables and the ranges studied are presented in Table 5.1.

Table 5.1: Variables and Ranges for Sensitivity Analysis

Variable	**Sensitivity Range**
Deterioration Rates	-20% to +20%
Performance Specified Level of Service	-20% to 20%

Each variable and associated range is evaluated individually in terms of total present worth cost compared to that obtained from Initial Program phase of the framework. The process illustrated in Chapter 4 is followed to develop the maintenance programs.

5.2 Deterioration Rates Sensitivity Analysis

In the case study, the deterioration rates were developed using the Markov model represented in the transition probability matrices (TPMs). The TPMs are used for the sensitivity analysis by changing the probabilities by percentage range from -20 % to 20 %. An example of varying the deterioration rate by changing the probabilities is shown in Table 5.2.

Table 5.2: TPM Sensitivity Adjustment Example

Treatment	**Roughness TPM**						**Rutting TPM**								
Hot Mix Overlay one lift (45mm)		**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	1	0.26	0.74	0	0	0	**1**	0.33	0.67	0	0	0	0	0	0
	2	0	0.04	0.96	0	0	**2**	0	0.54	0.46	0	0	0	0	0
	3	0	0	0.02	0.98	0	**3**	0	0	0.42	0.58	0	0	0	0
	4	0	0	0	0.67	0.33	**4**	0	0	0	0.61	0.39	0	0	0
	5	0	0	0	0	1	**5**	0	0	0	0	0.19	0.81	0	0
							6	0	0	0	0	0	0.61	0.39	0
							7	0	0	0	0	0	0	0.5	0.5
							8	0	0	0	0	0	0	0	1
Hot Mix Overlay one lift (45mm) + 5%		**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	1	0.273	0.777	0	0	0	**1**	0.346	0.703	0	0	0	0	0	0
	2	0	0.042	1.008	0	0	**2**	0	0.567	0.483	0	0	0	0	0
	3	0	0	0.021	1.029	0	**3**	0	0	0.441	0.609	0	0	0	0
	4	0	0	0	0.703	0.346	**4**	0	0	0	0.640	0.409	0	0	0
	5	0	0	0	0	1	**5**	0	0	0	0	0.199	0.850	0	0
							6	0	0	0	0	0	0.640	0.409	0
							7	0	0	0	0	0	0	0.525	0.52
							8	0	0	0	0	0	0	0	1

The case study is used to develop a maintenance and rehabilitation program for using the TPMs sets developed for the sensitivity analysis. For each trial, the output is recorded and the total cost is presented as shown in Table 5.3. Figure 5.1 graphically presents the total cost for the deterioration sensitivity analysis. In addition, the performance of roughness and rutting over the contract period for all cases are presented Appendix A.

Table 5.3: Sensitivity Analysis of Deterioration Rates on Maintenance Program Output and Cost

20% increase		10% increase		Base Case		10% decrease		20% decrease	
HM Overlay1	$ 1,520,000.00	HM Overlay1	$ 1,520,000.00	HM Overlay2	$ 2,228,000.00	Mil +HM Overlay2	$ 2,315,200.00	Mil +HM Overlay2	$ 2,315,200.00
Mil +HM Overlay2	$ 2,204,952.38	HM Overlay2	$ 2,121,904.76	No treatment	$ -	No treatment	$ -	No treatment	$ -
No treatment	$ -	No treatment	$ -	Mil +HM Overlay1	$ 1,390,294.78	No treatment	$ -	No treatment	$ -
HM Overlay1	$ 1,313,033.15	HM Overlay2	$ 1,924,630.17	No treatment	$ -	Mil +HM Overlay1	$ 1,324,090.27	HM Overlay1	$ 1,313,033.15
Mil +HM Overlay2	$ 1,904,720.77	No treatment	$ -	HM Overlay1	$ 1,282,757.70	No treatment	$ -	No treatment	$ -
No treatment	$ -	HM Overlay1	$ 1,190,959.77	No treatment	$ -	Mil +HM Overlay2	$ 1,814,019.78	Mil +HM Overlay2	$ 1,814,019.78
HM Overlay1	$ 1,134,247.40	HM Overlay2	$ 1,662,567.90	Mil +HM Overlay1	$ 1,143,798.96	No treatment	$ -	No treatment	$ -
HM Overlay1	$ 1,080,235.62	No treatment	$ -	No treatment	$ -	No treatment	$ -	No treatment	$ -
Mil +HM Overlay2	$ 1,567,018.49	HM Overlay2	$ 1,507,998.10	HM Overlay2	$ 1,507,998.10	Mil +HM Overlay1	$ 1,037,459.37	HM Overlay1	$ 1,028,795.83
No treatment	$ -	No treatment	$ -	No treatment	$ -	No treatment	$ -	No treatment	$ -
No treatment	$ -	No treatment	$ -	No treatment	$ -	No treatment	$ -	No treatment	$ -
Total Cost	**$ 10,724,207.82**	Total Cost	**$ 9,928,060.71**	Total Cost	**$ 7,552,849.54**	Total Cost	**$ 6,490,769.43**	Total Cost	**$ 6,471,048.76**

As noted in Table 5.3, the increase in the deterioration rate significantly increases the total cost of the maintenance program. In other words, as the deterioration rate of a maintenance activity, i.e. the pavement deteriorate faster, a maintenance or rehabilitation is to be applied sooner. That results in an increase of the number of maintenance or rehabilitation activities to be applied throughout the contract period. On the other hand, a decrease in the deterioration rate resulted in a slight decrease in the total maintenance cost. Consequently, the deterioration rate has a high impact on the maintenance program cost and therefore contractors should implement similar sensitivity analysis during the cost estimation as means to quantify the risk accepted.

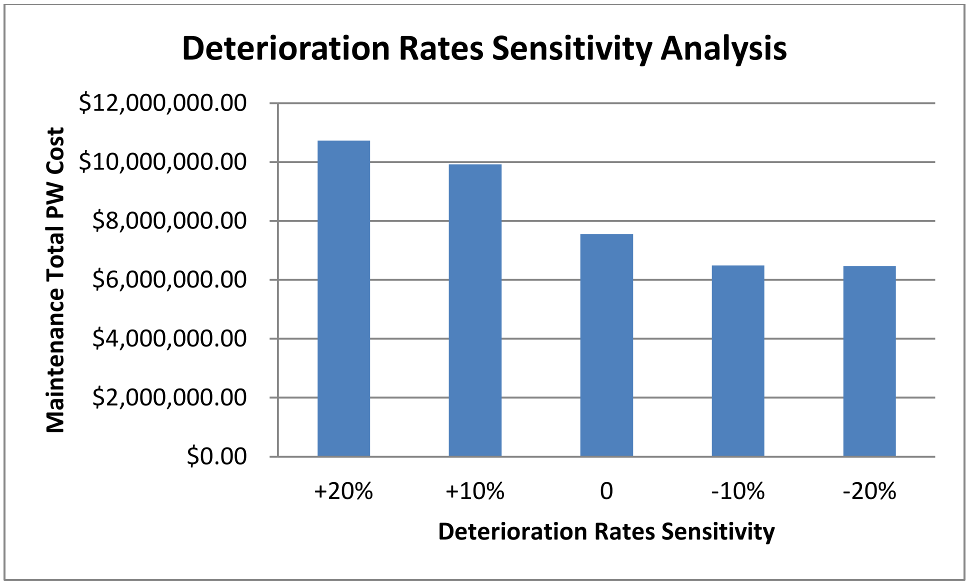

Figure 5.1: Deterioration Rates Sensitivity Analysis

5.3 Performance Specifications Sensitivity Analysis

Although the performance level of service is specified by the highway agency tendering the contract, it is of value to study the impact on the total cost of such constraint. In the case study the performance measures used are roughness and rutting. The specified level of service for each is 2 m/km and 12mm, respectively. The case study presented in Chapter 4 was used to develop maintenance and rehabilitation programs for a set of performance level of services. For the sensitivity analysis, the performance specification is relaxed and restricted by a range of 20%. Table 5.4 presents the output maintenance program and the final cost for each set of performance specifications while Figure 5.2 presents a summary of total cost for the performance specifications sensitivity analysis. In addition, performance of roughness and rutting over the contract period for all cases are presented Appendix A

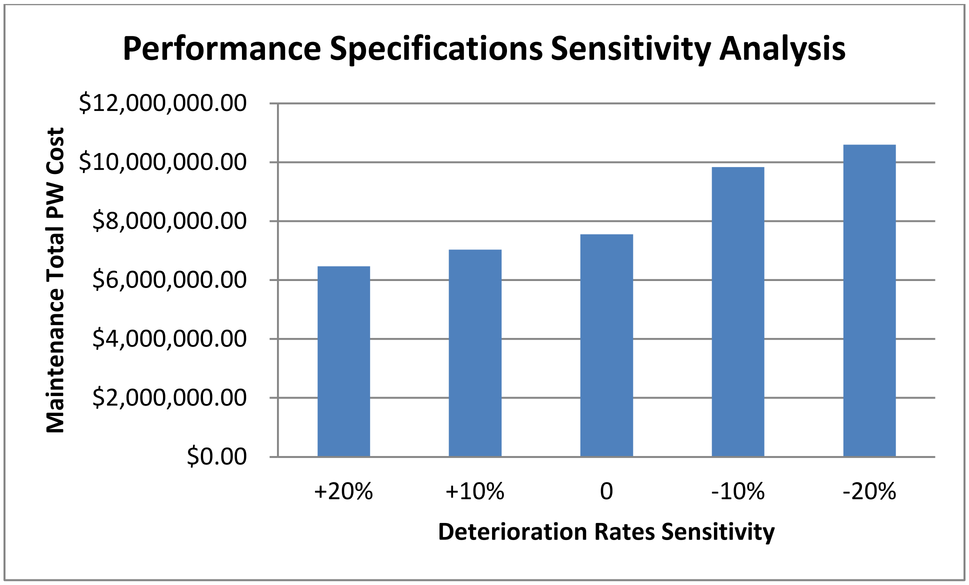

Figure 5.2: Performance Specifications Sensitivity Analysis

As seen in Table 5.4, also shown in Figure 5.2, relaxing the specified level of service slightly allows for more deterioration and therefore reduces the total cost of maintenance. However, restricting the specification, even by a slight percentage, increases the total maintenance cost significantly. Based on the sensitivity analysis of performance level of service, it is evident that the level of service specified has a high influence on the total maintenance cost; as such, contracting agencies should take that into account and carefully select the appropriate level of service.

Table 5.4: Sensitivity Analysis of Performance Level of Service on Maintenance Program Output and Cost

20% increase		10% increase		Base Case		10% decrease		20% decrease	
Mil +HM Overlay2	$ 2,315,200.00	HM Overlay1	$ 1,520,000.00	HM Overlay2	$ 2,228,000.00	HM Overlay2	$ 2,228,000.00	Mil +HM Overlay2	$ 2,315,200.00
No treatment	$ -	No treatment	$ -	No treatment	$ -	No treatment	$ -	No treatment	$ -
No treatment	$ -	Mil +HM Overlay2	$ 2,099,954.65	Mil +HM Overlay1	$ 1,390,294.78	HM Overlay1	$ 1,378,684.81	HM Overlay1	$ 1,378,684.81
HM Overlay1	$ 1,313,033.15	No treatment	$ -	No treatment	$ -	HM Overlay2	$ 1,924,630.17	Mil +HM Overlay2	$ 1,999,956.81
No treatment	$ -	HM Overlay1	$ 1,250,507.76	HM Overlay1	$ 1,282,757.70	No treatment	$ -	No treatment	$ -
HM Overlay1	$ 1,190,959.77	No treatment	$ -	No treatment	$ -	HM Overlay2	$ 1,745,696.30	Mil +HM Overlay2	$ 1,814,019.78
No treatment	$ -	HM Overlay1	$ 1,134,247.40	Mil +HM Overlay1	$ 1,143,798.96	No treatment	$ -	No treatment	$ -
Mil +HM Overlay2	$ 1,645,369.42	No treatment	$ -	No treatment	$ -	HM Overlay2	$ 1,583,398.00	HM Overlay1	$ 1,080,235.62
No treatment	$ -	HM Overlay1	$ 1,028,795.83	HM Overlay2	$ 1,507,998.10	No treatment	$ -	HM Overlay1	$ 1,028,795.83
No treatment	$ -	No treatment	$ -	No treatment	$ -	HM Overlay1	$ 979,805.55	HM Overlay1	$ 979,805.55
No treatment	$ -	No treatment	$ -	No treatment	$ -	No treatment	$ -	No treatment	$ -
Total Cost	**$ 6,464,562.34**	Total Cost	**$ 7,033,505.64**	Total Cost	**$ 7,552,849.54**	Total Cost	**$ 9,840,214.83**	Total Cost	**$ 10,596,698.40**

5.4 Conclusions

The inputs to the framework include alternative maintenance and rehabilitation activities and the corresponding cost and deterioration rates. Pavement deterioration is of stochastic nature and uncertainty is present. In addition, the development and selection of maintenance and rehabilitation programs are subject to the specified performance measures' level of service. The two parameters, deterioration rates and performance specification, are selected for sensitivity analysis. The deterioration rates represented in the TPM are used for the sensitivity analysis by changing the probabilities by percentage range from -10 % to 10 %. The performance specifications are relaxed and restricted by a range of 10%.

The sensitivity analysis showed that the increase in the deterioration rates results in an increase and in the total cost of the maintenance program. On the other hand, restricting the performance specified level of services increased the cost significantly. As a result, agencies tendering warranty projects should carefully select the level of services to avoid higher maintenance and rehabilitation programs' cost.

Chapter 6
Conclusions and Recommendations

In PBCs, the client agency specifies certain clearly defined minimum performance measures to be met or exceeded during the contract period and payments are explicitly linked to the contractor successfully meeting or exceeding those performance measures. Therefore, the PBC maintenance and rehabilitation selection differs significantly from that of traditional asset management contract and more complex due to the pavement deterioration process and probability of failure to achieve the specified level of service for various performance measures along the contract period.

The objective of this research was to develop a framework that facilitates the selection of maintenance and rehabilitation activities for pavement assets under PBCs. The framework consists of two phases. Phase-One, called Initial Program, uses historical data, performance modeling, and optimization to establish and select the maintenance and rehabilitation program for the bidding stage. Phase-Two, called Project Asset Management, is implemented after the contract is awarded. This phase uses the contract performance monitoring data and the cost estimate from Phase-One as a baseline budget to update and validate the established program through performance modeling and optimization. A case study using data from the Ministry of Transportation Ontario (MTO) pavement management system (PMS2) is introduced to illustrate the use of the framework.

The MTO's PMS2 data base was used to develop deterioration rates for applicable maintenance activities used in this study. The Markov model was used due to availability of sufficient data and the model ability to capture the probabilistic behavior of pavement and the time dependent uncertainty deterioration process as well as for different maintenance and rehabilitation activities. The cost of the maintenance activities used in this study was obtained from MTO. For the purpose of the case study, roughness and rutting are selected as specified performance measures. Roughness and rutting are widely used in PBCs and the PMS2 contains the historical data for these performance measures. Although only two performance measures are used in this case study, the framework can be extended for any number of performance measures.

Phase-One of, Initial Program, was used to develop the initial maintenance program used for the bidding stage. The optimization method was used to obtain a maintenance program that maintains the specified performance level of service with the lowest cost. To assist with the optimization process, Evolver software is utilized. Evolver is a genetic algorithm optimization add-in for Microsoft Excel.

To illustrate Phase-Two, Project Asset Management, two scenarios were developed. Overestimated deterioration rate, and underestimated deterioration rates of maintenance activity (Hot mix overlay one lift 45 mm) applied at year 4 of the contract period. The implementation of the framework resulted in maintenance program that maintained the performance measures specified level of service over the contract period. In addition, the framework adapted for a variation in the predicted performance to the actual performance allowing for re-optimization and development of alternative maintenance program.

A sensitivity analysis of deterioration rates and the specified performance measures' level of services were performed. Based on the sensitivity analysis of performance level of service, it is evident that the level of service specified has a high influence on the total maintenance cost; as such, contracting agencies should take that into account and carefully select the appropriate level of service.

In Addition, the deterioration rate has a high impact on the maintenance program cost and therefore contractors should implement similar sensitivity analysis during the cost estimation as means to quantify the risk accepted.

In this study, a few maintenance alternatives were considered to demonstrate the framework. Therefore, involving a comprehensive list of maintenance and rehabilitation activities will result in a more precise output of the framework. In addition, with increased number of maintenance and rehabilitation alternative, a more optimized program can be developed.

Furthermore, the optimization model considers the deterioration rate and cost, among others, as the variables in developing the maintenance and rehabilitation program. In this study, the deterioration rates considered were for maintenance activities that affected both performance measures considered, namely roughness and rutting. It is of value to consider routine maintenance activities such as crack sealing, patching, etc. that would improve certain performance measures such as cracking while not improving other performance measures such as roughness. Therefore, investigating and incorporating such effects is some of the future work to be considered.

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Appendix A

Sensitivity Analysis Results

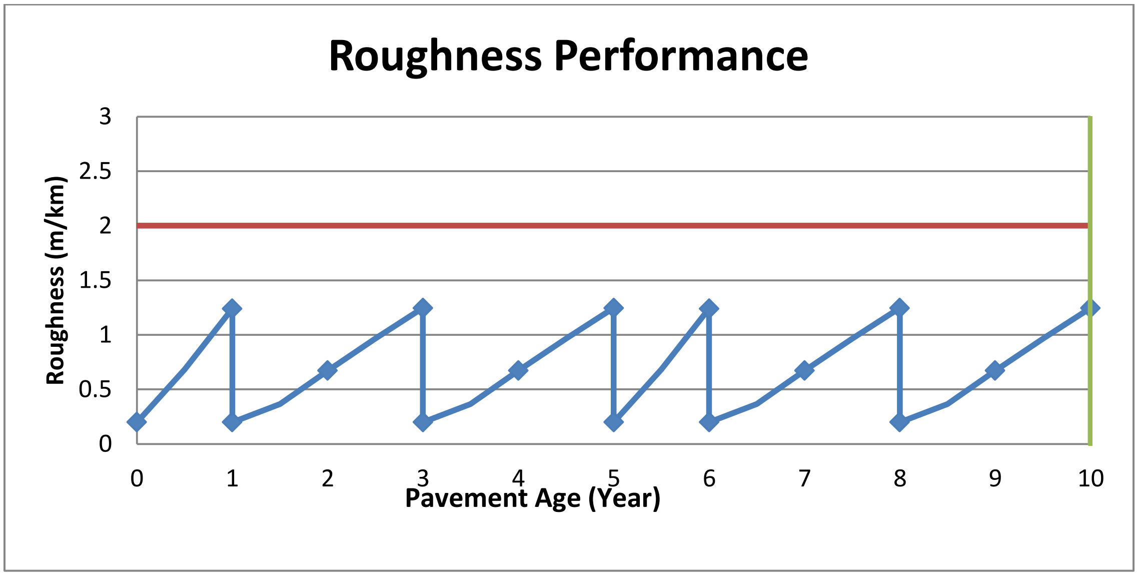

Figure A 1: Roughness Performance (10% Increase in Deterioration)

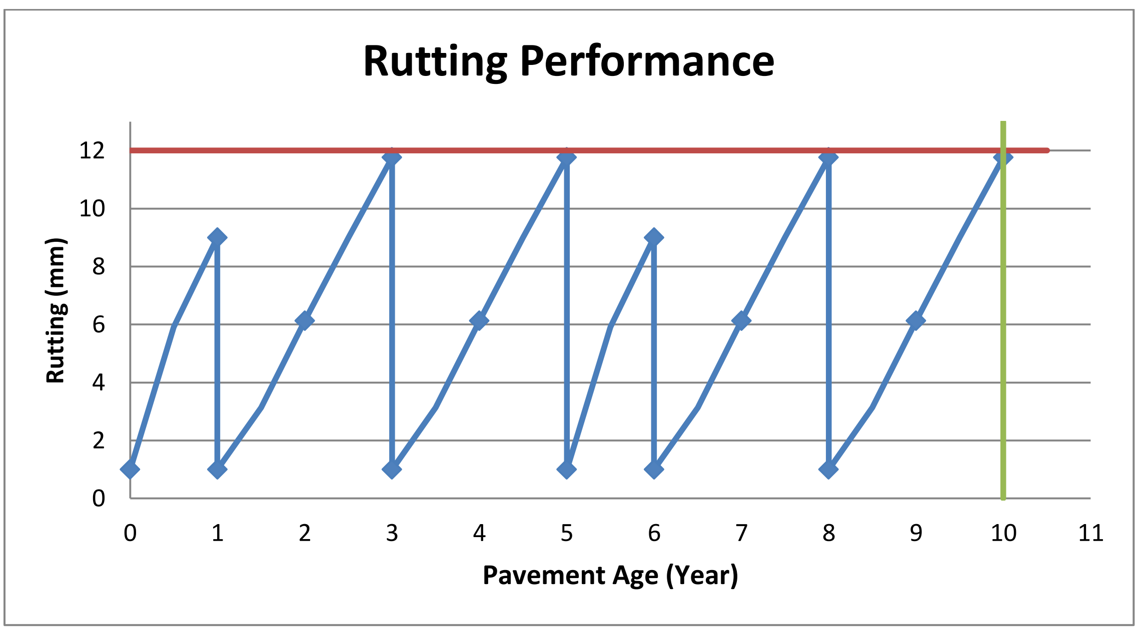

Figure A 2: Rutting Performance (10% Increase in Deterioration)

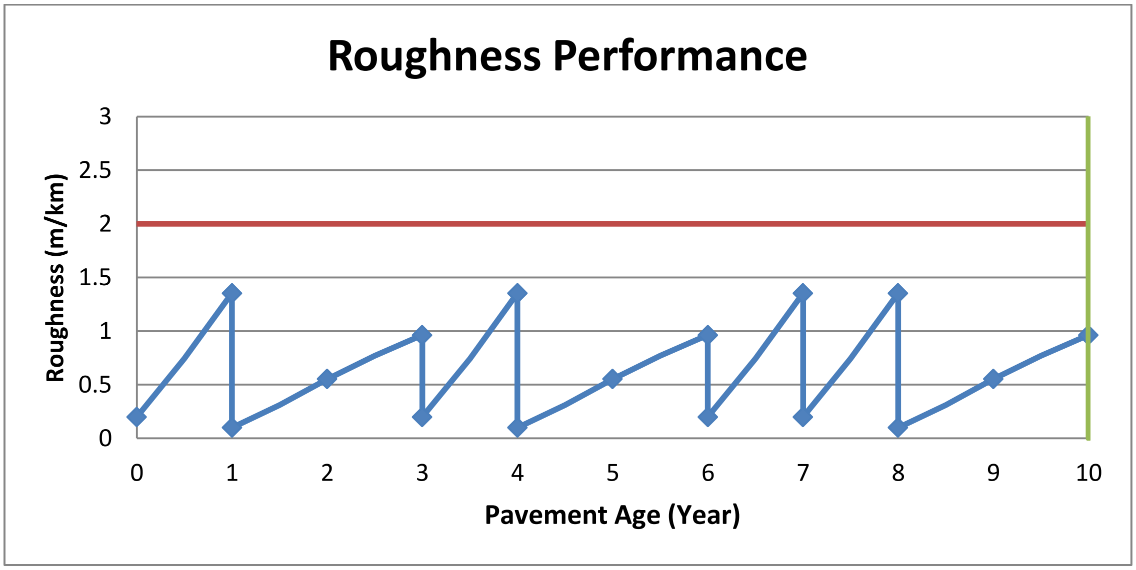

Figure A 3: Roughness Performance (20% Increase in Deterioration)

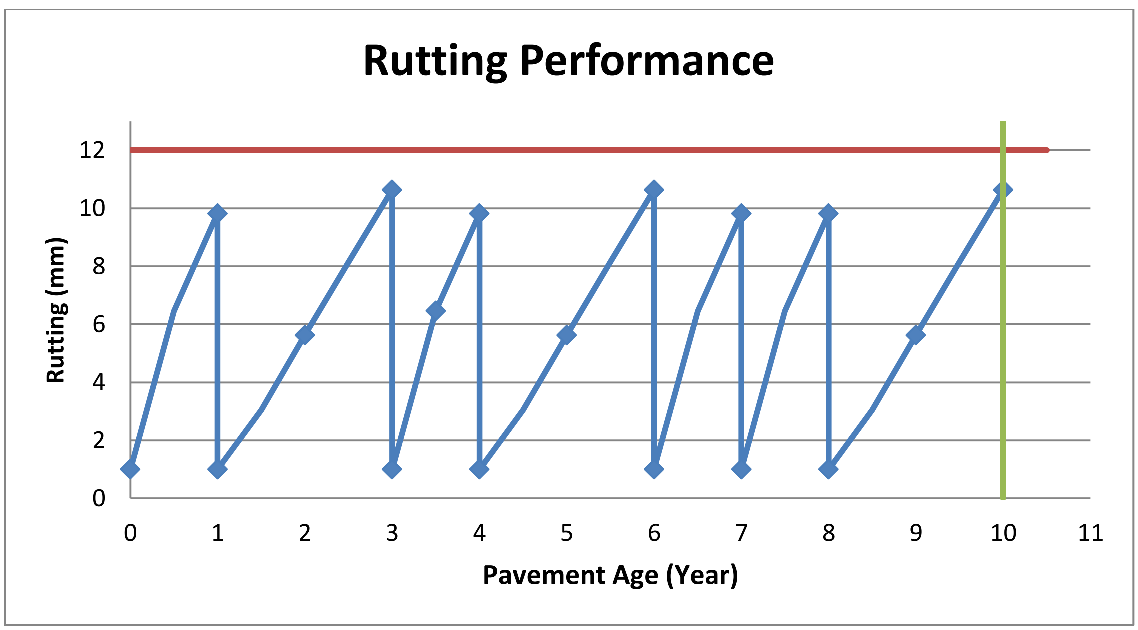

Figure A 4: Rutting Performance (20% Increase in Deterioration)

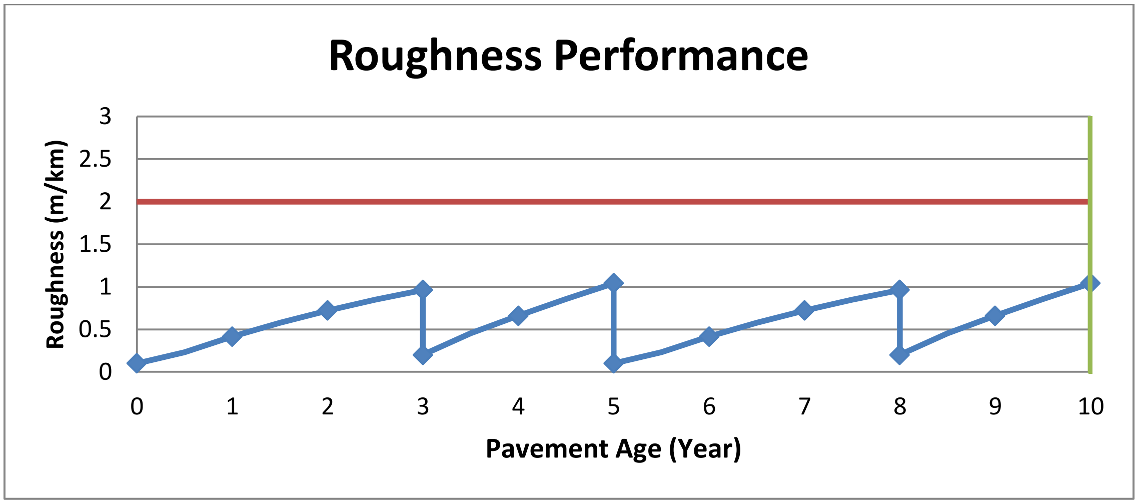

Figure A 5: Roughness Performance (10% Decrease in Deterioration)

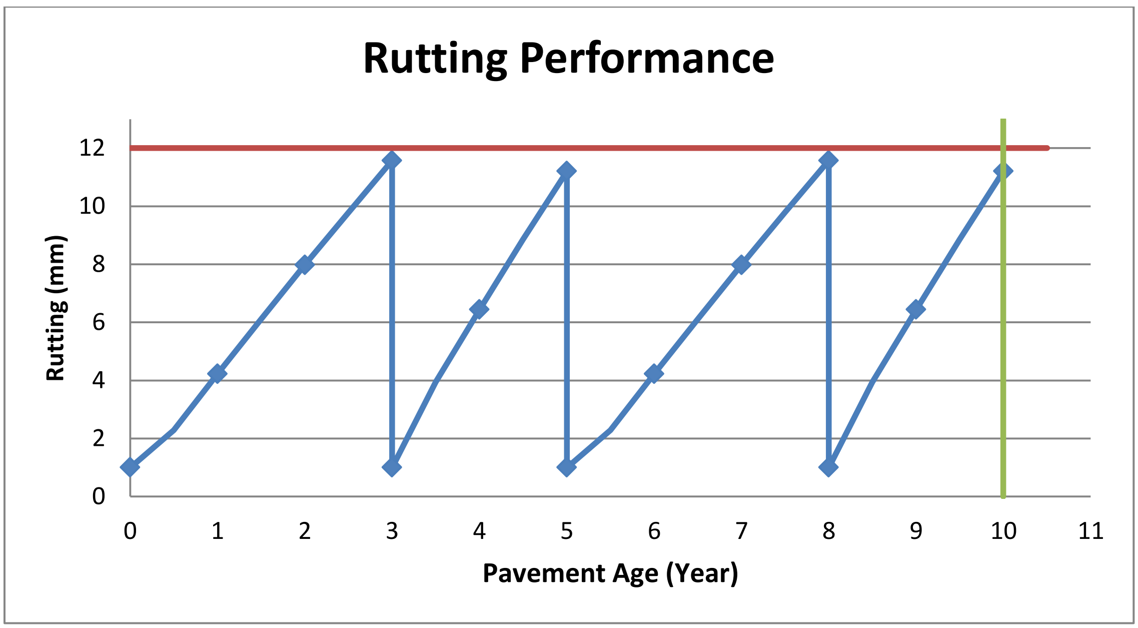

Figure A 6: Rutting Performance (10% Decrease in Deterioration)

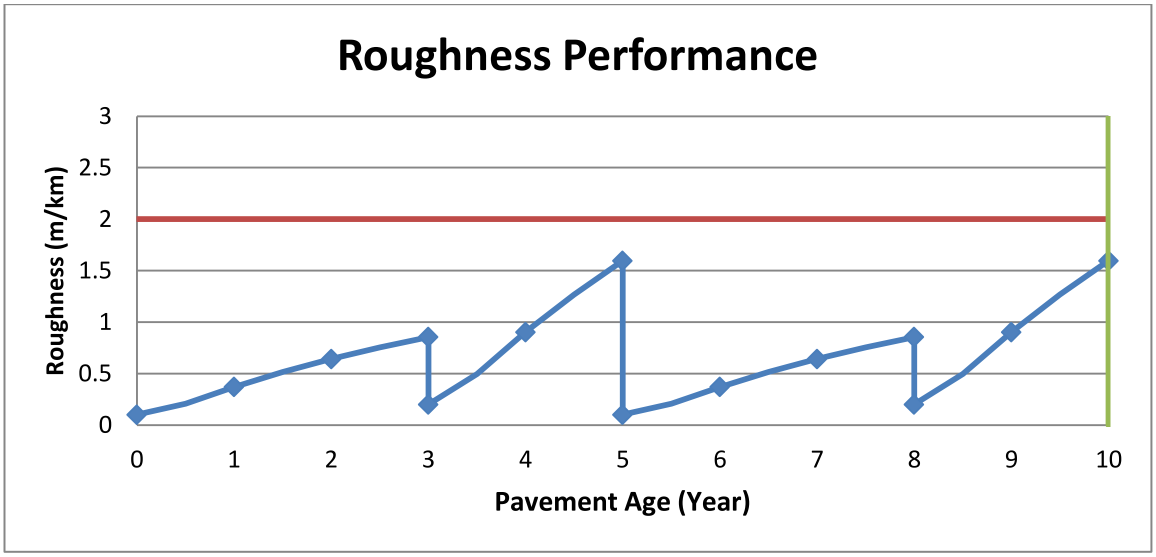

Figure A 7: Roughness Performance (20% Decrease in Deterioration)

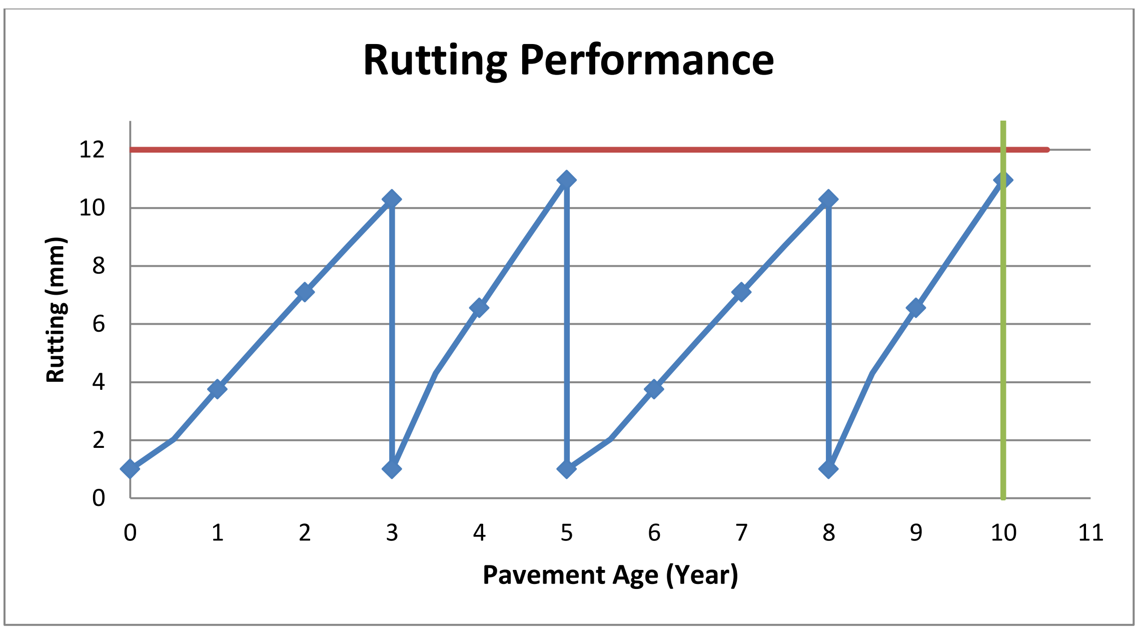

Figure A 8: Rutting Performance (20% Decrease in Deterioration)

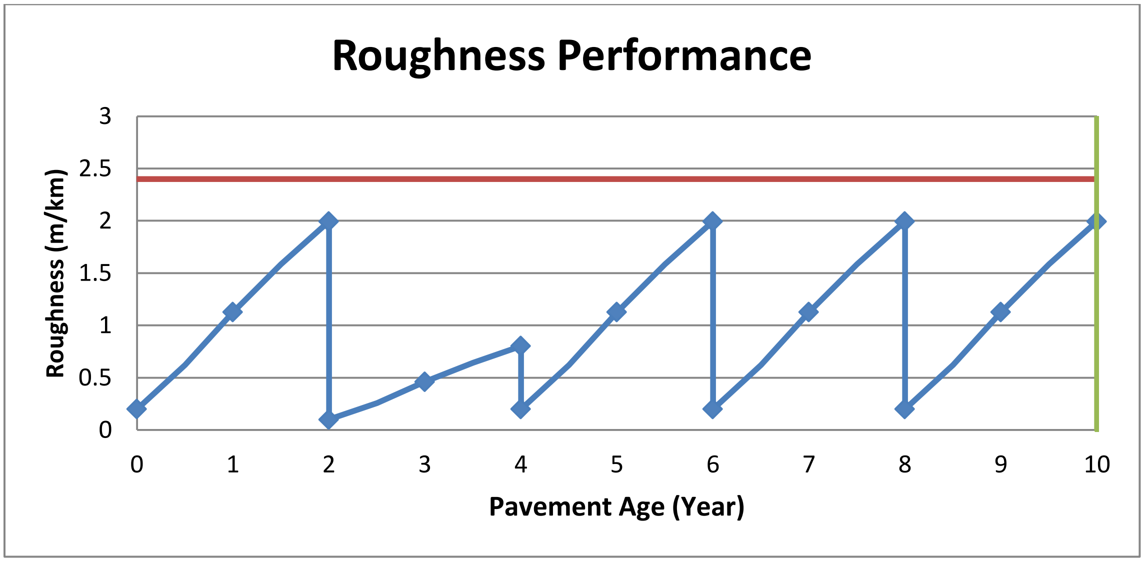

Figure A 9: Roughness Performance (10% Increase in Performance Level of Service)

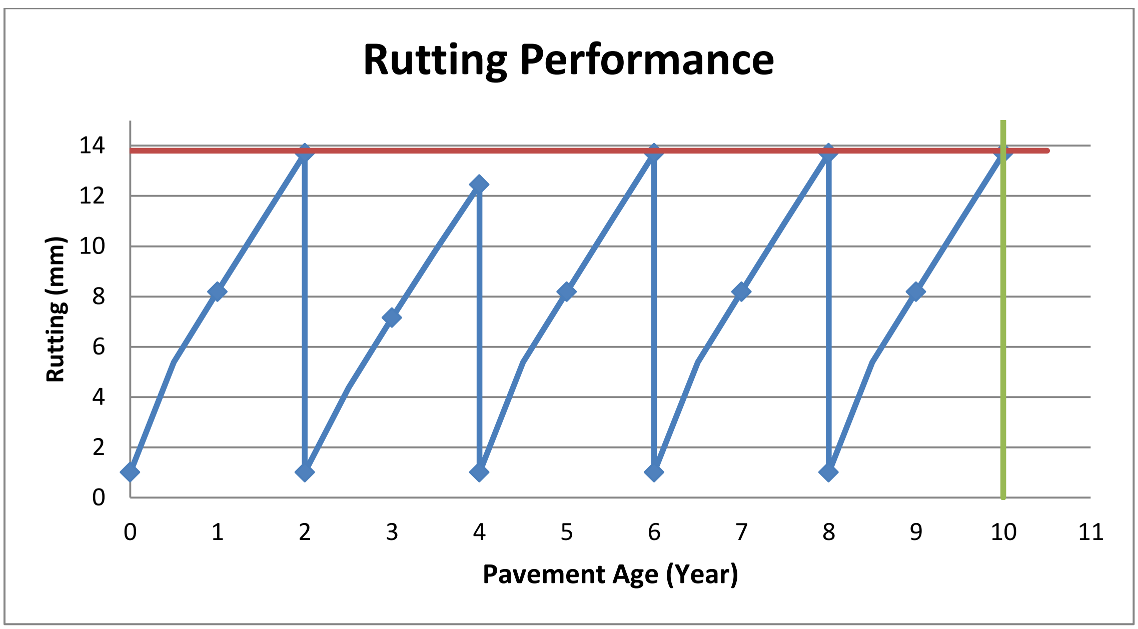

Figure A 10: Rutting Performance (10% Increase in Performance Level of Service)

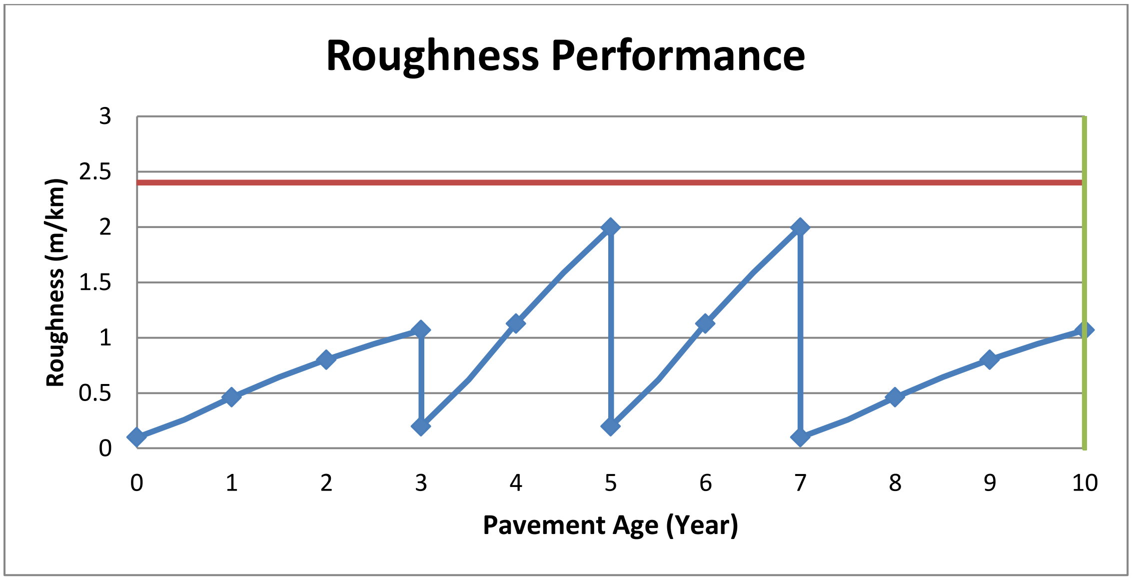

Figure A 11: Roughness Performance (20% Increase in Performance Level of Service)

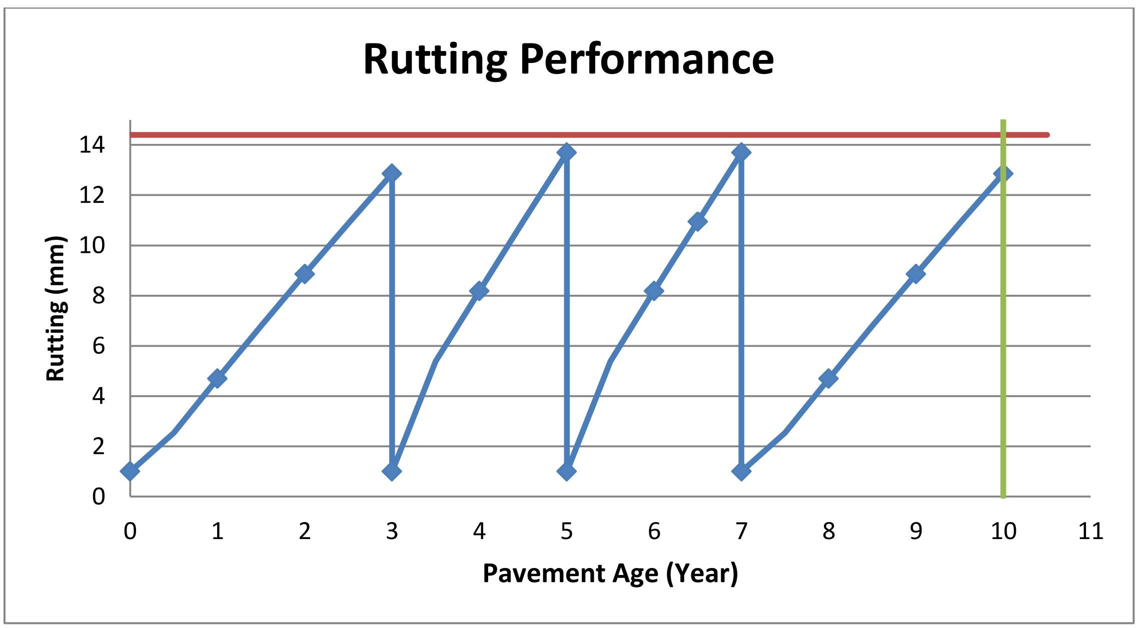

Figure A 12: Rutting Performance (20% Increase in Performance Level of Service)

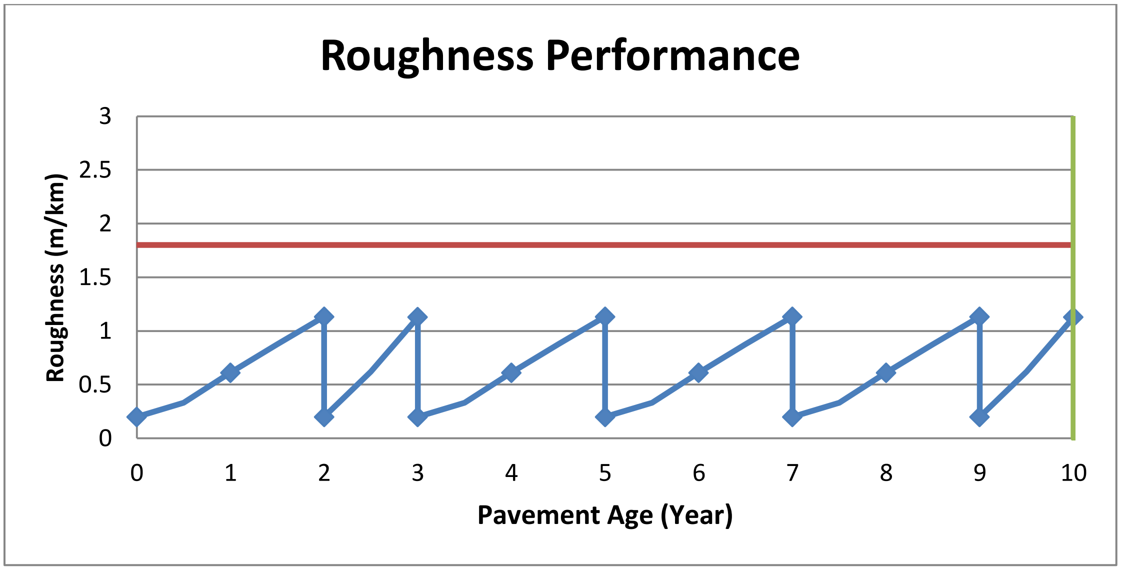

Figure A 13: Roughness Performance (10% Decrease in Performance Level of Service)

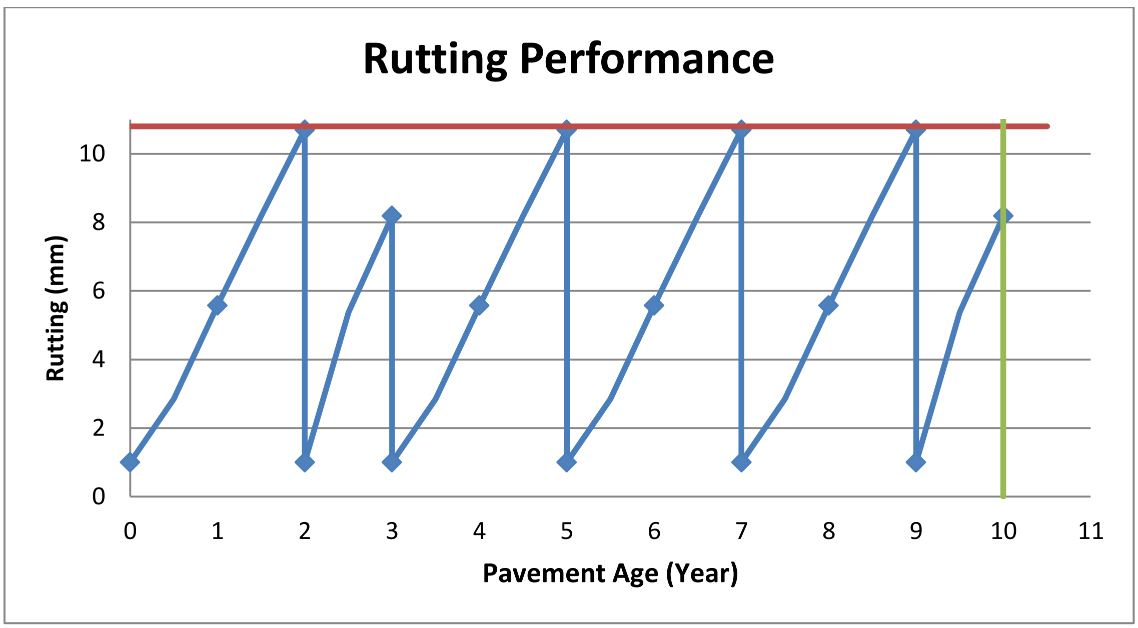

Figure A 14: Rutting Performance (10% Decrease in Performance Level of Service)

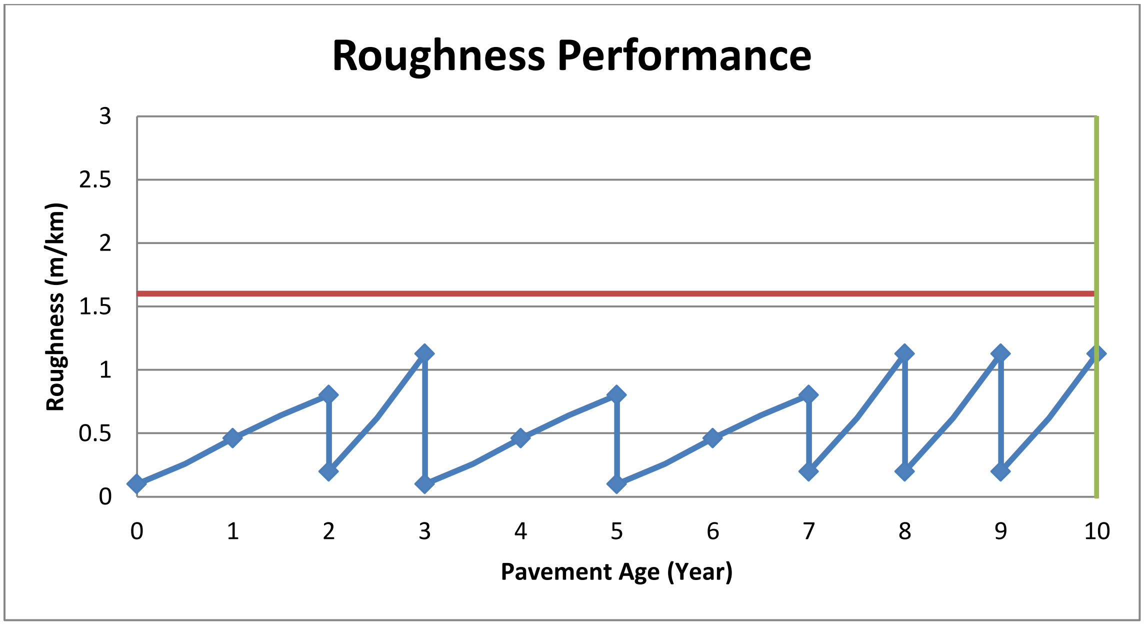

Figure A 15: Roughness Performance (20% Decrease in Performance Level of Service)

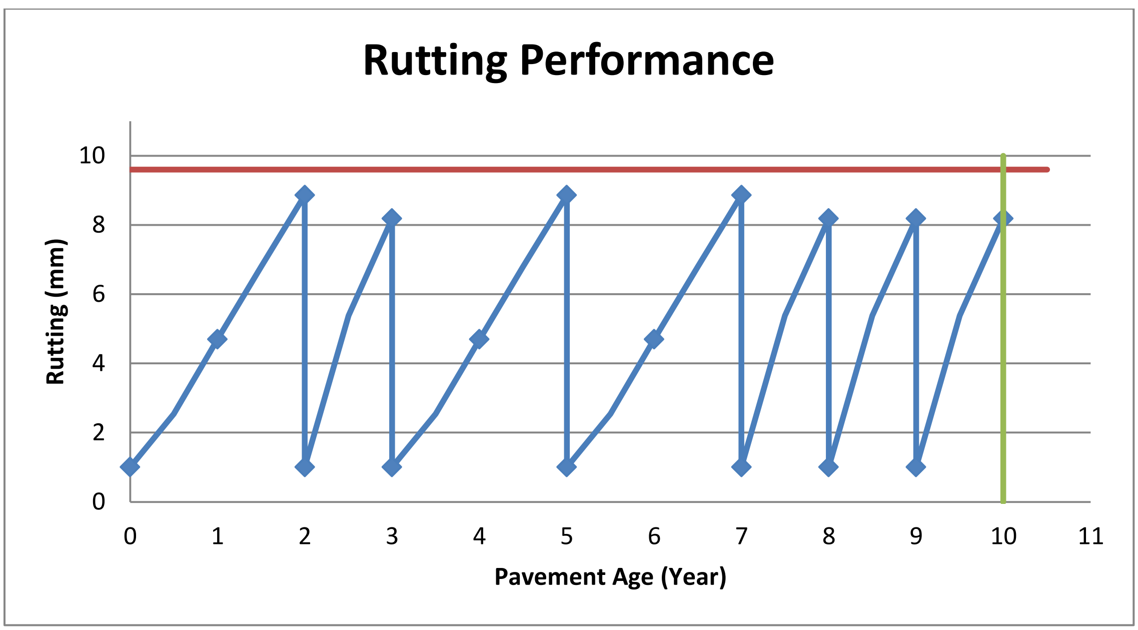

Figure A 16: Rutting Performance (20% Decrease in Performance Level of Service)