Development Practices for Municipal Pavement Management Systems Application

by

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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

Pavement Management Systems (PMS) are widely used by transportation agencies to maintain safe, durable and economic road networks. PMS prioritize the maintenance and rehabilitation of pavement sections by evaluating pavement performance at the network level. There are many PMS software packages that have been developed over the past decades for provincial/state road agencies. However, sometimes due to lack of budget and experience, adopting the existing PMS for a road agency is not cost effective. Thus, it is important to introduce a simple, effective, and affordable PMS for a local agency and municipality.

This research is carried out in partnership between the City of Markham and the Centre for Pavement and Transportation Technology (CPATT) located at the University of Waterloo. For the purpose of developing a PMS for local agencies, an extensive literature review on PMS components was carried out, with emphasizing data inventory, data collection, and performance evaluation. In addition, the literature review also concentrated on the overall pavement condition assessment. In July 2011, a study on "Evaluation of Pavement Distress Measurement Survey" was conducted as a part of this research and was distributed to cities and municipalities across Canada. The study focused on the current state-of-the-practice in pavement distress and condition evaluation methods used by local agencies to compare the results from the literature review. The components of the proposed PMS framework are also developed based on the literature review with some modifications and technical requirements. The City of Markham is selected as a case study, since it represents a local agency and provides all the data, to illustrate the validation of the proposed PMS framework.

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Dedication

I would like to dedicate this thesis to my grandparents, parents, and my brother Amir for supporting me throughout the years of my academic study.

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Chapter 1 Introduction

1.1 Background

Pavement Management Systems (PMS) are widely used by transportation agencies to maintain safe, durable and economic road networks (TAC 2012). PMS prioritize the maintenance and rehabilitation of pavement sections by evaluating pavement performance at the network level (Reza et al. 2006). There are many PMS software packages that have been developed over the past decades for provincial/state road agencies such as the Highway Development and Management Tool (HDM-4). However, sometimes due to lack of budget and experience, adopting the existing PMS for a road agency is not cost effective. Thus, it is important to introduce a simple, effective, and affordable PMS for a local agency and municipality.

1.2 Research Scope and Objectives

This research is carried out in partnership between the City of Markham and the Centre for Pavement and Transportation Technology (CPATT) located at the University of Waterloo. Therefore, developing a simple PMS would assist the local agencies in maintaining their road network effectively.

The main objectives of the research project include defining:

- the inventory data required for the local agencies;
- the pavement performance data that should be collected during the condition survey by local agencies;
- the density levels and severity levels that should be used in assessment of pavement condition;
- the key steps required to implement a PMS.

In short, the research methodology includes development of a framework that can be utilized by the City of Markham and/or other cities and municipalities as a guideline for developing their own simple PMS.

1.3 Research Methodology

For the purpose of developing a PMS for local agencies, an extensive literature review on PMS components was carried out, with emphasizing data inventory, data collection, and performance evaluation. In addition, the literature review also concentrated on the overall pavement condition assessment. In July 2011, a study on "Evaluation of Pavement Distress Measurement Survey" was conducted as a part of this research and was distributed to cities and municipalities across Canada. The study focused on the current state-of-the-practice in pavement distress and condition evaluation methods used by local agencies to compare the results from the literature review. The components of the proposed PMS framework are also developed based on the literature review with some modifications and technical requirements.

1.4 Thesis Organization

This thesis consists of six chapters. The contents of each chapter are explained below.

Chapter One provides an introduction to the research project. A general overview of the thesis scope and objectives is provided. In addition, the research methodology is explained.

Chapter Two provides a literature review that covers the history of the development of pavement management systems, operational levels and users of the pavement management system, its components, and the existing PMS tools.

Chapter Three explains the proposed framework that could be used as a pavement management system for local agencies.

Chapter Four summarizes the results from the study on "Evaluation of Pavement Distress Measurement Survey" that was conducted in July 2011, which were distributed to cities and municipalities across Canada to study the current state-of-the-practice in pavement distress and condition evaluations.

Chapter Five is a case study which illustrates the validation of the proposed framework. The city of Markham is selected as a case study since it represents a local agency and provides all the data.

Chapter Six summarizes the main conclusions of this research and recommendations.

Chapter 2 Literature Review

2.1 Introduction

A pavement management systems (PMS) is "set of tools or methods that assist decision makers in finding optimum strategies for providing and maintaining pavements in a serviceable condition over a given period of time" (Haas et al. 1994). Pavement planning or programming of investments, design, construction, maintenance and rehabilitation, and periodic evaluation of pavement performance and research are the major components of a pavement management system (Reza et al. 2006). Pavement management systems (PMS) are used by transportation agencies to create and maintain safe, dependable and economically viable road networks (TAC 2012). Improving the efficiency of decision making, providing feedback on the consequences of decisions, facilitating the coordination of activities within the agency, and ensuring the consistency of decision made at different management levels within the same organization are the functions of PMS (Haas et al. 1994, TAC 2012).

The term pavement management system was first introduced in the late 1960s and early 1970s as decision support tools for all activities in providing and maintaining pavement (Peterson et al. 1987, Muench et al. 2004). A basic new look at pavement design using a systems approach was first initiated in 1968 by the researchers at the University of Texas to ensure the best use of existing resources (Hudson et al. 1968). At the same time, similar efforts were conducted in Canada to organize the overall pavement design and management (Hutchinson et al. 1968, Haas et al. 1994). The last similar effort was performed by Scrivner and others at the Texas Transportation Institute of Texas A&M University (Scrivner et al. 1968). The results of works established by these three groups provide the overall historic perspective for pavement management systems (Haas et al. 1994). A pavement management system was then described by Hudson in 1979 as "…a coordinated set of activities, all directed toward achieving the best value possible for the available public funds in providing and operating smooth, safe, and economical pavements." (Hass 1978, Muench et al. 2004, Hudson 1979). The term "activities" was defined as works related to pavement planning, design, construction, maintenance, evaluation and research (Haas 1978, Muench et al. 2004). Most of the results developed in early pavement management systems were summarized in two books by Haas (Haas et al. 1977, Haas 1978).

2.2 Network Level vs. Project Level

“Network level” and “project level” are the two different operating levels in a pavement management system. The primary principle at the network level is to develop a priority program and schedule of work for the whole network and is generally concerned with high-level decisions relating to budget, policy, and network planning (Haas et al. 1994, Kirbas 2010). Major component activities at the network level are road sectioning, data acquisition, and data processing. Project level on the other hand represents the physical implementation of network decisions (Haas et al. 1994, TAC 2012). Shown in Table 2.1 are the major component activities for network level and project level.

Table 2.1: Network Level and Project Level Major Component Activities (Haas et al. 1994, TAC 2012)

Network Management Level
• Sectioning, data acquisition (field data on roughness, surface distress, structural adequacy, surface friction, geometrics, traffic, costs and other data) and data processing. • Criteria for minimum acceptable serviceability, maximum surface distress, minimum structural adequacy, etc. • Application of deterioration prediction models. • Determination of current needs and future needs, evaluation of options and budget requirements. • Identification of alternatives, development of priority programs and schedule of work (rehabilitation, maintenance, new construction).
Project Management Level
• Subsectioning, detailed field / lab and other data on scheduled projects, and data processing. • Technical (prediction deterioration) and economic analysis of within-project alternatives. • Selection of best alternative, detailed quantities, costs, and schedules. • Implementation (construction, periodic maintenance).

2.3 Users of PMS

A pavement management system is a tool that processes the information for use by decision makers. Legislative, Administrative, and Technical are the three level users who make decisions when using a pavement management system (Haas et al. 1994, TAC 2012). Figure 2.1

summarizes some of the decision support requirements from a pavement management system for each level user (Falls et al. 2001). However, depending on the agency (i.e. state/provincial, city, county) the focus and scope of the level users may differ (Haas et al. 1994, TAC 2012).

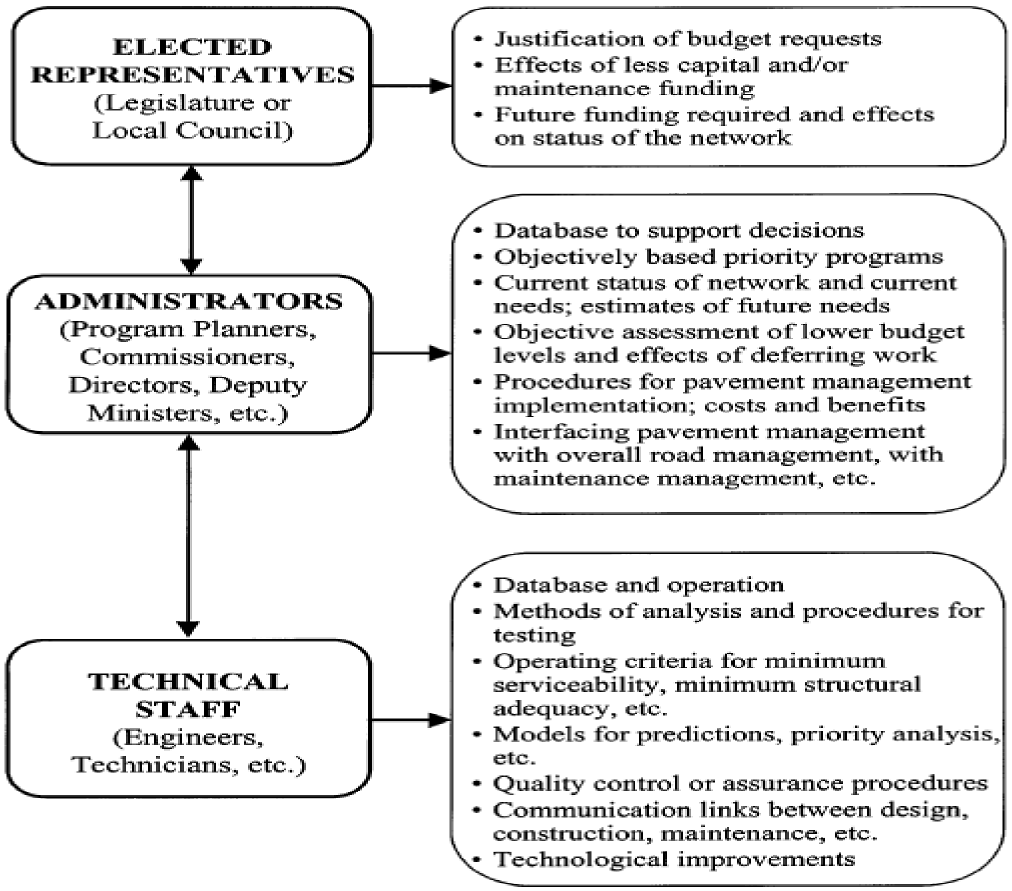


Figure 2.1: Major Classes of Pavement Management System Users and Some of their Decision Support Requirement (Falls et al. 2001)

2.4 Pavement Management System Components

Inventory data, pavement condition assessment, establishing criteria, prediction models for pavement performance deterioration, rehabilitation and maintenance strategies, priority programming of rehabilitation and maintenance, economic evaluation of alternative pavement design strategies, and program implementation are the necessary components of a pavement management system.

2.4.1 Data Inventory

A pavement management system coordinates all activities needed for providing pavement structures in a cost-effective manner (Haas et al. 1994, TAC 2012). In order to efficiently select and coordinate activities for each road segment, it requires collecting a broad database including pavement condition and performance. Table 2.2 encapsulates the classes of data required for the pavement management system (Haas 1991).

Table 2.2: Major Classes and Component types of Pavement Data (Haas 1991)

Section Reference and Description	
Performance Related Data • Roughness • Surface Distress • Deflection • Friction • Layer Material Properties	**Geometric Related Data** • Section Dimensions • Curvature • Cross Slope • Grade • Shoulder/Curb
Historical Related Data • Maintenance History • Construction History • Traffic • Accidents	**Environmental Related Data** • Drainage • Climate (Temperature, rainfall, freezing)
Policy Related Data • Budget • Available Alternatives (Maintenance and rehabilitation)	**Cost Related Data** • Construction Cost • Maintenance Cost • Rehabilitation Cost • User Cost

Usually, every functional division (i.e. planning, operation,..) in agencies have various methods of referencing the location of pavement sections. Identifying pavement sections within the network using a common referencing method is one of the first tasks for developing the pavement management system (Haas et al. 1994, TAC 2012). Node-link, branch-section, geographic information system (GIS), and route-milepost are the four basic methods of referencing pavement sections (Hass et al. 1994, TAC 2012).

The key points in the network are defined as nodes and the links are the sections between each node in the node-link method. Intersections, boundaries, and change in pavement characteristics are usually defined as nodes. In the branch-section method, the overall features of the pavement network such as roads are expressed as branches and similar units of the branches are expressed as sections (Haas et al. 1994, TAC 2012). A geographic information system (GIS) can define the location of every feature of the network using the coordination system. The last referencing method is the route-milepost system which is widely used among the state highway agencies. In this method, routes are defined by a unique name or number, and mileposts are numbered consecutively along the length of the route (Haas et al. 1994, TAC 2012).

Geometric data is related to the physical characteristics or features of the pavement section and can be used as basic planning information and to express if the existing geometry satisfies current standards.

Not only do drainage and shoulder characteristics have a direct impact on pavement performance, but change in the climatic conditions also is an important factor. Thus, collecting environmental data is one of the main classes of data that are essential to collect. Pavement performance data is essential to evaluate the current condition of the pavement structure. Cost of new construction, maintenance, rehabilitation, and usually user costs is the data that should be included in the cost inventory. Models of vehicle operating cost, traffic volumes, and condition of pavement are the methods that are used to estimate user costs (Haas et al. 1994, TAC 2012).

2.4.2 Pavement Condition Assessment

PMS prioritize the maintenance and rehabilitation of pavement sections by evaluating pavement performance at the network level (Reza et al. 2006).To evaluate pavement performance, most provincial/states in Canada and the United States perform data collection activities in one or more of the following four main areas: surface distress, roughness, structural adequacy, and friction (NCHRP 2004). Collection and utilization of pavement distress data varies amongst agencies. Each agency typically develops their own data collection guidelines or protocols according to their needs. However, some agencies such as the Ministry of Transportation of Ontario (MTO), American Association of State Highway and Transportation Officials (AASHTO), American Society for Testing and Materials (ASTM), Strategic Highway Research Program (SHRP), and the Federal Highway Administration (FHWA) usually establish well developed guidelines to standardized data collection methodologies (Chamorro et al. 2008). These protocols can be found at (MTO 1989, MTO 1995, AASHTO 2003, ASTM 2003, FHWA 2003). Most of the agencies use a distress index, index/rating, priority rating, and serviceability as the output for the distress survey (NCHRP 2004). However, almost all agencies have differences in quantifying both the severity and density of distresses. More than 80% of the agencies combine their distress index or ratings with other indices or ratings such as roughness (NCHRP 2004).

2.4.2.1 Distress Type

Pavement distress data collection is one of the essential factors for evaluating the pavement performance. Distress types are divided into three categories of cracking, surface deterioration, and distortion (Reza et al. 2006). Table 2.3 summarizes the type of pavement distresses which are collected by some of the Canadian and USA agencies for flexible pavement. Moreover, Table 2.3 indicates which agencies collect International Roughness Index (IRI) and Skid Resistance (SN).

Table 2.3: Types of Pavement Distress Collected by Agencies for Flexible Pavement (NCHRP 2004, Papagiannakis et al. 2009)

Agencies	Performance Condition Index	Cracking	Rutting	Ravelling	Flushing/ Bleeding	Rippling/ Shoving	Distortion	Patching	Potholes	IRI	Skid Resisitance
Ontario	PCI	x	x	x	x	x	x			x	
British Columbia	PCR	x	x	x	x	x	x		x	x	
Quebec	PCI	x								x	
Manitoba	PQI	x	x							x	
Alaska	PCI	x	x					x		x	
California	PCS	x	x	x	x		x		x		x
Florida	PCR	x	x	x	x	x	x	x	x		
Georgia	PCI	x	x	x	x	x	x		x	x	
Indiana	PCR	x	x							x	
Iowa	PCI	x					x			x	
Kansas	PCI	x	x							x	
Louisiana	PCI	x	x					x		x	
Maine	PCR	x	x							x	
Minnesota	PQI	x	x	x				x		x	
Mississippi	PCR	x		x	x				x		
New Mexico	PSI	x	x	x		x					
Ohio	PCR	x	x	x	x			x			
Oregon	PCI	x	x	x	x			x	x		
Pennsylvania	OPI	x	x	x				x			
Washington DC	PSC	x						x			
Wisconsin	PDI	x	x	x	x		x	x			
	Total	**21**	**17**	**12**	**9**	**5**	**7**	**9**	**6**	**12**	**1**

Based on Table 2.3, it can be concluded that all 21 agencies included in the evaluation collect cracking (longitudinal wheel cracking, meander and mid-lane cracking, transverse cracking, and alligator cracking). It also can be observed that, 17 out of 21 agencies collect rutting, 12 agencies are collecting IRI, raveling as a surface deterioration distress is collected by 12 agencies, and skid resistance is collected only by the California Department of Transportation. The least collected data are shoving, potholes, distortion, and flushing.

2.4.2.2 Distress Severity Levels and Distress Density Levels

Distress severity levels and density severity levels are the important factors after identifying the distress types for evaluating the pavement performance. The term severity indicates the condition of the pavement, or practically how bad the distress is. On the other hand, density describes the extent of occurrence or frequency of the distress (MTO 1989). In 1990, the Strategic Highway Research Program (SHRP) developed a Distress Identification Manual for the Long-Term Pavement Performance Project (SHRP-P-338) (Chamorro et al. 2008). However, this manual has been continuously updated by the FHWA of U.S. Department of Transportation. The manual consists of three types of pavement (Asphalt Concrete, Jointed PCC, and Continuously Reinforced Concrete) with almost all having three severity levels (low, moderate and high) (FHWA 2003). Table 2.4 presents the distresses considered by the SHRP manual per pavement type.

Table 2.4: Distresses and Severity Levels per Pavement Type by SHRP Manual (Chamorro et al. 2008)

Asphalt Concrete		**Jointed PCC**		**Continuously Reinforced Concrete**	
Distress Type (Units)	**Severity Levels**	**Distress Type (Units)**	**Severity Levels**	**Distress Type (Units)**	**Severity Levels**
Fatigue Cracking (m^2)	3	Corner Brakes (N^o)	3	Durability "D" Cracking (m^2)	3
Block Cracking (m^2)	3	Durability Cracking (m^2)	3	Longitudinal Cracking (m)	3
Edge Cracking (m)	3	Longitudinal Cracking (m)	3	Transverse Cracking (m)	3
Longitudinal Cracking (m)	3	Transverse Cracking (m)	3	Map Cracking and Scaling (m^2)	-
Reflection Cracking (m)	3	Joint Seal Damage (m Longitudinal and N^oTransverse)	3	Polished Aggregate (m^2)	-
Transverse Cracking (m)	3	Spalling Longitudinal Joints (m)	3	Popouts(N^o)	-
Patch Deterioration (m^2 and N^o)	3	Spalling Transverse Joints (m and N^o)	3	Blowups (N^o)	-
Potholes (m^2)	3	Map Cracking and Scaling (m^2)	-	Transverse Construction Joint Deterioration (N^o)	3
Rutting (mm)	-	Polished Aggregate (m^2)	-	Lane-to-Shoulder Dropoff (mm)	-
Shoving (m^2)	-	Popouts(N^o)	-	Lane-to-Shoulder Separation (mm)	-
Bleeding (m^2)	-	Blowups (N^o)	-	Patch Deterioration (m^2 and N^o)	3
Polished Aggregate (m^2)	-	Lane-to-Shoulder Dropoff (mm)	-	Punchouts (N^o)	3
Raveling (m^2)	-	Lane-to-Shoulder Separation (mm)	-	Spalling Longitudinal Joints (m)	3
Lane-to-Shoulder Dropoff (mm)	-	Faulting (mm)	-	Water Bleeding and Pumping (m and N^o)	-
Water Bleeding and Pumping (m and N^o)	-	Patch Deterioration (m^2 and N^o)	3	Longitudinal Joint Seal Damage (m)	-
		Water Bleeding and Pumping (m and N^o)	-		

Table 2.5 presents the distress severity levels and distress density levels that are used by some of the Canadian and USA agencies for evaluating the condition of the flexible pavement.

Table 2.5: Severity Levels and Density Levels Consideration for Agencies for Flexible Pavement Distress Data Collection. (MTO 1989; Opus International Consultants Limited 2009; NCHRP 2004, Papagiannakis et al. 2009)

	Severity Levels		Density Levels		
Agencies	**Three Severity Levels**	**Five Severity Levels**	**Three Density Levels**	**Five Severity Levels**	**Quantity/Area (%)**
Ontario		x		x	
British Columbia	x			x	
Quebec	x				x
California	x				x
Florida	x				x
Georgia	x		x		
Indiana	x				x
Iowa	x				x
Kansas	x				x
Minnesota	x				x
Mississippi	x				x
Ohio	x				x
Pennsylvania	x				x
Washington DC	x				
Total	**13**	**1**	**1**	**2**	**11**

As shown in Table 2.5, most agencies consider three severity levels (low, moderate and high) for distress types. On the other hand, the density levels are calculated as a percentage by dividing the area of each distress (distress quantity) over the area of inspected pavement section (Sharaf 2004).

2.4.2.3 Pavement Performance Index

Agencies tend to establish pavement performance indices that incorporate different pavement physical attributes to quantify the overall pavement condition. Each agency calls and calculates its overall condition index differently to some extent. Pavement performance indices, such as Pavement Condition Index, are a mathematical equation of which the inputs are pavement distresses, IRI and rutting (Papagiannakis et al. 2009, NCHRP 2004).

Table 2.6 presents the available pavement performance indices that are being used by provincial/state and municipal agencies.

Table 2.6: Available Pavement Performance Indices (Silva et al. 2008)

Pavement Performance Indices
Composite Condition Index (CCI)
Hansen's Overall Condition Index (OCI)
International Roughness Index (IRI)
Pavement Condition Index (PCI)
Pavement Condition Rating (PCR)
Pavement Quality Index (PQI)
Pavement Structural Condition (PSC)
Qualitative Condition Index (QCI)
Riding Comfort Index (RCI)
Pavement Distress Index (PDI)
Structural Adequacy Index (SAI)
Surface Distress Assessment (SDA)
Surface Distress Index (SDI)
Pavement Serviceability Index (PSI)
overall Pavement Condition (OPI)
Pavement Condition Survey (PCS)

Table 2.6 summarizes the pavement performance indices that are being used by some of the agencies. It can be concluded from Table 2.3 that 8 agencies out of 21 agencies are using the PCI as the pavement performance index to express their pavement condition.

2.4.2.4 Data Collection Methodology

Provincial/state agencies collect pavement performance data manually, using semi-automated tools, automated tools, or two or more of the three. Manual survey inspection requires a trained inspector or a team of trained inspectors who are assessing the type, severity, and density of the distress by visual inspection. This method is labor intensive, relatively unsafe, and subjective (Smith et al. 1996). In automated or semi-automated data collection, video cameras, laser sensors, and strobe lights, are mounted to the vehicle and as vehicle passes on the roads data are instantaneously collected. Then the taken photos are analyzed with the aid of automated or semi-automated software to report the pavement distress. This is a safe, quick and more reliable method (Smith et al. 1996, Tighe et al. 2008). Tables 2.7 and 2.8 illustrate some of the techniques available for collecting pavement surface cracking data and roughness data, respectively.

Table 2.7: Technologies for Collecting Pavement Surface Cracking Data

System	System Provider
ARAN- Pavement View Digital Images	Fugro Roadware Inc. (Fugro 2011a)
The Laser Road Surface Tester (RST)	Infrastructure Management Services (IMS 2011)
Laser Crack Measurement System	Pavemetrics System Inc. (Pavemetrics 2011)
Digital Highway Data Vehicle DHDV	WayLink Sysytem Corporation (WayLink 2011)
PathRunner Data Collection System	Pathway Services Inc. (Pathway 2011a)

Table 2.8: Technologies for Collecting Roughness

System	System Provider
ARAN - Laser Longitudinal Profiling Sysytem	Furgo Roadware Inc. (Fugro 2011b)
The Laser Road Surface Tester (RST)	Infrastructure Management Services (IMS 2011)
PathRunner-Inertial Road Profiler	Pathway Services Inc. (Pathway 2011b)
Digital Highway Data Vehicle DHDV	WayLink Sysytem Corporation (WayLink 2011)
eRoadInfo Pavement High Speed Profiling	Surface Systems & Instruments, LLC (SSI 2011)
SurPRO 200 Rolling Profiler	International Cybernetics Corporation (ICC 2011)

Table 2.9 presents the types of data which are collected using the automated data collection techniques by some of the states.

Table 2.9: Data Collected Automatically by Each Agency (Timm 2004)

Agency	IRI	Rutting	Cracking	Faulting	Friction	Other
Arizona	X	X			X	
Arkansas	X	X	X	X		
Colorado	X	X	X			
Illinois	X	X	X			
Indiana	X	X	X	X		
Kansas	X	X		X		
Louisiana	X	X	X	X		
Maine	X	X	X			
Maryland	X	X	X		X	
Michigan	X	X	X			
Minnesota	X	X	X	X		
Mississippi	X	X	X	X		
Missouri	X	X				
Nebraska	X	X	X	X		
New Jersey	X	X	X			
New York	X	X		X		
Oklahoma	X	X	X	X		X
Pennsylvania	X	X	X	X		
South Dakota	X	X		X		X
Texas	X	X				
Vermont	X	X	X			
West Virginia	X	X				
Total	**22**	**22**	**15**	**11**	**2**	**2**

2.4.2.5 Ministry of Transportation of Ontario (MTO) Manuals for Pavement Condition Assessment

The Ministry of Transportation of Ontario (MTO) has developed their own pavement distress condition rating survey manuals for flexible, rigid, surface treated and composite pavements (MTO 1989, MTO 1995). For each distress type, there are five severity levels (very slight, slight, moderate, severe and very severe) and five density levels (few, intermittent, frequent, extensive and throughout). However, for surface treated pavement, there are three severity levels (slight, moderate, severe) and three density levels (intermittent, frequent, extensive). The severity and density level for each pavement type is assigned subjectively by a surveyor. Table 2.10 shows a summary of a study that was completed for MTO which reviewed and recommended which distresses should be collected by MTO on the four different types of pavement.

Table 2.10: MTO Pavement Distresses by Pavement Type (Tighe et al. 2008)

Flexible	**Rigid**	**Surface Treated**	**Composite**
Ravelling	Ravelling	Ravelling	Ravelling
Flushing	Polishing	Flushing	Flushing
Rippling/Shoving	Scaling	Streaking	Spalling
Wheel track rutting	Potholing	Potholing	Tenting or cupping
Distortion	Joint cracking or spalling	Rippling and shoving	Wheel track rutting
Longitudinal wheel track cracking	Faulting	Wheel track rutting	Joint failure
Single or multiple	Distortion	Distortion	Distortion and settlement
Alligator cracking	Joint Failure	Longitudinal Cracking	Longitudinal meander cracking
Meander and mid-lane	Longitudinal meander cracking	Transverse cracking multiple	Pavement edge breaking
Transverse alligator	Transverse cracking	Transverse joint reflective cracking	Alligator cracking
Centreline alligator	Sealant loss	Centreline cracking single	
Pavement edge single multiple	Diagonal corner or edge cracking	Centreline cracking multiple	
Pavement edge alligator			

Appendix A summarizes various distresses and associated density level and severity levels for every distress for both flexible pavement and rigid pavement based on MTO's manuals (MTO 1989, MTO 1995). MTO uses an overall pavement performance index called Pavement Condition Index (PCI_{MTO}). This index is a function of Distress Manifestation Index (DMI) and Ride Comfort Index (RCI) (Tighe et al. 2008). The DMI is a composite subjective measure of severity and density of pavement surface distresses, and it varies from 0 to 10, where 0 represents a poorest pavement condition and 10 indicates a new pavement (Ningyuan et al. 2004).

$$DMI = 10 * \left(\frac{DMImax - \sum_{i=1}^{n} wi(si+di)}{DMImax}\right) \quad \text{(Equation 2.1)}$$

Where:

i =Distress type

Wi =Relative weight of a distress manifestation

Si =Severity of a distress manifestation

Di =Density of a distress manifestation

DMI_{max}=The maximum theoretical value dedicated to an individual pavement distress (196 for Portland cement concrete, 216 for composite pavement, 208 flexible pavement, and 180 for surface treated pavement)

Tables 2.11 and 2.12 present the weighting factors for each pavement distress index, and severity and density levels, respectively.

Table 2.11: MTO Weighting Factors of Distress Index by Pavement Type (Ningyuan et al. 2004)

AC Pavement	W	PCC Pavement	W	COM Pavement	W	ST Pavement	W
Ravelling	3	Ravelling	0.5	Ravelling	3	Ravelling	3
Flushing	1.5	Polishing	1.5	Flushing	1.5	Flushing	2
Rippling or Shoving	1	Scaling	1.5	Spalling	2	Streaking	1
Rutting	3	Potholing	1	Tenting or cupping	2.5	Potholing	1
Distortion	3	Joint cracking or spalling	2	Rutting	3	Rippling or Shoving	2
Multiple cracking	1.5	Faulting	2.5	Joint failure	3	Rutting	3
Alligator cracking	3	Distortion	1	Distortion and settlement	1	Distortion	3
Mender mid-lane cracking	1	Joint failure	3	Longitudinal mender cracking	2	Longitudinal cracking	1
Transverse alligator	3	Longitudinal mender cracking	2	Transverse cracking multiple	1	Pavement edge breaking	2
Centreline alligator	2	Transverse cracking	2	Transverse joint reflective cracking	2	Alligator cracking	3
Pavement edge single/multiple	0.5	Sealant loss	0.5	Centreline cracking single	0.5		
Pavement edge alligator	1.5	Diagonal corner/edge cracking	2.5	Centreline cracking multiple	1.5		

Table 2.12: MTO Weighting Factors of Distress Severity and Density of Pavement (Tighe et al. 2008)

Severity of Distress (s_i)		**Density of Distress (d_i)**		
Description	s_i	**Description**	**Percentage**	d_i
Very Slight	0.5	Few	<10	0.5
Slight	1	Intermittent	10-20	1
Moderate	2	Frequent	20-50	2
Severe	3	Extensive	50-80	3
Very Severe	4	Throughout	>80	4

The overall pavement condition index is calculated by the following equation (Ningyuan et al. 2004).

$PCI_{MTO} = 10 * DMI * Ci * \sqrt{0.1 * RCI}$ (Equation 2.2)

Where:

PCI_{MTO} = MTO Pavement Condition Index (0-100)

RCI = Riding Comfort Index obtained from pavement roughness measures (0-10). Table 2.13 presents the RCI rating scale

DMI = Distress Manifestation Index (0-10)

Ci = Coefficient calibration for each pavement type

Table 2.13: MTO Ride Condition Rating Guide (MTO 1989)

RCI	**Ride Condition**	**Guidelines**
8-10	Excellent	Very smooth ride
6-8	Good	Smooth ride with few bumps
4-6	Fair	Comfortable ride with intermittent bumps
2-4	Poor	Uncomfortable ride with frequent bumps
0-2	Very Poor	Uncomfortable ride with constant bumps

PCI_{MTO} varies from 0 to 100, where 0 indicates the poorest pavement condition and 100 represents the newest pavement condition. Figure 2.2 presents categorization of the pavement condition index.

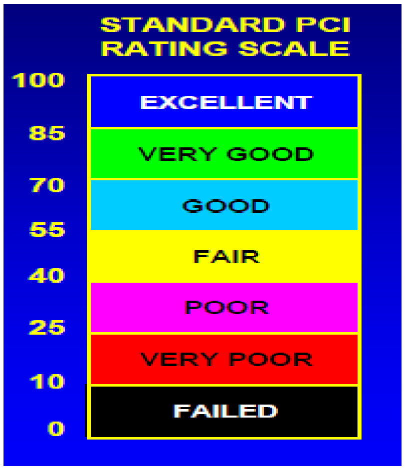


Figure 2.2: Pavement Condition Index and Rating (Emery 2006)

2.4.2.6 British Columbia Ministry of Transportation (BCMoT) Manuals for Pavement Condition Assessment

The British Columbia Ministry of Transportation (BCMoT) has developed their own pavement distress condition rating survey manual for flexible pavements (BCMoT 2009). For each distress type there are three severity levels (low, moderate and high) and five density levels (few, intermittent, frequent, extensive and throughout). The severity and density level is assigned subjectively by an evaluator for every 50m segment according to the pavement condition rating manual (BCMoT 2009). Tables 2.14 and 2.15 are the density and severity levels considered by the BCMoT for the flexible pavement.

Table 2.14: BCMoT Pavement Distress Density Levels for Flexible Pavement (BCMoT 2009)

Pavement Distress Rating System - Density levels						
Distress Type	**Units**	**Few**	**Intermittent**	**Frequent**	**Extensive**	**Throughout**
Longitudinal Wheel Path Cracking (LWP)	Length	<10%	10-20%	20-50%	50-80%	80-100%
Longitudinal Joint Cracking (LJC)	Length	<10%	10-20%	20-50%	50-80%	80-100%
Pavement Edge Cracking (PEC)	Length	<10%	10-20%	20-50%	50-80%	80-100%
Transverse Cracking (TC)	Spacing	10-20 m	7-10 m	4-7 m	2-4 m	<2 m
Meandering Longitudinal Cracking (MLC)	Length	<10%	10-20%	20-50%	50-80%	80-100%
Alligator Cracking (AC)	Area	<10%	10-20%	20-50%	50-80%	80-100%
Rutting (RUT)	Length	<10%	10-20%	20-50%	50-80%	80-100%
Shoving (SHV)	Length	<10%	10-20%	20-50%	50-80%	80-100%
Distortion (DST)	Length	<10%	10-20%	20-50%	50-80%	80-100%
Bleeding (BLD)	Length	<10%	10-20%	20-50%	50-80%	80-100%
Potholes (POT)	Number	1	2	3 to 5	6 to 9	>10
Ravelling (RAV)	Length	<10%	10-20%	20-50%	50-80%	80-100%

Table 2.15: BCMoT Pavement Distress Severity Levels for Flexible Pavement (BCMoT 2009)

Pavement Distress Rating System - Density levels			
Distress Type	**Low Severity**	**Moderate Severity**	**High Severity**
Longitudinal Wheel Path Cracking (LWP)	Single cracks with no spalling; mean unsealed crack width <5 mm	Single or multiple cracks; moderate spalling; mean unsealed crack width 5-20 mm	Single or multiple cracks; severe spalling; mean unsealed crack width > 20 mm; alligator
Longitudinal Joint Cracking (LJC)	Single cracks with no spalling; mean unsealed crack width <5 mm	Single or multiple cracks; moderate spalling; mean unsealed crack width 5-20 mm	Single or multiple cracks; severe spalling; mean unsealed crack width > 20 mm; alligator
Pavement Edge Cracking (PEC)	Single cracks with no spalling; mean unsealed crack width <5 mm	Single or multiple cracks; moderate spalling; mean unsealed crack width 5-20 mm	Single or multiple cracks; severe spalling; mean unsealed crack width > 20 mm; alligator
Transverse Cracking (TC)	Single cracks with no spalling; mean unsealed crack width <5 mm	Single or multiple cracks; moderate spalling; mean unsealed crack width 5-20 mm	Single or multiple cracks; severe spalling; mean unsealed crack width > 20 mm; alligator
Meandering Longitudinal Cracking (MLC)	Single cracks with no spalling; mean unsealed crack width <5 mm	Single or multiple cracks; moderate spalling; mean unsealed crack width 5-20 mm	Single or multiple cracks; severe spalling; mean unsealed crack width > 20 mm; alligator
Alligator Cracking (AC)	Not rated	Interconnected cracks forming a complete block pattern; slight spalling and no pumping	Interconnected cracks forming a complete block pattern; moderate to severe, pieces may move and pumping may exist
Rutting (RUT)	Less than 10 mm	10-20 mm	Greater than 20 mm
Shoving (SHV)	Barely noticeable	Rough Ride	Very rough ride
Distortion (DST)	Not rated	Noticeable swaying motion; good car control	Fair to poor car control
Bleeding (BLD)	Not rated	Distinctive appearance with free excess asphalt	Free asphalt gives pavement surface a wet look; tire marks are evident
Potholes (POT)	Less than 25 mm deep	25 to 50 mm deep	Greater than 50 mm deep
Ravelling (RAV)	Not rated	Aggregate and binder worn away; surface texture rough and pitted; loose particles exist	Aggregate and/or binder worn away; surface texture is very rough and pitted

The BCMoT uses an overall pavement performance index called Pavement Condition Ratio (PCR). This index is a function Pavement Distress Index (PDI) and Ride Comfort Index (RCI) (BCMoT 2009). The PDI is a modified version of PCI, which was developed by the U.S. Army Corps of Engineers (USACE) (Shahin 2005). The PDI is scaled from 0 to 10, with 10 representing a newest pavement condition and 0 represents a poorest pavement condition. The PDI is determined by calculating "deduct values" for each distress type that is present from the perfect score which is 10. Figures 2.3 and 2.4 present the example deduct value and the PDI categories, respectively.

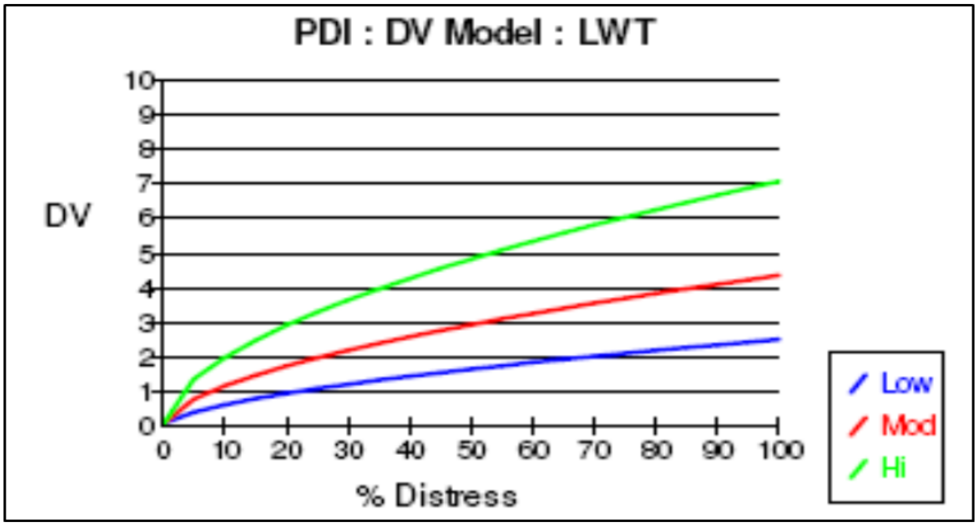


Figure 2.3 : Deduct Value Example (BCMoT 2009)

Good 10 to 7	Pavement surface is relatively new with only a few different types of distress present at low severity. Routine maintenance including crack sealing and patching may be required.
Fair 7 to 5	Pavement surface would typically have a minimum of three to four predominant types of distress with varying levels of severity and density. At this condition, pavements would be identified as a rehabilitation need with a wider range of treatments possible.
Poor < 5	Pavement surface condition is in poor condition and deteriorated to the state where substantial rehabilitation is required.

Figure 2.4: PDI Categories (BCMoT 2009)

The RCI is used to determine the pavement roughness. Figures 2.5 and 2.6 present the roughness categories and PCR categories. The PCR is calculated by the following equation:

$$PCR = PDI^{0.5} * RCI^{0.5} \quad \text{(Equation 2.3)}$$

Where:

PCR = Pavement Condition Rating (0-10)

PDI = Pavement Distress Index (0-10)

RCI = Ride Comfort Index (0-10)

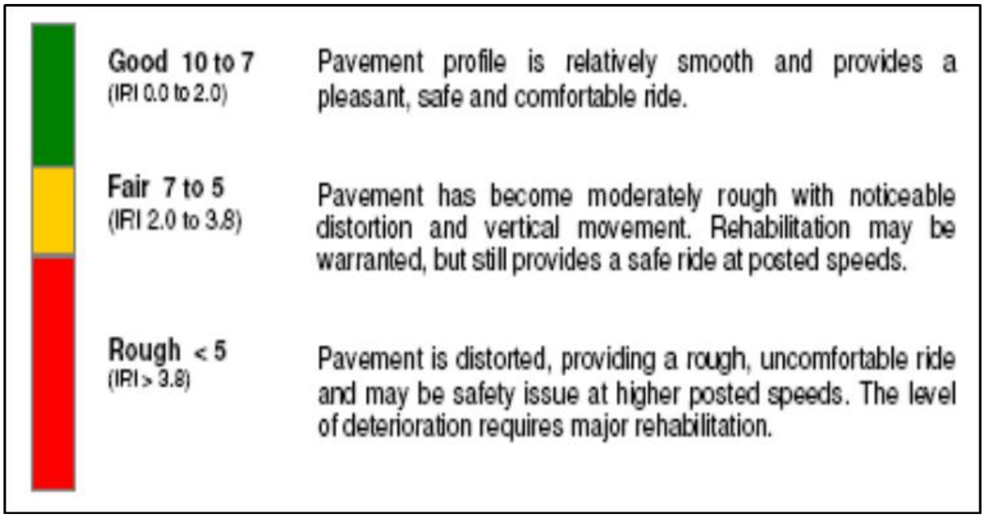


Figure 2.5: Roughness Categories (BCMoT 2009)

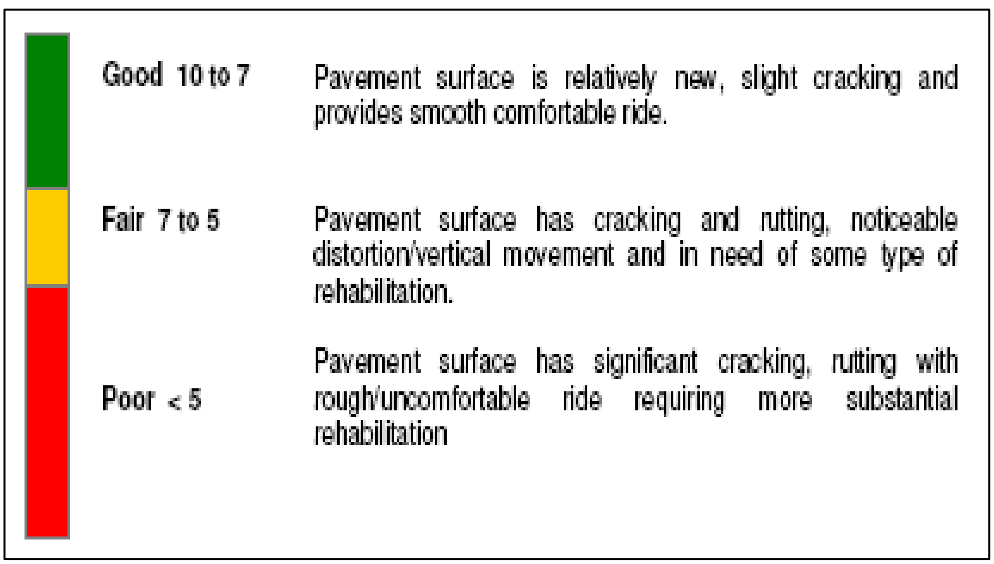


Figure 2.6: PCR Categories (BCMoT 2009)

2.4.2.7 Distress Data Collection Performance Measurement in Agencies

Table 2.16 presents a summary of the performance measurements rating that some of the agencies are using to evaluate their road network pavement condition.

Table 2.16: Distress Data Collection Performance Measurement in Agencies (NCHRP 2004, Papagiammakis et. al 2009)

State/Agency	Survey/Score Name	Rating Computation
Alberta	Surface Condition Rating (SCR) converted to Surface Distress Index (SDI) Pavement Quality Index (PQI) combination of SCR and SDI	PQI= (100*$e^{(-0.2221*IRI)\text{^}0.7}$)*$SDI^{0.3}$
Arizona	Present Serviceability Rating (PSR) 0-5	PSI AASHTO expression
California	Pavement Condition Survey (PCS)	Combinations of individual distresses observed on a pavement are evaluated for severity and broadly classified into overall levels of structural distress.
Delaware	Overall Pavement Condition (OPC)	OPC = (Threshold Value) + [(Remaining Service Life)*(Reduction Rate)]
Florida	Pavement Condition Rating (PCR)	Crack, Ride, and Rutting – the three indices are equally important, and the lowest one represents Overall Pavement Condition
Indiana	Pavement Quality Index (PQI)	Combine PCR with IRI and Rutting into Pavement Quality Index (PQI) = PCR* a$(IRI)^b$
Iowa	Pavement Condition Index (PCI)	PCI = 100 – Deduct values, Deduct = f(Distress type, Severity, and Extent)
Main	Pavement Condition Index (PCI 0-5)	Deduct Values
Minnesota	RQI: Ride Quality Index SR: Surface Rating PQI: Pavement Quality Index (Combination of RQI and SR)	PQI = $\sqrt{(RQI)(SR)}$ SR =$e^{(1.386-(.045)(TWD))}$ TWD = Total Weighed Distresses
Ohio	Pavement Condition Rating (PCR)	PCR = 100-Deduct, Deduct= (Weight of Distress)(Weight for Severity)(Weight for Extent)
Tennessee	Pavement Quality Index (PQI)	PSI: Pavement Serviceability Index (Based on Roughness) PDI: Pavement Distress Index (Based on Distresses) PQI = $PDI^{0.7}$*$PSI^{0.3}$
Wyoming	Present Serviceability rating (PSR) 0-5	PSI AASHTO expression

2.4.3 Establishing Criteria (Minimum Acceptable Level)

"A criterion is a specified limit for some measure of pavement behaviour, response, performance, deterioration, or operating characteristic against which comparisons of actual measurements or estimates can be made" (Haas et al. 1994). In network level, a criterion is established to identify the current and future needs (Haas et al. 1994, TAC 2012).

2.4.4 Prediction Models for Pavement Performance Deterioration

Transportation agencies are required to use the deterioration modeling to predict the future condition of a pavement so that proper rehabilitation/preservation decisions are made. The deterioration models can be classified into three main categories: deterministic, stochastic, and artificial intelligence models (Elhakeem 2005). Deterministic models are best fitted if a large amount of data is available. These models could vary from the straight-line extrapolation to regression analysis models (Elhakeem 2005). Markovian models are the most common stochastic techniques and have been widely used due to their need for less data (Elhakeem 2005). They are able to combine observed performance data with expert opinion. The Artificial Neural Networks also work well with noisy data and enable carrying out parallel computation for multiple tasks, such as optimization and prediction (Elhakeem 2005).

2.4.5 Rehabilitation and Maintenance Strategies

Different rehabilitation and maintenance alternatives can be employed after determining the current pavement condition, the minimum acceptable level, and the prediction model for pavement performance deterioration. Maintenance treatment strategies are categorized as preventive maintenance and corrective maintenance. The preventive maintenance strategies are those activities that are employed at levels of pavement deterioration considerably above the minimum acceptable levels such as chip seal, crack sealing (Haas et al. 1994, TAC 2012). On the other hand, the corrective maintenance strategies are those activities that are employed at levels of pavement deterioration near or even below the minimum acceptable levels such as hot-and cold-mix patching (Haas et al. 1994, TAC 2012). The rehabilitation strategies are those activities that are used when the levels of deterioration are considerably below the acceptable limits. However, a priority programming process is required for each agency to select the appropriate alternative strategies. Table 2.17 shows the rehabilitation and maintenance alternatives used in Ontario for flexible pavement.

Table 2.17: Rehabilitation and Maintenance Alternatives Used in Ontario for Flexible Pavement (Haas et al. 1994, TAC 2012)

Rehabilitation	• Hot-Mix Resurfacing • Partial Depth Removal and Resurfacing • In-place Recycling • Full Depth Removal and Resurfacing • Cold-Mix with Sealing Course • Surface Treatment • Pulverization, Remixing and Resurfacing
Preventive Maintenance	• Potholes • Roadside Maintenance • Drainage Maintenance • Localized Spray Patching • Localized Distortion Patching • Minor Crack Sealing
Corrective Maintenance	• Rout and Seal Cracks • Hot-mix Patching • Surface Sealing • Asphalt Strip Repairs • Distortion Corrections • Drainage Improvements • Frost Treatments • Roadside Slopes and Erosion Control

2.4.6 Economic Evaluation of Rehabilitation and Maintenance Alternatives

The economic evaluation is commonly used in the selection of maintenance and rehabilitation strategies for the pavement segments. Equivalent uniform annual cost method, present worth method, rate-of-return method, benefit-cost ratio, and cost-effectiveness method are the five economic analysis methods (Haas et al. 1994, TAC 2012). Combining all initial capital costs and all cyclical future expenses into equal annual payments over the analysis period is the process of equivalent uniform annual cost. The present worth method uses an appropriate discount rate to discount all future sums to the present. The rate-of-return method "…considers both costs and benefits and calculates the discount rate at which the costs and benefits for a project is equal" (Haas et al. 1994). The benefit-cost ratio is expressed as a ratio of present worth or equivalent uniform annual benefits over the present worth or equivalent uniform annual costs. "The cost-effectiveness method can be used to compare alternatives where significant, nonmonetary outputs are involved" (Haas et al. 1994, TAC 2012).

2.4.7 Priority Programming of Rehabilitation and Maintenance Alternatives

"One of the key components of pavement management is to compare investment alternatives at both the network and project levels, within some funding or budget constraint" (Haas et al. 1994). Integrating information, identification of needs, priority analysis, and output reports are the four major steps for developing a priority programming method (Haas et al. 1994). Every priority programming method should address the following questions (Haas et al. 1994):

- Which sections should be considered for maintenance and rehabilitation?
- Which alternatives should be utilized for the selected section?
- When should the selected alternatives be applied?

Table 2.18 summarizes the various classes of priority programming methods with their pros and cons.

Table 2.18: Different Classes of Priority Programming Methods (Haas et al. 1994, Haas et al. 1985a)

Class of Method	Advantages and Disadvantages
Simple subjective ranking of projects based on judgement	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; may be 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; may be 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)

2.4.8 Implementation

Implementation of a pavement management system varies for different agencies depending on their need and resources. To implement the pavement management system several steps can be identified as follow (Haas et al. 1994):

Step 1: Decision for implementation: this can be initiated by federal directive, legislative directive, or by senior administration within the agency.

Step 2: Form steering committee: the committee is responsible for reviewing other systems, identifying needs, developing basic agenda for implementation, and monitoring implementation.

Step 3: Review existing organization methods and procedures: activities include reviewing nature of organization, defining building block based system framework, and reviewing existing databases, methods and procedures.

Step 4: Develop staged implementation plan and schedule: activities include defining system users and requirements, defining stages and expected products, developing work plan, schedule and cost estimates, and assign responsibilities.

Step 5: Define selection procedures: this step reflects the need at network level and project level.

Step 6: Carryout actual work for each implementation according to stage 4: it includes planned activities, updates to plan and schedule, documentation training, software installation, and progress checks.

Step 7: Monitor system and carryout periodic improvements.

2.5 Pavement Management System Types

PMS available systems can be categorized in two categories. The first category is called "Commercial Off-the-Shelf" (COTS) systems (Mizusawa 2009). COTS are defined as an application or system software that is marketed widely as a prepackaged product (Mizusawa 2009). These systems are available to the transportation agencies to use under an established commercial licensing or leasing agreement such as The Highway Pavement Management Application (HPMA), Pavement View Plus^{R}, Micropaver^{TM} (Mizusawa 2009). The second category is called "Proprietary Systems Developed" (PSD) systems or bespoke systems which are developed either by an external consultant or in house to meet an agency's needs such as Alberta's Municipal Pavement Management System (MPMS) (McPherson 2005).

2.5.1 PMS Available Systems

This section provides an overview of available PMS systems that are used by agencies.

2.5.1.1 HDM-4 (HDM-4 2011)

The Highway Development and Management Tool (HDM-4) is a system that analyzes improving existing roads and implementing new funding and management approaches (Mizusawa 2009). The HDM-4 provides deterioration models for various funding levels and management strategies over 5 to 40 years (Mizusawa 2009). In addition, it prepares multi-year programs of projects within resource constraints and analyzes costs and benefits of one or more project or investment alternatives (Mizusawa 2009).

2.5.1.2 HPMA

The Highway Pavement Management Application (HPMA) is a tool developed by Stantec Consulting (Stantec 2011) for evaluating highway networks and developing multi-year work programs for rehabilitation and maintenance (Mizusawa 2009). In addition, it can be used to record and monitor information concerning road side inventory. This system utilizes Pavement Quality Index (PQI) to present the overall condition of the pavement. Moreover, it uses cost benefit analysis and Heuristic Decision Rules for economic analysis and optimization purpose, respectively (Mizusawa 2009). The optimization analysis is based on the total enumeration and incremental benefit/cost ranking (Kerali et al. 1998).

2.5.1.3 PAVEMENT View^R

PAVEMENT ViewR (PAVEMENT View 2011) is a system that is designed based on the U.S. Army Corps of Engineers Pavement Management Methodology and SHRP Distress Identification Manual for the long term pavement performance (LTPP) program. This system has the capability of evaluating pavement overall condition, developing pavement performance models, determining maintenance and repair needs, and analyzing the consequence of different budget scenarios (Mizusawa 2009). The OCI is used to present the overall pavement condition and the economic analysis is based on the capital improvement plans (Mizusawa 2009).

2.5.1.4 SMEC Asset Management System

This system was developed by SMEC Consulting in Australia based on the World Bank Highway Development and Management (HDM) pavement models for predicting pavement deterioration and road user costs under different maintenance scenarios (SMEC 2011, Mizusawa 2009). This system uses PCI to presents the overall condition of the pavement. Moreover, it uses cost benefit analysis and Heuristic Decision Rules for economic analysis and optimization purpose, respectively (Mizusawa 2009). This system currently is being used by 50 different local governments in Australia, and international sites include Yemen, Addis Ababa, Kuala Lumpur, Hong Kong, and Philippines cities (SMEC 2011).

2.5.1.5 Micropaver™

Micropaver™ is a tool initially developed to help the Department of Defense (DOD) of USA to manage the maintenance and rehabilitation activities for its pavements (Paver™ 2011). This software can be used to select and provide cost effective maintenance and repair alternatives for roads, streets, parking lots, and airfields (Paver™ 2011). This system has the capability of evaluating pavement overall condition, developing pavement performance models, determining maintenance and repair needs, and analyzing the consequence of different budget scenarios (Mizusawa 2009). The PCI is used to present the overall pavement condition and the economic analysis is based on the cost effectiveness analysis methodology (Mizusawa 2009). The software is used by many USA public institutions such as the US Air Force, the US Navy, the US Army, and USA cities (Paver™ 2011).

2.5.1.6 AgileAssets Pavement Analysis

AgileAssets Pavement Analysis software is developed by AgileAssets Inc. (AgileAssets 2011) and it consists of eight components such as network optimization, network scenario analysis, pavement performance analysis, work program management, pavement management database, project life cycle cost analysis, graphing, and reporting (AgileAssets 2011). The PCI is used to present the overall pavement condition and the optimization is based on the cost effectiveness analysis methodology (AgileAssets 2011).

2.6 Summary

This chapter reported on a literature review of the history of the development of pavement management systems. In addition, the literature review included the PMS components, focusing on data inventory such as data collection and performance evaluation, and on the overall pavement condition assessment. Based on the literature review it can be concluded that there are many steps needed to follow and there is a vast range of information and methods available for each step to fulfill the requirement for developing and implementing the PMS. For a local agency, sometimes due to the agency's lack of budget and complexity of the existing PMS software packages, adopting the existing PMS is not cost effective. Therefore, introducing a simple, effective, and affordable PMS for a local agency and municipal is the intention of this research.

Chapter 3 Research Methodology

Developing and implementing a PMS requires some general steps to be followed, as discussed in Chapter Two. However, there are many methods available for each step to fulfill the requirements. Thus, for the local agencies that have lower budget than the provincial/state agencies implementing such PMS is not cost effective. This chapter explains the proposed framework that could be used in a pavement management system for local agencies. The intention of the proposed research methodology is to introduce a simple, effective, and affordable PMS for local road agencies. One of the main areas included in this research methodology is to discuss collection of pavement for local agencies. Thus, in 2011 the survey "Evaluation of Pavement Distress Measurement Survey" was developed and distributed to cities and municipalities across Canada to study the current state-of-the-practice in pavement distress and condition evaluations. The results of the survey are discussed in Chapter Four. The City of Markham is chosen as a case study to illustrate the validation of the research methodology and the results are discussed in Chapter Five.

Figure 3.1 represents the research methodology which consists of six main steps: referencing method, data inventory, evaluate current road network status, predict models for pavement performance deterioration, economic evaluation of rehabilitation and maintenance alternatives, and priority programming of rehabilitation and maintenance alternatives. The step related to evaluating current road network status contains three subsections, initially, it is essential for local agencies to evaluate the overall pavement condition of each road section. Then the local agencies should evaluate the overall road network condition and finally in the third subsection the local agency should divide the road network into homogeneous sections for analysis.

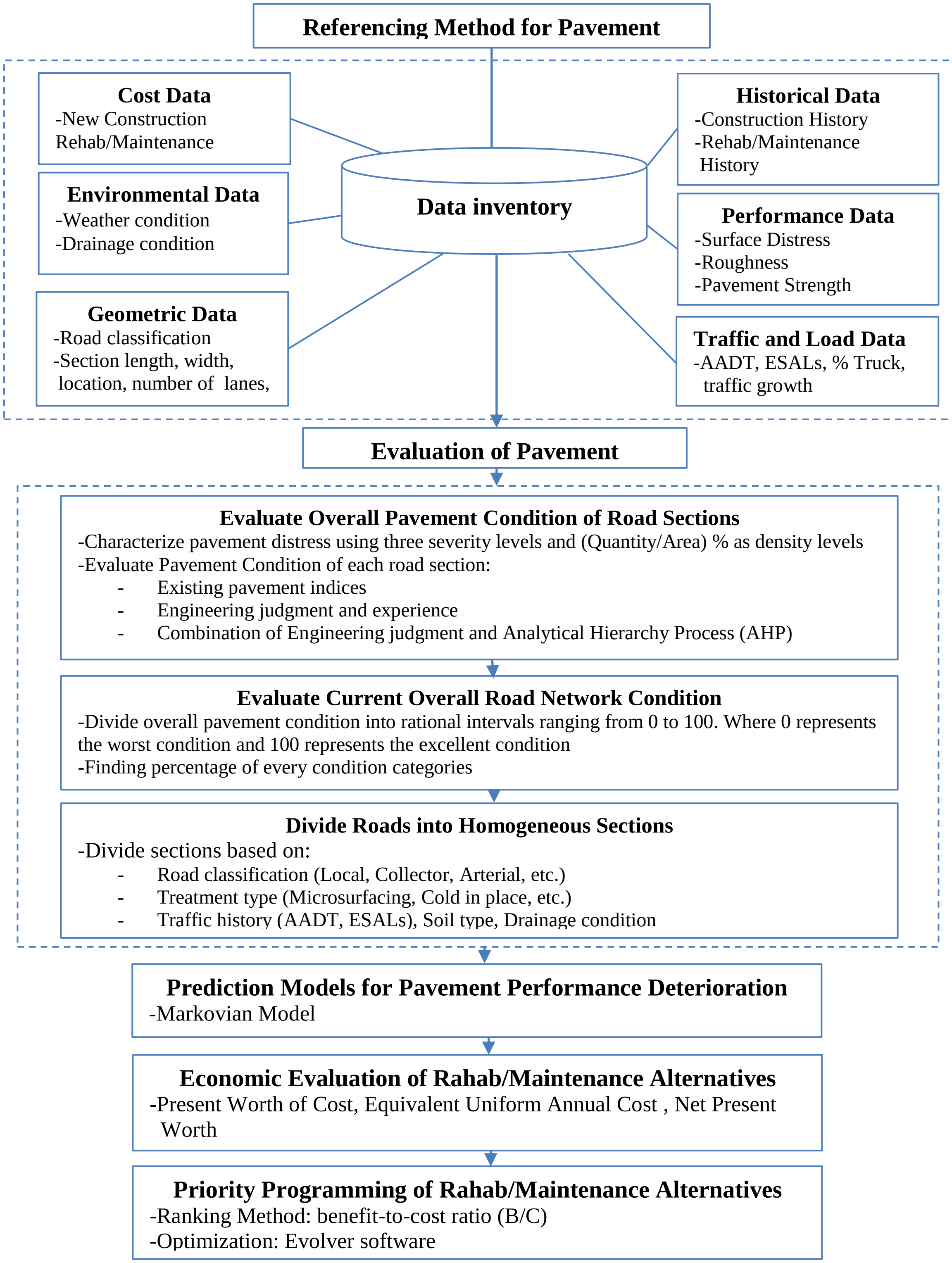


Figure 3.1: Research Methodology

The following sections describe each step in detail.

3.1 Referencing Method

The first step is to develop a method of referencing for pavement sections. The basic method for referencing pavement sections includes node-link, branch-sectioning, route-km post, and Geographic Information Systems (GIS). GIS is one of the referencing methods that have the capability of defining pavement sections by integrating data (condition, history, etc…), and generating maps for pavement management reports. Most agencies in Canada including the Ministry of Transportation of Ontario (MTO) and Alberta Transportation (AT) are implementing GIS (TAC 2012). Moreover, at the municipal level, agencies such as Calgary, Edmonton, and Montreal, etc. are rapidly implementing GIS for their road network (TAC 1997, TAC 2012). Thus, GIS is set as the best practice for referencing pavement sections.

3.2 Data Inventory

The next step involved obtaining various types of inventory data such as performance data, historic data, policy data, geometric data, environment, traffic and load data, and cost related data. Due to the limited budget, cities and municipalities cannot afford to obtain and collect all the necessary data; however, the following data is the key to obtaining an efficient and effective pavement management system.

3.2.1 Historical Data

Historical data can be categorized as to construction-related (the year and type of the initial construction), and treatment-related (any rehabilitation or maintenance treatment and the year at which these treatments are applied after the initial construction).

3.2.2 Traffic and Load Data

The proper use and collection of traffic and load data, such as Average Annual Daily Traffic (AADT), percent trucks, traffic growth, and annual Equivalent Single Axle Loads (ESALs), are highly important in a PMS. An extensive amount of research on load equivalency factors was accomplished as a part of the AASHTO Road Test (AASHTO 93). The most accurate method to estimate the number of ESALs is to use weight-in-motion (WIM) devices. However, due to the expense involved with the WIM equipment, the total ESALs during the design period can be determined as follows (Huang 2004, TAC 2012):

$$ESAL = (ADT)_{0}*(T)*(T1)*(G)*(D)*(L)*(365)*(Y) \quad \text{(Equation 3.1)}$$

where:

ADT_0 = Average daily traffic at the start of the design period;
T = Percentage of Trucks in ADT;
T_1 = Number of 80KN single axle load applications per truck (Truck factor);
G = Growth factor;
D = Directional distribution factor;
L = Lane distribution factor;
Y = Design period in years.

The growth factor (G) can be calculated using the following formula (Huang 2004, TAC 2012):

Total growth factor, $G = [(1 + r)^Y – 1] / r$ (Equation 3.2)

Where:

r = Annual rate of traffic growth;
Y = Design period in years.

Tables 3.1 and 3.2 represent typical truck factors for major truck classes in Ontario and lane distribution factor, respectively (MTO 2008, TAC 2012).

Table 3.1: Typical Truck Factors for Major Truck Classes in Ontario

Major Truck Classes	Typical Truck Factor, TF	Range of Typical Truck Factor
2 and 3-axle trucks	0.5	0.05-1.0
4-axle trucks	2.3	0.2-4.0
5-axle trucks	1.6	0.3-3.5
6 and more axle trucks	5.5	2.0-7.0

Table 3.2: Lane Distribution Factor

Number of Lanes in Each Direction	Percent of 80-kN (18-Kip) ESAL in Design Lane
1	100
2	80-100
3	60-80
4	50-75

3.2.3 Performance Data

Performance data is also necessary and should be obtained by the local agencies for the pavement management system. The performance data is collected, depending on the agency's available budget, usually every two to five years for the road network using manual, semi-automated tools, automated tools, or two or more of the three. The survey can be conducted on every 30 m, 50 m, 100 m, etc. intervals. Many provincial/states agencies collect one or more of the surface distress, friction, roughness, and structural adequacy as their performance data. Local agencies; on the other hand, due to different traffic volume, budget limit, speed limit, and user expectation, should collect fewer and specific types of pavement performance data. Thus, a survey was developed in 2011 and distributed to cities and municipalities across Canada to study the current state-of-the-practice in pavement distress and condition evaluations. The survey results are presented in Chapter Four.

3.2.4 Geometric Data

The local agency should also obtain geometric data. The geometric data defines the physical characteristics and features of the pavement sections such as location, length, width, number of lanes, shoulder type and width, classification (local, collector, arterial, etc.) and, grade of the section (Haas et al. 1994, TAC 2012).

3.2.5 Environmental Data

The environmental conditions such as maximum and minimum temperatures, freeze thaw cycles, precipitation, and drainage conditions have an important impact on the pavement deterioration rate, and the associated selection of proper rehabilitation and maintenance alternatives by local agencies. Thus, this data should also be included.

3.2.6 Cost Data

The cost of new construction, maintenance and rehabilitation should also be maintained since it is useful for the economic analysis, prioritization, and project selection process.

3.3 Evaluation of Pavement Condition

The first step in evaluating the current road network status is to quantify the overall pavement condition for each pavement section. Agencies, after identifying the pavement distress and evaluating each distress condition based on its severity levels and density levels, could calculate the overall pavement condition of each road by the three different methods. The first method is to adapt the current well developed pavement indices such as MTO index (PCI_{MTO}). The second method is to use the engineering judgement and experience. The third method, which is the emphasis of this research, is to use both the engineering judgement and the Analytical Hierarchy Process (AHP) to assign weights for each pavement performance data. AHP is a theory of relative measurements of intangible criteria (Saaty 1980). AHP is based on eigenvector methods that are usually applied to establish the relative weights for different criteria (Vishal et al. 2008). The AHP determines the weights for each criterion indirectly by relative importance score between criteria (Saaty 1980). The final weighting is then normalized by the maximum eigenvalue for the matrix to minimize the impact of inconsistencies in the ratios. The method is illustrated in the following steps (Alyami et al. 2012).

Let C = $\{C_1, C_2, C_3, \ldots, C_n\}$ be the (n) pavement performance data identified to be assigned weights.

Let A = (a_{ij}) be a square matrix where a_{ij} presents the relative importance between pairs (C_i,C_j) as shown in the following matrix:

$$\mathbf{A}= \begin{bmatrix} a_{11}a_{12} \ldots & a_{1n} \\ a_{21}a_{22} \ldots & a_{2n} \\ a_{n1}a_{n2} \ldots & a_{nn} \end{bmatrix}$$

where:

$$a_{ij} = \frac{1}{a_{ji}}, \text{ for all } i,j = 1,2,3,\ldots. n \qquad \text{(Equation 3.3)}$$

The term a_{ij} assumes a value of relative importance between C_i and C_j in a scale from 1-9 as shown in Table 3.3.

The matrix A should be filled based on the engineering judgment and experience.

Table 3.3: Comparison Scale (Saaty 1980)

Intensity of importance	Definition
1	Equal importance
3	Moderately more important
5	Strongly more important
7	Very strongly more important
9	Extremely more important
2,4,6,8	Intermediate values between adjacent scale values

Let w = $\sum$ {w_1, w_2, w_3…w_n}=1 be the weights for each pavement performance data. The weight can be obtained as follow:

$$W_i = \frac{1}{n}\sum_{j=1}^{n} \frac{a_{ij}}{(\sum_{k=1}^{n} a_{kj})} \qquad \text{for i,k = 1,2,…..n} \qquad \text{(Equation 3.4)}$$

The eigenvalue (λ_{max}) is obtained as follows:

The sum of the resultant vector of (A*w/w) divided by number of pavement performance data (n) where:

w = Weight vector.

The Consistency Index (C.I.) = $\frac{((\lambda_{max}) - n)}{(n-1)}$ (Equation 3.5)

The Consistency Ratio (C.R.) = $\frac{C.I}{\text{Random Index (R.I)}}$ (Equation 3.6)

where:

Random Index (R.I.) is a constant that depends on the pavement performance data (n) as shown in Table 3.4. In addition, a consistency ratio less than 0.1 indicates consistent pairwise comparison.

Table 3.4: Random Index (Saaty 1980)

n = 1	R.I = 0.00
n = 2	R.I = 0.00
n = 3	R.I = 0.59
n = 4	R.I = 0.90
n = 5	R.I = 1.12
n = 6	R.I = 1.24
n = 7	R.I = 1.32
n = 8	R.I = 1.41
n = 9	R.I = 1.45
n = 10	R.I = 1.49

After determining weights for each pavement performance data, the overall pavement condition (OPC) is calculated by:

$$\text{OPC} = \sum_{i=1}^{n}(\text{C1} * \text{W1} + \text{C2} * \text{W2} + \cdots \text{Cn} * \text{Wn}) \qquad \text{(Equation 3.7)}$$

where,

OPC = Overall Pavement Condition;

C_i = Pavement performance data;

W_i = Calculated weight associated to each pavement performance data.

The next step after calculating the overall pavement condition for each section is to find the current overall road network condition by finding the percentage of different OPC categories. Table 3.5 is an example of OPC categories.

Table 3.5: Example of OPC Categories

OPC (Overall Pavement Condition) Classification	Condition
OPC (100-85)	Excellent
OPC (85-70)	Very Good
OPC (70-55)	Good
OPC (55-40)	Fair
OPC (40-0)	Poor

To have a better understanding of current road network condition, each class of road (local, collector, arterial, etc.) should be examined separately by dividing each road class into homogenous sections. Each road class should further divide into subsections based on the common rehabilitation/maintenance type, same range of traffic volume and ESALs, same soil type, and drainage condition for the analysis purposes.

3.4 Prediction Models for Pavement Performance Deterioration

Transportation agencies should use a deterioration model to predict the future condition of a pavement so that proper rehabilitation/preservation decisions can be made. Markovian models are the most common stochastic techniques and have been widely used due to their less need for data (Elhakeem 2005). This research used the Markovian model to predict pavement performance deterioration for all the road classes based on the specific treatment type.

The first step for the Markov chain model involved constructing a Transition Probability Matrix (TPM) which predicts change over a period of time. TPM is a matrix of order (n x n), where n is the number of possible condition states. TPM shows the probability of going from one candidate stage to another over a period of time as shown in Figure 3.2. For example, there is a 35% probability of staying in condition state 2 after one year of service and a 65% probability of moving from state 2 to state 3.

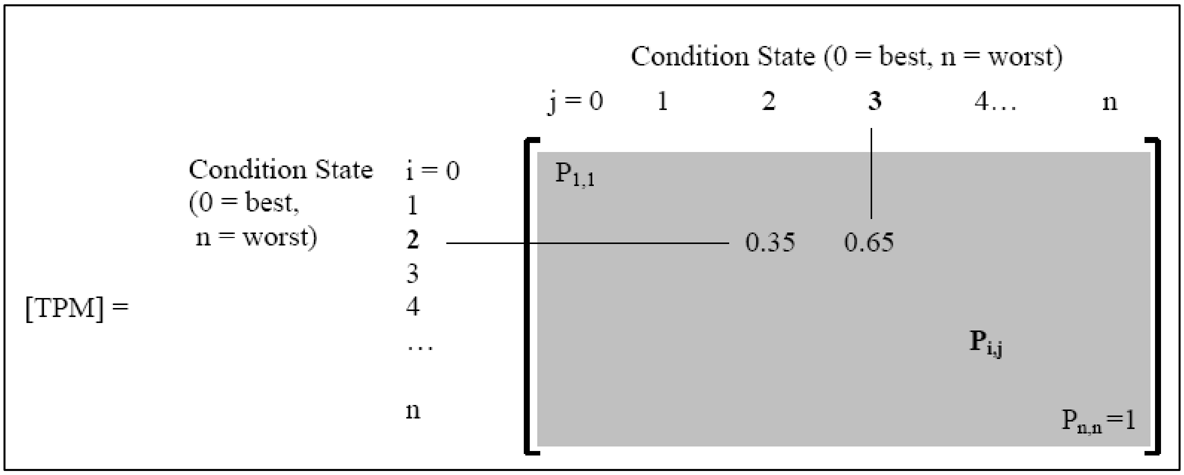


Figure 3.2: Transition Probability Matrix (Elhakeem 2005)

Where $P_{i,j}$ represents the probability of deterioration from state i to state j over a specific time period called the transition period t.

To estimate the future-state vector $[FP_t]$, the initial probabilty vector IP_o , the state of new asset at t = 0, is multiplied by the TPM matrix (Elhakeem 2005).

State: 0 = best, 1, 2,………n=worst
IP_o = [1, 0, 0………0] at t=0

Therefore, FP_t can be calculated as (Elhakeem 2005):

$$[FP_t]_{1\times n} = [IP_o]_{1\times n} \cdot [TPM]^t_{n\times n} \quad \text{(Equation 3.8)}$$

Figure 3.3 shows a sample transition probability matrix with state transition matrix.

Transition Probability Matrix (TPM)
From one condition to another

	10	9	8	7	6	5	4	3	2	1	0	States	
10	0.8	0.2	0	0	0	0	0	0	0	0	0	10	New
9	0	0.7	0.3	0	0	0	0	0	0	0	0	9	
8	0	0	0.6	0.4	0	0	0	0	0	0	0	8	
7	0	0	0	0.5	0.5	0	0	0	0	0	0	7	
6	0	0	0	0	0.5	0.5	0	0	0	0	0	6	
5	0	0	0	0	0	0.4	0.6	0	0	0	0	5	
4	0	0	0	0	0	0	0.3	0.7	0	0	0	4	
3	0	0	0	0	0	0	0	0.2	0.8	0	0	3	
2	0	0	0	0	0	0	0	0	0.5	0.5	0	2	
1	0	0	0	0	0	0	0	0	0	0.4	0.6	1	
0	0	0	0	0	0	0	0	0	0	0	1.0	0	Critical

State Transitions: LIFE EXPECTANCY (YEARS) 20

Condition State

Age	0	1	2	3	4	5	6	7	8	9	10	
0	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	New
1	0.80	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
2	0.64	0.30	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
3	0.51	0.34	0.13	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
4	0.41	0.34	0.18	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	
5	0.33	0.32	0.21	0.10	0.04	0.01	0.00	0.00	0.00	0.00	0.00	
6	0.26	0.29	0.22	0.13	0.07	0.02	0.00	0.00	0.00	0.00	0.00	
7	0.21	0.25	0.22	0.16	0.10	0.04	0.01	0.00	0.00	0.00	0.00	
8	0.17	0.22	0.21	0.17	0.13	0.07	0.03	0.01	0.00	0.00	0.00	
9	0.13	0.19	0.19	0.17	0.15	0.09	0.05	0.02	0.01	0.00	0.00	
10	0.11	0.16	0.17	0.16	0.16	0.11	0.07	0.04	0.02	0.00	0.00	
11	0.09	0.13	0.15	0.15	0.16	0.12	0.09	0.06	0.04	0.01	0.00	

Figure 3.3: TPM and State Transition Matrix (Elhakeem 2005)

3.5 Economic Evaluation of Rehabilitation and Maintenance Alternatives

The economic evaluation is commonly used in the selection of maintenance and rehabilitation strategies for the pavement segments. The present worth (PW), net present worth (NPW), and the equivalent uniform annual cost (EUAC) are the common methods that are being used by agencies to properly evaluate competing alternatives (TAC 2012). The PW represents the equivalent dollars at the beginning of the analysis period (Rahman 2004, TAC 2012).

$$PW = C * [1 / (1 + i_{Discount})]^n \quad \text{(Equation 3.9)}$$

where:

PW = Present Worth ($);

C = Future Cost ($);

$i_{Discount}$ = Discount rate (e.g. 4% = 0.04);

n = Period in years between future expenditure and present.

The NPW represents the total dollars that needed for the analysis period.

$NPW = IC * \sum_{j=1}^{k}(M\&R_j * [1/(1 + i_{Discount})])^{nj} - SV * [1/ (1 + i_{Discount})]^{AP}$ (Equation 3.10)

where:

NPW = Net Present Worth ($);

IC = Initial Cost ($);

K = Number of future maintenance, preservation and rehabilitation activities;

$M\&R_j$ = Cost of j^{th} future maintenance, preservation and rehabilitation activity ($);

$i_{Discount}$ = Discount rate;

n_j = Number of years from the present of the j^{th} future maintenance, preservation or rehabilitation treatment

SV = Salvage Value ($)

AP = Number of years in analysis period

The EUAC presents the dollars needed for every year to pay for the project (TAC 2012).

$EUAC = NPW * [(i_{Discount} * (1 + i_{Discount})^{AP}) / ((1 + i_{Discount})^{AP} - 1)]$ (Equation 3.11)

where:

EUAC = Equivalent Uniform Annual Cost ($);

NPW = Net Present Worth ($);

$i_{Discount}$ = Discount rate;

AP = Number of years in analysis period

3.6 Priority Programing of Rehabilitation and Maintenance Alternatives

Local agencies should prioritize the road sections need and select the appropriate rehabilitation and maintenance alternatives using either the ranking method or optimization method. Road sections are prioritized in the ranking method based on the descending order of the benefit-to-cost ratio (B/C). The drawback with the ranking method is that it fails to consider alternative funding levels (Hegazy 2010). The other approach to prioritizing the road sections is optimization. Optimization is the most complex method of priority programming. The optimization method can give the optimal solution based on various objective functions (e.g..

maximize pavement condition, minimum budget, etc.) while considering various constraints. Since the optimization method is very complex to develop, the local agencies could use the already developed optimization software such as Evolver to prioritize their road network level. The ranking method and use of Evolver software is further illustrated in the case study presented in Chapter Five.

3.7 Summary

This chapter discussed the research methodology that was developed for the local agencies to use in their pavement management systems. This chapter explains the six main steps applied in the research methodology. The proposed framework consists of six main steps: referencing method, data inventory, evaluation of pavement condition, prediction models for pavement performance deterioration, economic evaluation of rehabilitation and maintenance alternatives, and priority programming of rehabilitation and maintenance alternatives. In this research methodology, GIS was selected as the method for referencing pavement sections and various inventory data was discussed. In addition, Markovian model was selected as an appropriate prediction model for pavement performance deterioration, and simple ranking and Evolver software were selected methods for Priority Programing of Rehabilitation and Maintenance Alternatives.

Chapter 4 Survey Results

Evaluating pavement performance is a key element of identifying sections in need of maintenance or rehabilitation. To evaluate pavement performance, most provincial/states in Canada and the United States perform data collection activities in one or more of the following four main areas: surface distress, roughness, structural adequacy, and friction (NCHRP 2004). To study the current state-of-the-practice in pavement distress and condition evaluations for provincial/states in Canada and the United States, an extensive literature review was carried and the results were discussed in Chapter Two. However, when looking at the municipal pavement management needs it is noted that local agencies experience different traffic volumes, budget levels, speed limits, and various user expectations. In 2010, the Transportation Association of Canada (TAC) Pavement Asset Design and Management Guide (PADMG) developed and distributed to organizations across Canada, including cities, provincial, federal and territorial agencies, consulting firms, and academic institutions to benchmark current state-of-the-practice (TAC 2012). The survey results are summarized and analyzed by Tighe (Tighe 2010, TAC 2012). Looking at the TAC PADMG survey results, it was necessary to develop and conduct a new survey benchmark municipal PMS needs. As part of this, various questions were asked including asking what types of pavement distresses are currently collected by local agencies and how many distress and severity levels are being considered for each distress. Finally the survey asked how an overall pavement condition index was calculated by the municipal agency. Thus, in 2011 the survey "Evaluation of Pavement Distress Measurement Survey" was developed as part of this research and was distributed to cities and municipalities across Canada to study the current state-of-the-practice in pavement distress and condition evaluations.

A total of nine surveys were completed including seven cities (Edmonton, Hamilton, Moncton, Saskatoon, Victoria, Calgary, and Niagara Region) and two consultants (Golder Associates Ltd. and Applied Research Associates (ARA)). The questions that were asked are presented followed by the results of the survey. Figures 4.1-4.4 summarize the questions that were asked from each agency.

Pavement Type	Data Collection	Do You Collect the Corresponding Data	Methodology Used to Collect data	Please Specify Tool	Protocol Used	If agency-specific protocols are used, please attach or e-mail copies
Flexible	Raveling	Yes	Both			
	Flushing/Bleeding	No	Both			
	Rippling/Shoving	No	Both			
	Rutting	No	Both			
	Distortion	No	Both			
	Longitudinal Wheel Track Cracking	No	Both			
	Longitudinal Joint Cracking	No	Both			
	Alligator Cracking	No	Both			
	Meander and mid-lane Longitudinal Cracking	No	Both			
	Transverse Cracking	No	Both			
	Centreline Cracking	No	Both			
	Pavement Edge Cracking	No	Both			
	Map/Block Cracking	No	Both			
	Patching	No	Both			
	Potholes	No	Both			
	Please specify if Agency collect data other than the one mentioned above by writing the distress name and completing the questions					
		No	Both			
		No	Both			
		No	Both			
		No	Both			
		No	Both			

Figure 4.1: Survey Page 1 of 4

Pavement Type	Data Collection	Do You Collect the Corresponding Data	Methodology Used to Collect data	Please Specify Tool	Protocol Used	If agency-specific protocols are used, please attach or e-mail copies
		No	Both			
Rigid	Raveling	No	Both			
	Polishing	No	Both			
	Scaling	No	Both			
	Potholing	No	Both			
	Joint Cracking or Spalling	No	Both			
	Faulting	No	Both			
	Distortion	No	Both			
	Joint Failure	No	Both			
	Joint Sealent Loss	No	Both			
	Longitudinal Meander Cracking	No	Both			
	Transverse Cracking	No	Both			
	'D' Cracking	No	Both			
	Patching	No	Both			
	Diagonal Corner/Edge Cracking	No	Both			
	Please specify if Agency collect data other than the one mentioned above by writing the distress name and completing the questions					
		No	Both			
		No	Both			
		No	Both			
		No	Both			
		No	Both			
	IRI (International Roughness Index)	No	Both			
	Friction (Skid Resistance)	No	Both			

Figure 4.2: Survey Page 2 of 4

Severity Level	If Other Please Specify	Density Level	If Other Please Specify	Distress Weigthing Factor if Applicable
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		
Other		Other		

Figure 4.3: Survey Page 3 of 4

Monitoring Frequency Every:	Sampling Techniques/Frequency Every:	If Other Please Specify	Data Collected By	Overall Condition Index	If Other Please Specify	Please Indicate How Overall Condition Index is Calculated and Provide Formula

Figure 4.4: Survey Page 4 of 4

Figure 4.5 shows the percentage of agencies that collect the different types of pavement distresses to evaluate flexible pavement of their overall road networks.

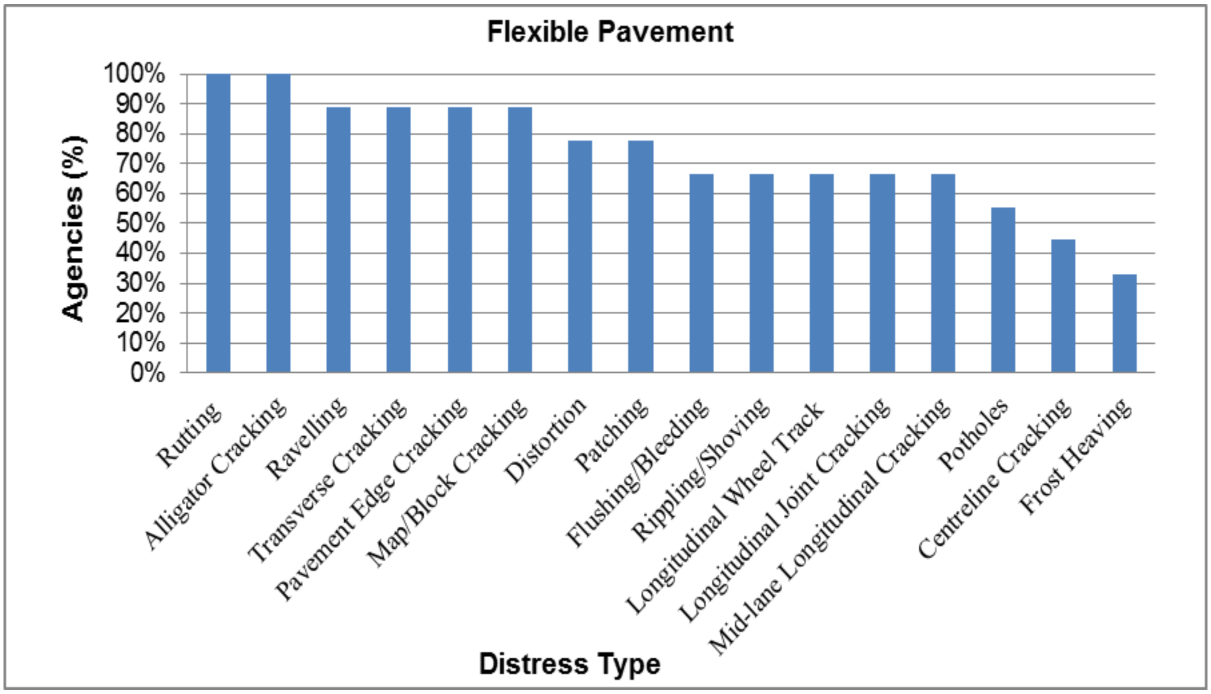


Figure 4.5: Percentage of Agencies Collecting Flexible Pavement distresses

As noted in Figure 4.5, rutting, alligator cracking, ravelling, transverse cracking, pavement edge cracking, map/block cracking, distortion, and patching are the dominant distresses that are collected by local agencies in evaluation of their road networks. Figure 4.5 also indicates that centreline cracking and frost heaving are the least commonly collected pavement distress for flexible pavements. In addition, the survey results indicate 67% of agencies collect the International Roughness Index (IRI) and no agencies collect structural adequacy data or friction data for their road networks.

The survey results for the rigid pavement is based only on four agencies since not all the local agencies construct rigid pavement as an alternative for their road network pavement. Figure 4.6 illustrates the percentage of the agencies that collect various types of rigid pavement distresses in evaluation of their overall road networks.

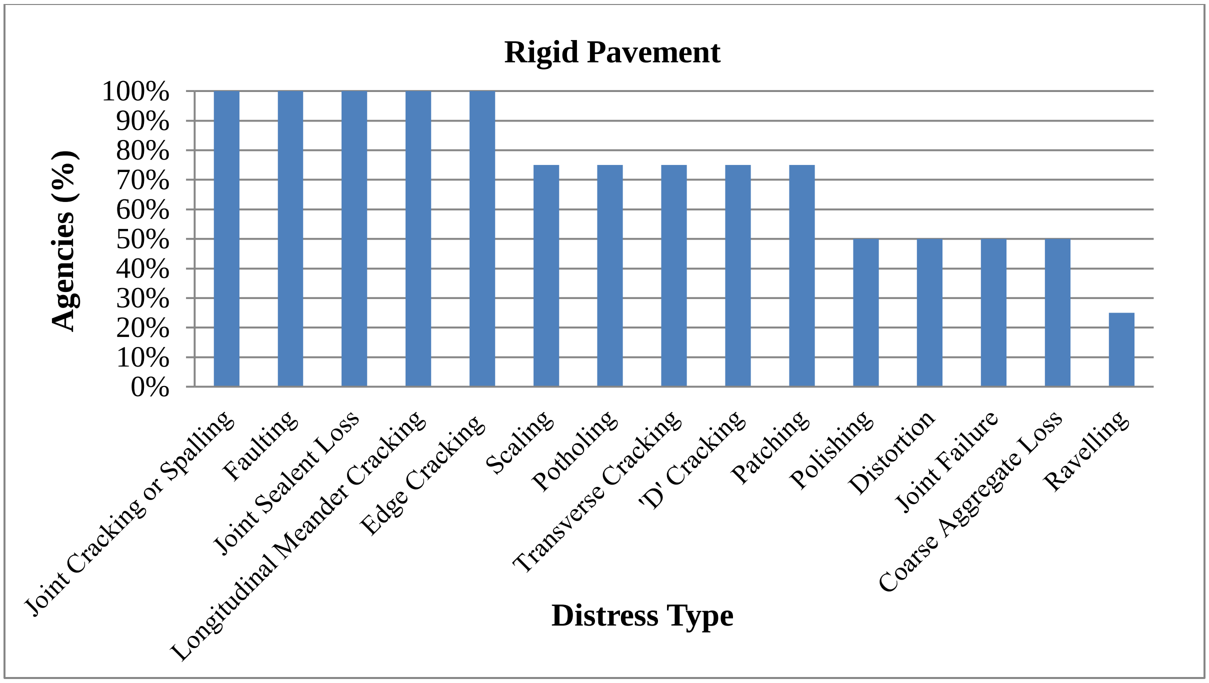


Figure 4.6: Percentage of Agencies Collecting Rigid Pavement distresses

It can be concluded from Figure 4.6 that all agencies are collecting spalling, faulting, joint sealant lost, longitudinal mender cracking, and edge cracking to evaluate their road network pavement condition. In addition, the ravelling is the least collected distress.

As noted in Figure 4.7, the Ministry of Transportation Ontario (MTO) protocols and the American Society for Testing and Materials (ASTM) protocols are the most utilized protocols by the Canadian cities and municipalities as guidelines to collect pavement distress.

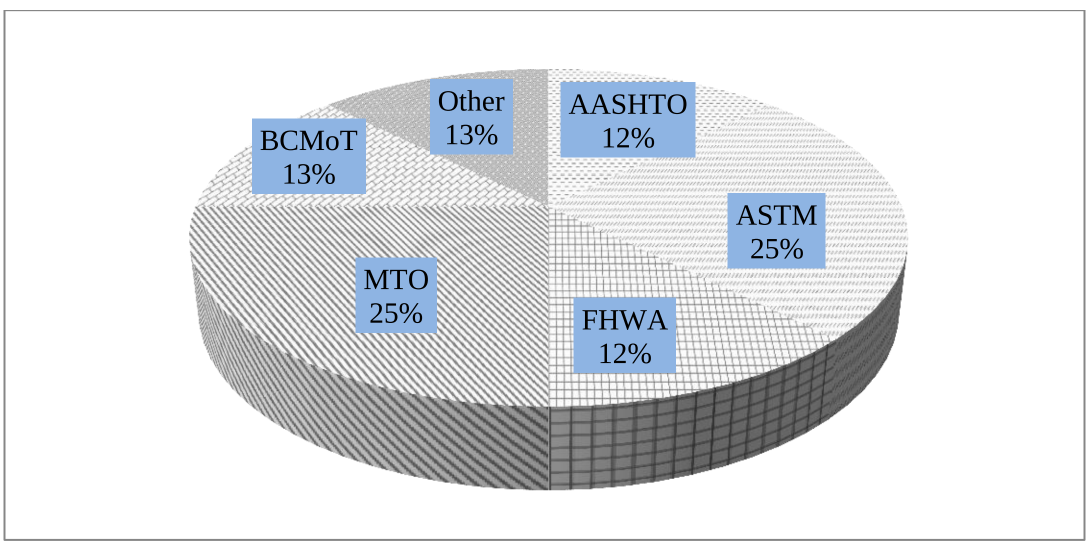


Figure 4.7: Percentage of Protocols Utilize by Canadian Agencies for Collecting Pavement Distress

Table 4.1 illustrates the number of agencies that use different severity levels and density levels to characterize each type of collected data for the flexible pavement.

Table 4.1: Number of agencies that Use Different Severity Levels and Density Levels for Flexible Pavement

	Severity Levels (# of agencies)		Density Levels (# of agencies)			
Data Type	Three Severity Level	Five Severity Level	Three Density Level	Five Density Level	Quantity/Area	Others
Ravelling	3	3	0	2	4	
Flushing/Bleeding	2	2	0	2	2	
Rippling/Shoving	2	2	0	2	2	
Rutting	4	2	0	2	3	% Length
Distortion	3	2	0	2	3	
Longitudinal Wheel Track Cracking	3	2	0	2	2	Length
Longitudinal Joint Cracking	3	0	0	1	2	Length
Alligator Cracking	5	2	0	2	4	AREA LINEAR SPACING AREA LINEAR
Meander and mid-lane Longitudinal Cracking	4	1	0	2	2	Length
Transverse Cracking	4	2	0	2	2	AREA LINEAR SPACING AREA LINEAR, Length
Centreline Cracking	2	1	0	2	1	
Pavement Edge Cracking	4	2	0	2	2	AREA LINEAR SPACING AREA LINEAR, %Length
Map/Block Cracking	4	2	0	2	3	AREA LINEAR SPACING AREA LINEAR
Patching	3	2	0	2	3	
Potholes	2	2	0	2	0	Count
Frost Heaving	0	0	0	0	0	
Excessive Crown	2	0	0	0	0	% length
Coarse Aggregate Loss	1	0	0	0	1	
Structural Integrity	1	0	0	0	1	
Drainage	1	0	0	0	1	

It can be concluded from Table 4.1 that most agencies use three severity levels and percentage of the affected area as the density levels (area of each distress over the area of inspected pavement section) to identify the pavement distress. Table 4.2 shows the number of agencies that utilize different data collection methodology for the flexible pavement.

Table 4.2: Number of Agencies that Use Different Data Collection Methodology for Each Type of Data for the Flexible Pavement

	Data Collection Methodology (# of agencies)		
Data Type	**Manually**	**Semi-Automated/Automated**	**Both**
Ravelling	5	2	1
Flushing/Bleeding	4	1	1
Rippling/Shoving	3	2	1
Rutting	2	4	2
Distortion	5	1	1
Longitudinal Wheel Track Cracking	3	1	2
Longitudinal Joint Cracking	3	2	1
Alligator Cracking	4	3	2
Meander and mid-lane Longitudinal Cracking	4	1	1
Transverse Cracking	3	3	2
Centreline Cracking	3	1	1
Pavement Edge Cracking	4	2	2
Map/Block Cracking	4	2	2
Patching	5	2	1
Potholes	4	1	1
Frost Heaving	1	0	0

Some of the semi-automated/automated data collection tools that these agencies are using are as follows:

- ARAN
- Inertial Profiler for measuring rutting, IRI and skid resistance
- DYNATEST Model 8000E FWD for structural integrity of road
- DDCRS (Digital Direct Condition Rating System) in the RST inspection vehicle

4.1 Summary

This Chapter summarized the results from the 2011 survey that was carried out as part of the research. A total of nine surveys were returned including seven cities and two consultants. Based on the survey results, it can be concluded that the local agencies should collect roughness (IRI), rutting, alligator cracking, ravelling, transverse cracking, pavement edge cracking, map/block cracking, distortion, and patching as the performance data for flexible pavements. For evaluating the rigid pavement condition, agencies are collecting spalling, faulting, joint sealant lost, longitudinal mender cracking, edge cracking, transverse cracking, scaling, roughness (IRI), and potholing. Local agencies should also consider three severity levels and the percentage of the affected area over the total surveyed area for the density levels. In addition, the MTO protocols and the ASTM protocols are the most used protocols by the Canadian cities and municipalities as guidelines to collect pavement distress.

Chapter 5 Case Study

The City of Markham, which represents a local agency, is selected for a case study to illustrate the validation of the research methodology. The analysis of this chapter is based on the data which are provided by the City of Markham.

5.1 Referencing Method

The City of Markham uses a Geographic Information System (GIS) as a referencing method to represent the pavement sections. The GIS is used to generate maps for the road network in terms of pavement condition and road classification. Every road section in the City of Markham has a unique number that is called Segment ID which contains eight digits e.g. 00035-002. The first five digits in the Segment ID are generated randomly and it is called Unit ID1. The Unit ID1 is distinctive for each road segment. The last three digits in the Segment ID are called Unit ID2 which represents the number of intersections for each road segment.

5.2 Data Inventory

There are five sets of data provided by the City of Markham. The first set of data is composed of the surface distress condition survey that was conducted in 2008 and 2011 for the roads in the City of Markham. This data includes the road section unique ID, surface distress (patching, rutting, mapping, longitudinal cracking, alligator cracking, edge cracking, and transverse cracking) and roughness (IRI) condition for every 30m intervals of the road segment and the length of each segment. The second set of data includes the rehabilitation/maintenance history that includes, road segment ID, treatment strategy type, year of treatment and street name. The third set of data contains the AADT data that includes road segment ID, the AADT history for some of the road, the year that the AADT was collected, and the name of the road. The fourth set of data road includes the road segment ID, rehabilitation/maintenance year, road installation year, road classification, road length and width, and number of lanes. The fifth set is the ArcGIS file that only the road segment ID and the corresponding road speed limit is used. Software programming such as Microsoft Visual Studio and Excel Macro are used to correlate the given data. Table 5.1 illustrates the summary of the data that are used to analyze the road network.

Table 5.1: Sample of Excel File Created to analyze the road network

Seg_ID	Unique_ID	AlligNDX	LongiNDX	MapNDX	RutNDX	TransNDX	EdgeNDX	PatchNDX	RoughNDX
00019-019	00019_01900030F	100	100	100	92.508	100	100	100	69.9
00019-019	00019_01900060F	100	100	100	92.674	100	100	100	82.75
00019-019	00019_01900090F	100	100	100	92.175	100	100	100	84.7
00019-019	00019_01900120F	100	100	100	93.507	100	100	96.2	81.15
00019-019	00019_01900150F	100	100	100	94.006	100	100	100	85.5
00019-019	00019_01900180F	100	100	100	93.007	100	100	100	92.4
00019-019	00019_01900210F	100	100	100	93.34	100	100	86.2	77.55
00019-019	00019_01900240F	100	98.35	100	95.338	100	100	95.45	73.15

SEG_ID	AADT	Road Classification	Treatment	Treatment Year	STREET	FROM	TO
07684-037		MC1	EA	2010	Raymerville Dr	Michener Cres	Adrian Cres
01341-008		L1	S&P	2007	Cachet Pky	Ahorn Grove	Ahorn Grove
01341-009		L1	S&P	2007	Cachet Pky	Ahorn Grove	Ahorn Grove
01341-013		L1	S&P	2007	Cachet Pky	Warden Ave	Ahorn Grove
10812-001		L1	EA	2005	Heritage Corners Lane	16th Ave	Aileen Lewis Crt
04960-025		MC2	MICRO	2009	John St	same_street	Aileen Rd
07889-008		LC1	MICRO	2008	Robinson St	Arrowflight Dr	Alanadale Ave
00019-028	13776	MC2	EA	2009	14th Ave	Riviera Dr	Alden Rd
00817-001		MC1	EA	2006	Bentley St	Amber St	Alden Rd
04642-006		MC1	MICRO	2010	Hood Rd	McPherson St	Alden Rd
04642-006		MC1	MICRO	2009	Hood Rd	McPherson St	Alden Rd
10812-002		L1	EA	2005	Heritage Corners Lane	Aileen Lewis Crt	Alexander Hunter Pl

5.3 Evaluate Current Road Network Status

To evaluate the current road network status the overall condition of each road is determined using the existing method that the City of Markham is adopted. This method is based on the engineering judgment and experience. In addition, the roads' conditions are also calculated using the MTO's condition index and the AHP method. The results below are based on the City of Markham's existing method.

In 2011, Infrastructure Management Services (IMS) conducted a surface condition survey for 32,923 sections of the City of Markham road network. The survey includes collecting seven types of distress (transverse cracking, longitudinal cracking, alligator cracking, edge cracking, rutting, patching, and mapping) and roughness in terms of IRI for evaluating the surface condition index for the flexible pavements. Each distress is evaluated for three severity levels as explained in (City of Markham 2011). The City of Markham uses an overall pavement performance index called the Overall Condition Index (OCI) which is a function of Surface Condition Index (SCI) and Roughness Condition Index (RCI) to evaluate the road condition. The OCI varies from 0 to 100, with 100 representing a newly constructed or rehabilitated pavement, and 0 represents the poorest condition.

The OCI for each section is calculated by taking the minimum value among the collected surface distress multiply by 0.8 plus the roughness for each section multiply by 0.2.

$$OCI_{Section} = (\text{Min} \sum_{i=1}^{7} i) * 0.8 + RCI*0.2 \qquad \text{(Equation 5.1)}$$

where:

$OCI_{Section}$	=	Overall Condition Index of each section, ranging from 0 to100;
i	=	Surface Distress (Alligator cracking, edge cracking, transverse cracking, patching, rutting, longitudinal cracking, and mapping);
RCI	=	Roughness Condition Index.

The Overall Condition Index (OCI) of each road is calculated as follow:

$$OCI = \sum_{i=1}^{n}(OCI\ i * Length\ i) \ / \ \sum_{i=1}^{n} Length\ i \qquad \text{(Equation 5.2)}$$

Where:

i	=	Number of road segment with the same Unit ID1 and Unit ID2;
OCI	=	Overall Condition Index for each road segment, ranging from 0 to100;
Length	=	Inspected length for each road segment.

The following is the summary of the findings based on the 2011 surface condition survey. As shown in Figure 5.1, 53% of the City of Markham roads in 2011 are shown to be in an excellent condition, followed by 40%, 4%, 2%, and 1% in a very good, good, fair, and poor condition, respectively.

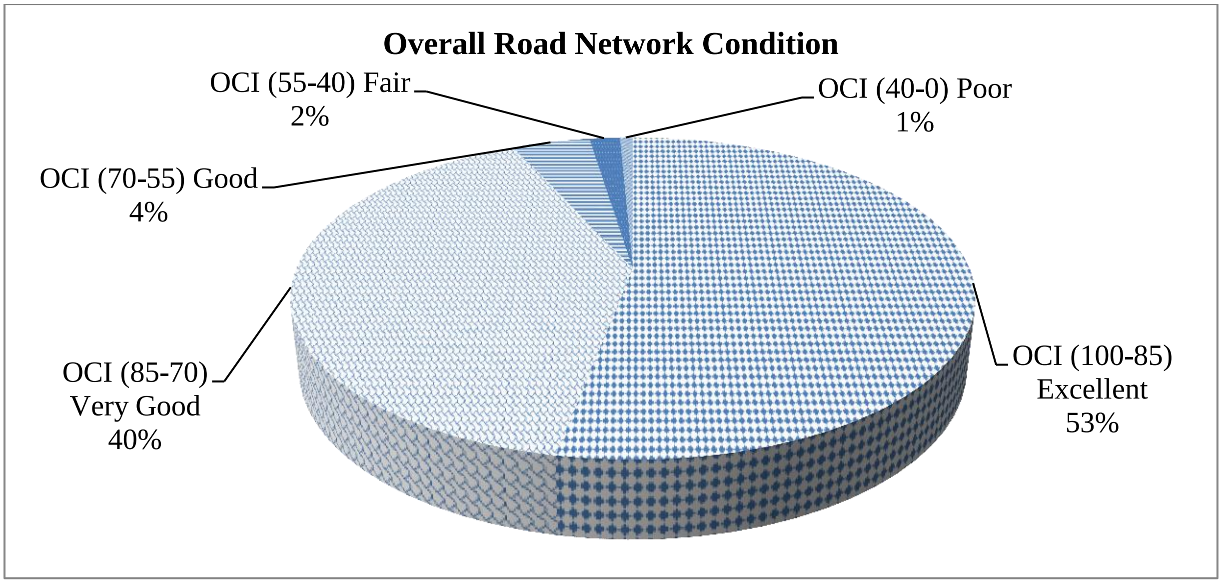


Figure 5.1: Overall Road Network Condition

The OCI for the roads, as it is mentioned earlier, is also calculated based on the AHP method. Table 5.2 represents the AHP table that was provided to the City of Markham for incorporating their engineering judgment and experience in the AHP method. This is necessary to identify the relative importance factor of each of the collected pavement performance data as compared to the other factors. The response from the various City of Markham engineering staff is shown in Table 5.3. This is then used to determine weights for each pavement performance data.

Table 5.2: AHP Table Provided to the City of Markham

	Edge Cracking	Transverse Cracking	Longitudinal Cracking	Alligator Cracking	Map Cracking	Patching	Roughness	Rutting
Edge Cracking	1.00							
Transverse Cracking		1.00						
Longitudinal Cracking			1.00					
Alligator Cracking				1.00				
Map Cracking					1.00			
Patching						1.00		
Roughness							1.00	
Rutting								1.00

Table 5.3: Response from the City of Markham

	Edge Cracking	Transverse Cracking	Longitudinal Cracking	Alligator Cracking	Map Cracking	Patching	Roughness	Rutting
Edge Cracking	1.00	5.00	5.00	7.00	7.00	0.33	3.00	5.00
Transverse Cracking	0.20	1.00	1.00	3.00	3.00	0.33	1.00	1.00
Longitudinal Cracking	0.20	1.00	1.00	3.00	3.00	0.33	1.00	1.00
Alligator Cracking	0.14	0.33	0.33	1.00	1.00	0.20	0.33	0.33
Map Cracking	0.14	0.33	0.33	1.00	1.00	0.20	0.33	0.33
Patching	3.00	3.00	3.00	5.00	5.00	1.00	3.00	3.00
Roughness	0.33	1.00	1.00	3.00	3.00	0.33	1.00	1.00
Rutting	0.20	1.00	1.00	3.00	0.33	0.33	1.00	1.00

Table 5.4 shows the calculations that are required for evaluating the pavement performance weights and verifying the consistency in the data pair-wise comparison.

Table 5.4: AHP Process to Calculate Weights for All the Pavement Performance Data

	A	B	C	D	E	F	G	H	I	J	K	L
1		Edge Cracking	Transverse Cracking	Longitudinal Cracking	Alligator Cracking	Map Cracking	Patching	Roughness	Rutting	Sum	Calcuted Weights	CI
2	Edge Cracking	1.00	5.00	5.00	7.00	7.00	0.33	3.00	5.00	33.33	0.31	8.10
3	Transverse Cracking	0.20	1.00	1.00	3.00	3.00	0.33	1.00	1.00	10.53	0.10	7.31
4	Longitudinal Cracking	0.20	1.00	1.00	3.00	3.00	0.33	1.00	1.00	10.53	0.10	7.30
5	Alligator Cracking	0.14	0.33	0.33	1.00	1.00	0.20	0.33	0.33	3.68	0.03	8.30
6	Map Cracking	0.14	0.33	0.33	1.00	1.00	0.20	0.33	0.33	3.68	0.03	8.30
7	Patching	3.00	3.00	3.00	5.00	5.00	1.00	3.00	3.00	26.00	0.24	10.83
8	Roughness	0.33	1.00	1.00	3.00	3.00	0.33	1.00	1.00	10.67	0.10	7.63
9	Rutting	0.20	1.00	1.00	3.00	0.33	0.33	1.00	1.00	7.87	0.07	8.54
10									Total	106.29	Sum	66.32

C.I	0.04
R.I	1.41
C.R	0.03

= Sum (B2:I2)

= (J2/$J$10)

= Sum (J2:J9)

=MMULT (B4:I4,$K$2:$K$9)/K4

=Sum (L2:L9)

The Consistency Index (C.I.) is calculated based on Equation 3.5. Since there are 8 pavement performance data the C.I = ((Sum (C.I) /8) – 8) / (8 – 1) = (66.32/8 – 8) / 7 = 0.04.

The Random Index (R.I) based on Table 3.4 is 1.41. The Consistency Ration (R.I) based on Equation 3.6 is calculated to be 0.03. Since the R.I is less than 0.1, thus indicating consistency in the pair-wise comparison. Table 5.5 shows the weighting factors that are obtained for each pavement performance data using the AHP method.

Table 5.5: Weighting Factors for Pavement Performance Data Using AHP Method

Edge Cracking	**31%**
Transverse Cracking	**10%**
Longitudinal Cracking	**10%**
Alligator Cracking	**3%**
Map Cracking	**3%**
Patching	**24%**
Roughness	**10%**
Rutting	**7%**

In addition to the AHP method and the City of Markham existing method, the MTO's pavement condition index was used as a third method to calculate the OCI for the road network. To use the MTO method, the same weighting factors from the AHP method were used. Based on Equation 2.1, the DMI is calculated to be 10, since the maximum theoretical value (DMI_{max}) is equal to

208 for the flexible pavement and the addition of all the pavement distress weighting factors are 0.9 excluding roughness. Therefore, the DMI = ((208 -0.9)/208)*10 = 0.9957 ~ 10. Knowing the DMI, the Equation 2.2 was used to calculate the PCI_{MTO}. In addition, the coefficient calibration C_i is considered to be 1. Table 5.6 shows the mean, variance, and standard deviation of the overall road network pavement condition using the three mentioned methods. Based on Table 5.6, it can be concluded that the results from the AHP method is very close to the City of Markham method.

Table 5.6: Comparing Different Methods

Methods	Mean	Variance	Standard Deviation
City of Markham	83.1	93.2	9.6
AHP	83.1	88.9	9.4
MTO	79.1	88.4	9.4

5.3.1 Current Pavement Condition for Each Road Classification

After calculating the OCI for each road, the next step involved dividing the roads into homogenous sections based on the road classification, treatment type, and AADT. Table 5.7 illustrates the rehabilitation and preservation strategies that have been used in the City of Markham with the life expectancy of each treatment.

Table 5.7: Maintenance and Rehabilitation Treatment Strategies

Road Rehabilitation	Life Expectancy (years)
Complete Reconstruction	20-25
Expanded Asphalt	10-15
Shave and Pave	5-10
Warm Mix	10-15
Road Preservation	**Life Expectancy (years)**
Microsurfacing	In Excess of 7 years
Chip Seal	3-6
Fog Seal	2-4

In the shave and pave and warm mix treatments the process involves milling 50mm of asphalt and placing 50mm asphalt. For the expanded asphalt the process involves pulverizing 150mm of the existing road and placing 50mm asphalt. For the microsurfacing the thickness would be determined by the aggregate size and in accordance with OPSS 1003 (OPSS 2006a), Class III Modified aggregate. For the Chip seal the thickness of the placing layer is determined by the aggregate size and in accordance with OPSS 1006 (OPSS 2006b), Class I aggregate. The reconstruction of the residential local roads includes replacing of 300mm of 50mm-crusher run limestone, 150mm of 20mm-crusher run limestone, 75mm HL8, and 40mm HL3. The reconstruction of the residential collector roads includes replacing of 450mm 50mm-crusher run limestone, 150mm of 20mm-crusher run limestone, 100mm HL8, 50mm HL3.

The City of Markham uses the Transportation Association of Canada (TAC) Geometric Design Guide for Canadian Road to classify its road network (TAC 1996). Table 5.8 shows the City of Markham road network classification system and the corresponding AADT for each road classification type of road (TAC 1996).

Table 5.8: AADT for Urban Roads (TAC 1996)

	AADT	
Road Classification	**Residential**	**Commercial**
Laneway	<500	<1000
Local	<1000	<3000
Collector	<8000	1000-12000
Minor Arterial	5000-20000	
Major Arterial	10000-30000	

After analyzing all the available data, a total of 643 road sections were utilized to analyze the network. The 643 road sections are classified according to the road classification and treatment type as summarized in Table 5.9.

Table 5.9: Distribution of Road Classification and Treatment Type

	Treatment Type						
Road Classification	**Shave and Pave**	**Expanded Asphalt**	**Cold in Place Recycling**	**Micro-surfacing**	**Chip Seal**	**Fog Seal**	**Total**
Laneway					17		17
Local	197	90	4	13	2	21	327
Collector	49	56		19			124
Minor Arterial	20	49	14	39			122
Major Arterial	6	16		31			53
Total	272	211	18	102	19	21	643

In addition to the proposed classifications, the data is classified further based on the AADT within each class. However, it was noticed that there are many roads with no AADT information. To overcome the issue, surrounding roads were examined, if the surroundings roads had an

AADT value in the database, then it was assumed to be the same. However, all of these assigned values were discussed and verified with the City of Markham engineering staff. However, there were cases where no AADT information was available. In this case, roads were classified only as noted in Table 5.9. Figures 5.2, 5.3, 5.4 and 5.5 show the OCI using the City of Markham method plotted against the age of the pavement for local road classification corresponding to each treatment strategy for the City of Markham road. Appendix B summarizes the OCI versus pavement age figures for the rest of the road classifications corresponding to each treatment strategy. Based on Figures 5.2, 5.3, 5.4, and 5.5, it can be concluded that the shave and pave and the expanded asphalt are the most commonly used treatment by the City of Markham for the local roads. In addition, Figures 5.2 and 5.4 indicate that there is a large range of OCI values corresponding to pavement age. These variations could be as a result of difference in soil type, traffic load, and pavement strength.

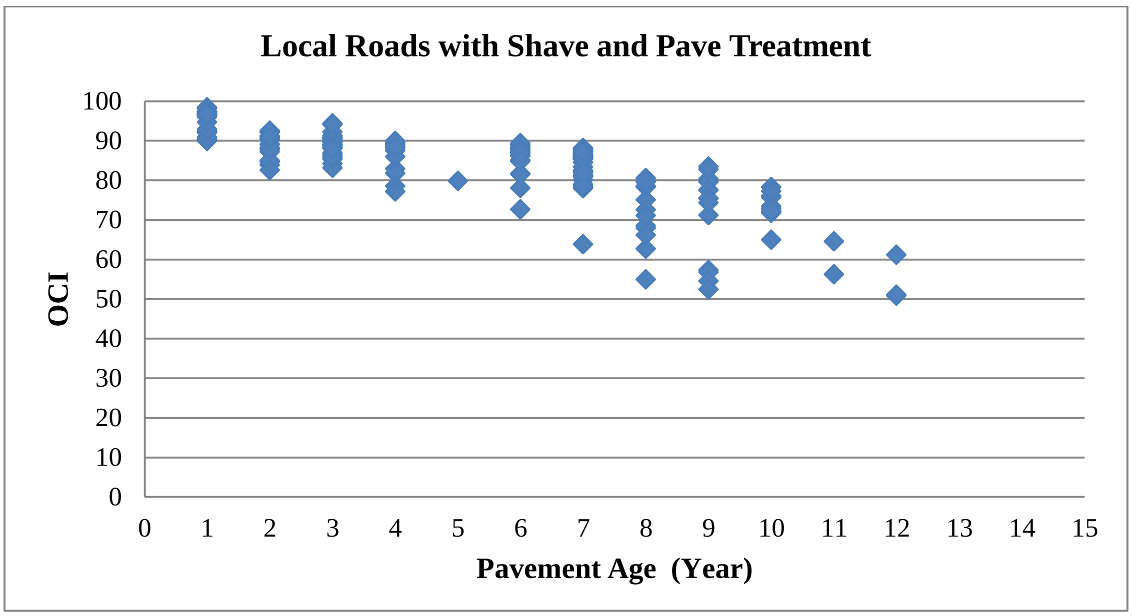


Figure 5.2: Local Roads with Shave and Pave Treatment

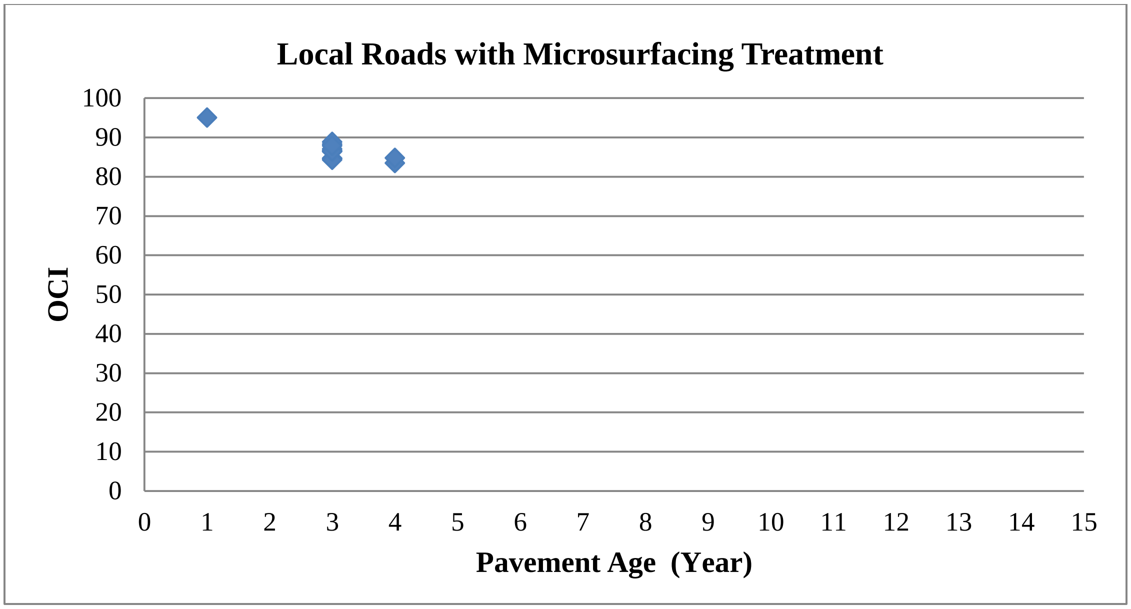


Figure 5.3: Local Roads with Microsurfacing Treatment

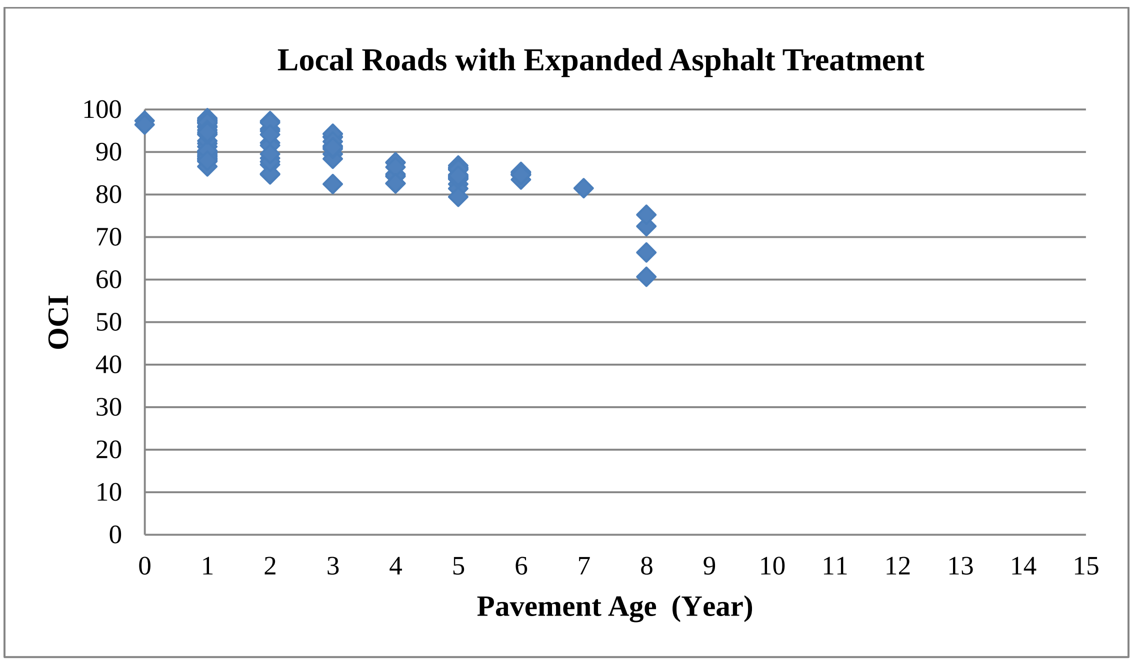


Figure 5.4: Local Roads with Expanded Asphalt Treatment

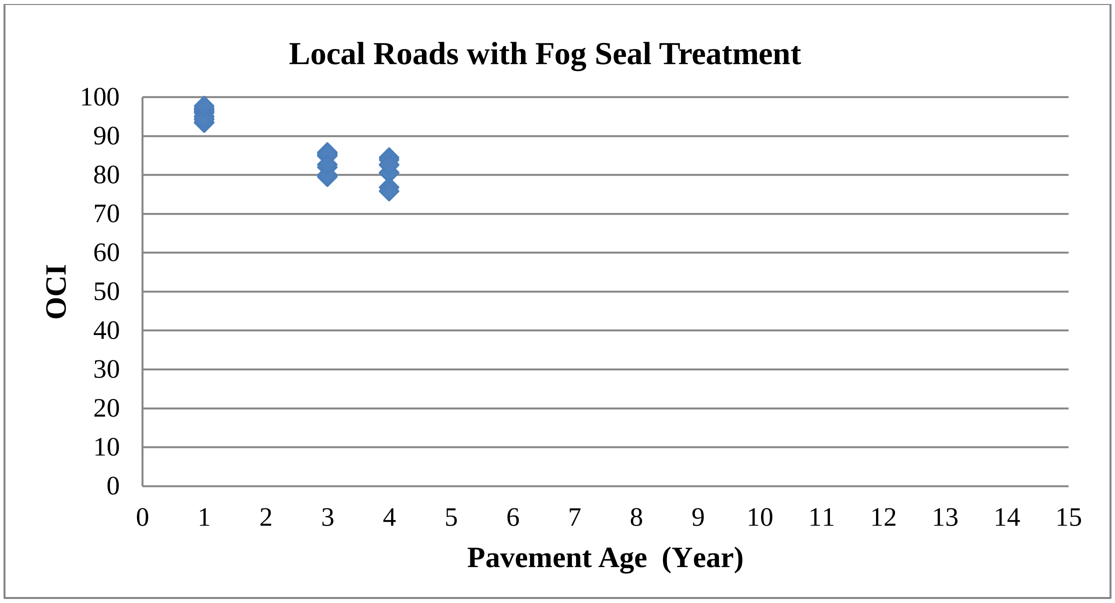


Figure 5.5: Local Roads with Fog Seal Treatment

As it mentioned earlier, in the case of available AADT information, roads were further classified based on the AADT. Figures 5.6 and5.7 show the OCI plotted against the age of the pavement with the specific AADT range for the local road classification corresponding to the shave and pave and the expanded asphalt treatment, respectively. Appendix C summarizes the complete set of Figures for all remaining road classes in the City of Markham. Normally traffic has a direct impact on the pavement condition; as the traffic load increases the pavement deteriorate faster. However, Figures 5.6 and 5.7 do not satisfy the correlation, since, the roads should be classified based on the equivalent single axle load (ESAL) not AADT. However, one of the requirements to calculate the ESAL, as it noted in Equation 3.1, is the truck percentage in AADT. Thus, the City of Markham should first collect the truck percentage and then classify the roads based on the ESALs.

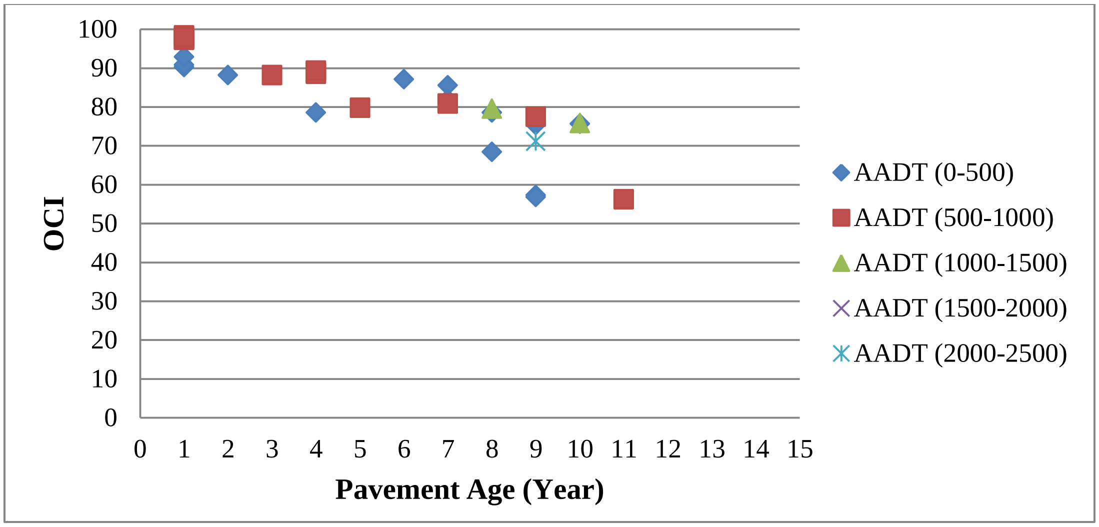


Figure 5.6: Local Roads with Shave and Pave Treatment for Different AADT

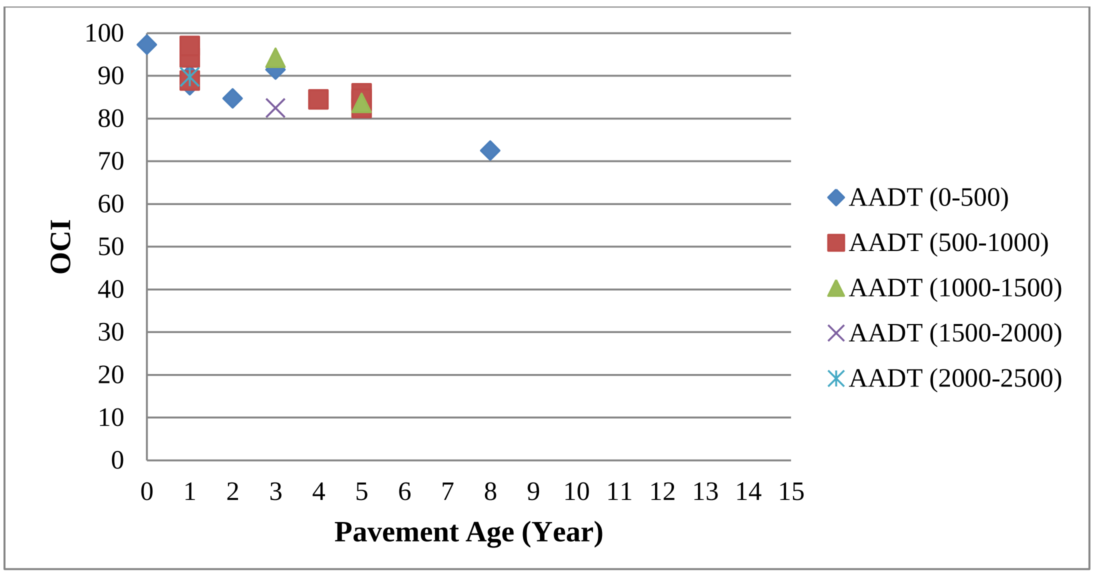


Figure 5.7: Local Roads with Expanded Asphalt Treatment for Different AADT

As mentioned earlier, based on Figures 5.2, 5.3, 5.4 and 5.5 there is a large range of OCI values corresponding to pavement age. As a result, boxplots are used to show the variation in OCI, as noted in Figures 5.8, 5.9, 5.10, 5.11, 5.12 and 5.14. The bottom and top of the box represent the 1st and 3rd quartile, respectively. The band near the middle of the box represents the median, and the top end and the bottom end of the whiskers represent the maximum and the minimum value, respectively. As noted in Figure 5.9, for example in year 9, there is a large range of performance. This could be as a result of difference in soil type, traffic load, and pavement strength. As shown in Figures 5.8 and 5.9, even though in some year the shave and pave has lower minimum OCI value than expanded asphalt but generally, the shave and pave has the higher median and maximum OCI value. Therefore, it can be concluded that for the local roads the shave and pave treatment has perform better over the years.

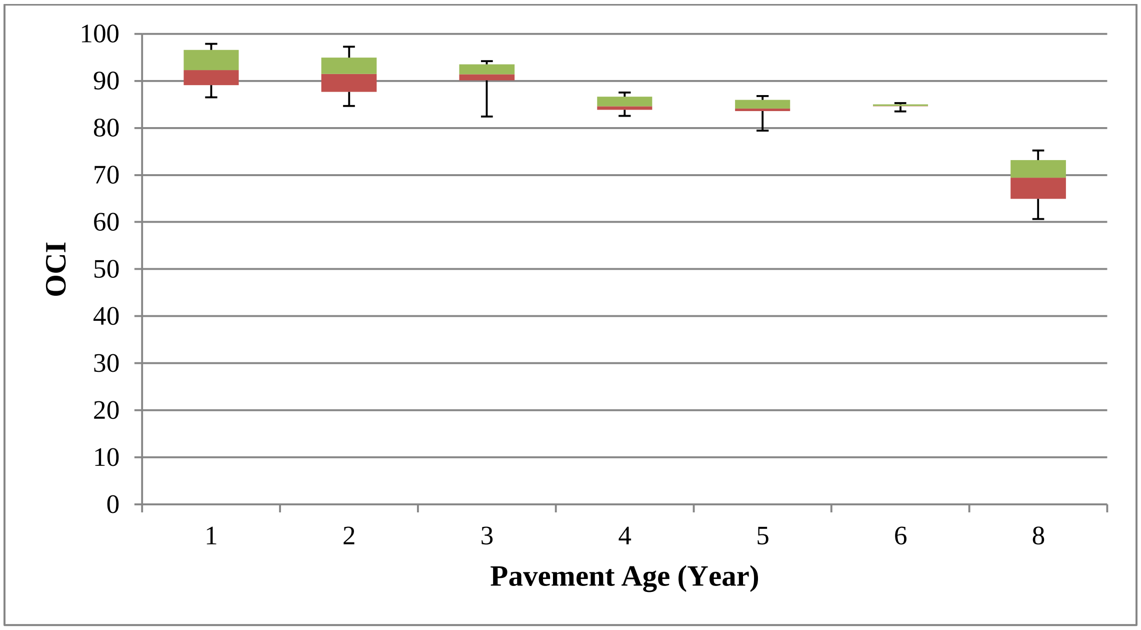


Figure 5.8: Boxplot of Local Roads with Expanded Asphalt Treatment

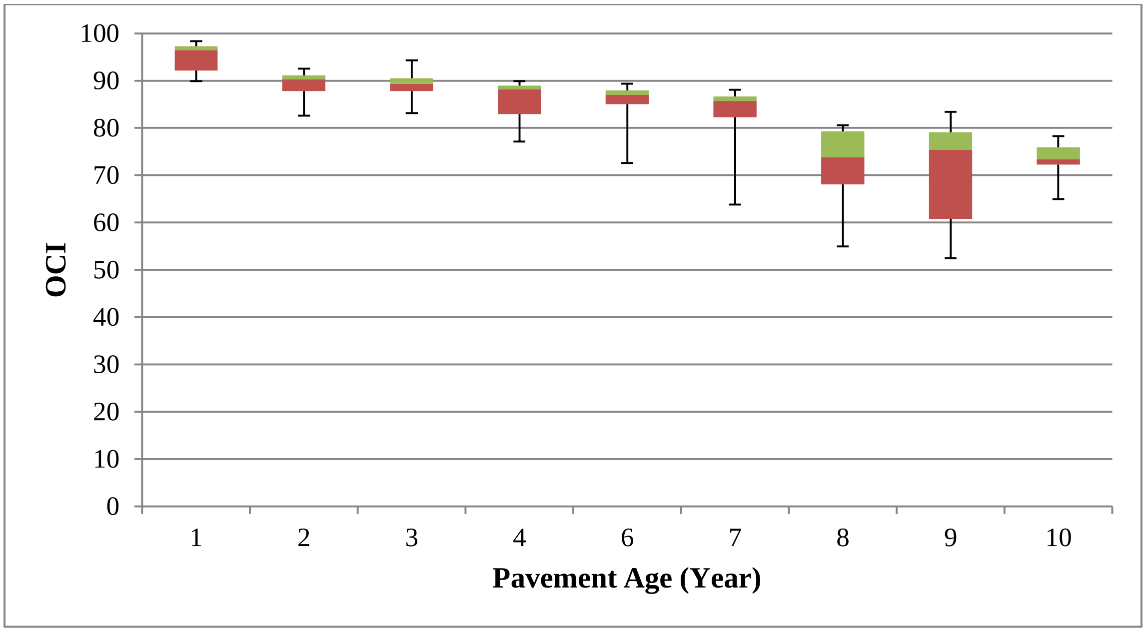


Figure 5.9: Boxplot of Local Roads with Shave and Pave Treatment

Figures 5.10 and 5.11 represent the boxplots for the collector road classification corresponding to the shave and pave and the expanded asphalt treatment, respectively. In addition, as can be seen in Figures 5.10 there are roads that have passed the expected service life, as shown in Table 5.7, for the shave and pave treatment but still have the OCI values similar to the ones that are at early stage of their service life. This could indicate that there might have been further treatment on that particular road but the treatment information was not recorded in the database, these outliers would appear to require some further investigation by the City of Markham engineering staff.

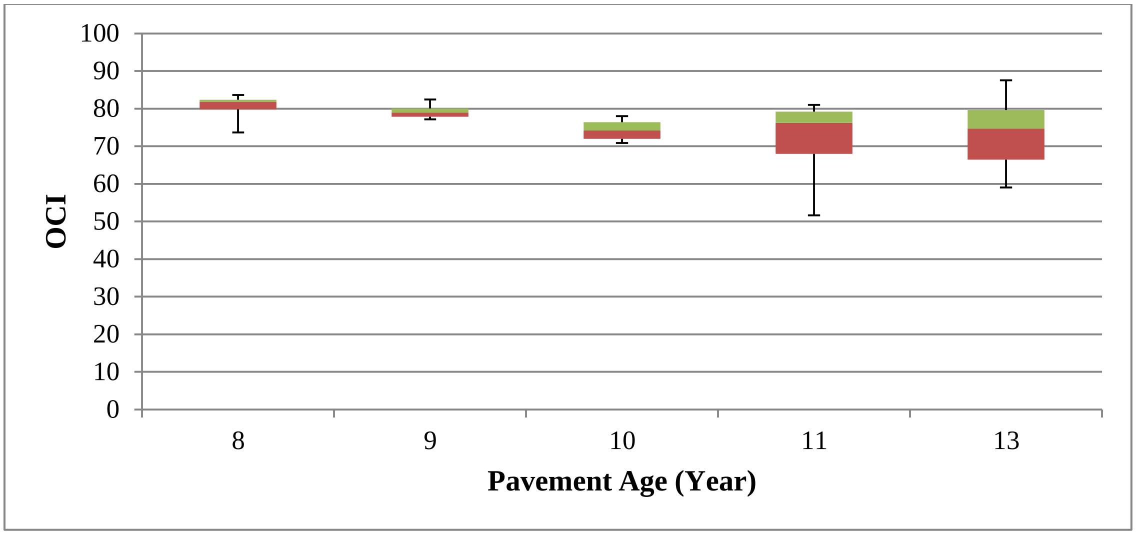


Figure 5.10: Boxplot of Collector Roads with Shave and Pave Treatment

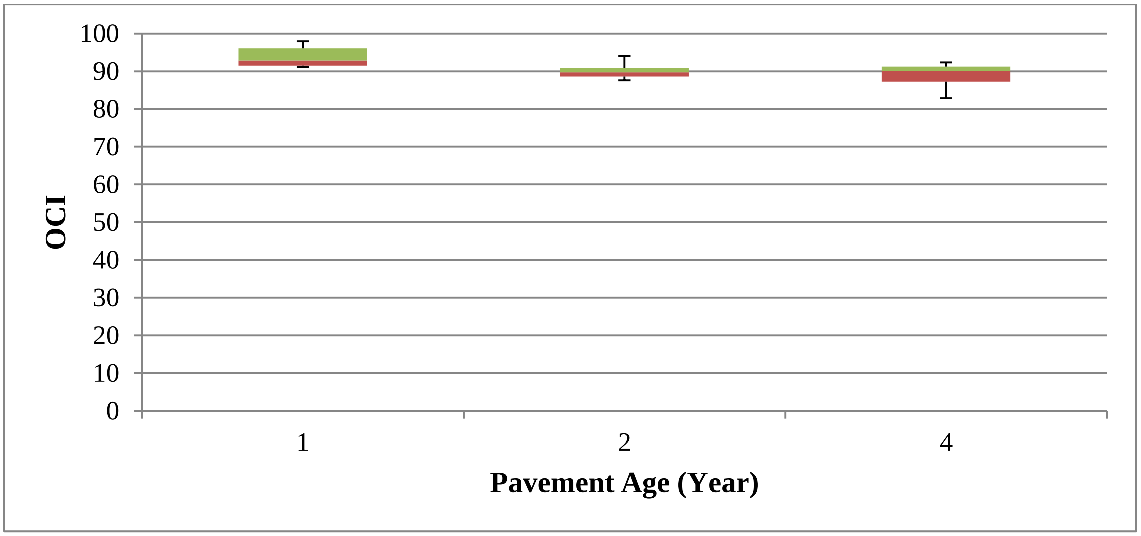


Figure 5.11: Boxplot of Collector Roads with Expanded Asphalt Treatment

Figures 5.12, 5.13 and 5.14 summarize the boxplots for the different applied treatment for the minor arterial roads. Overall, it appears that there is not a large range of OCI values for this type of road.

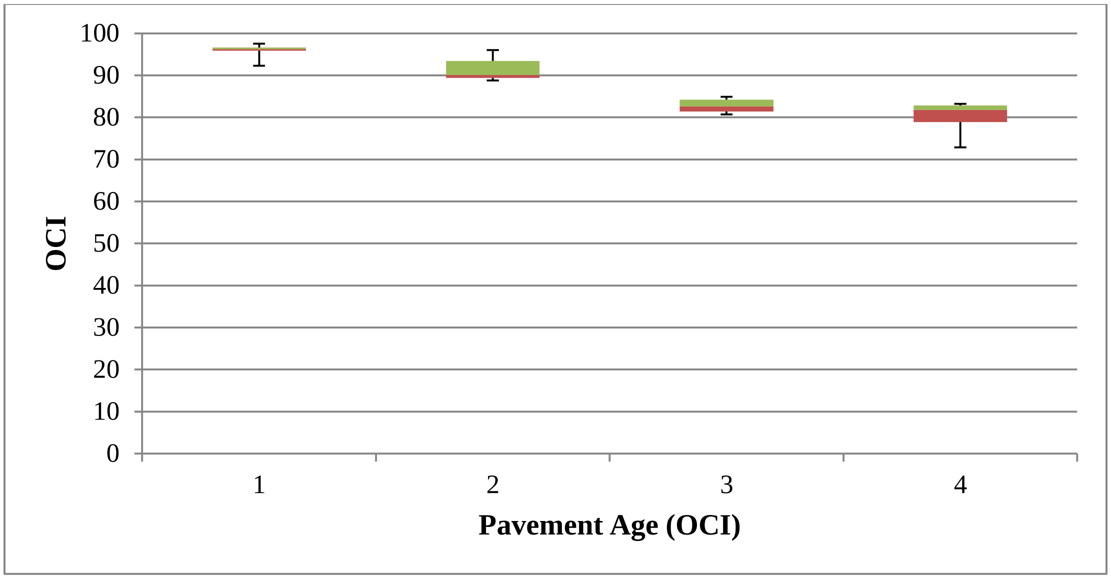


Figure 5.12: Boxplot of Minor Arterial Roads with Microsurfacing Treatment

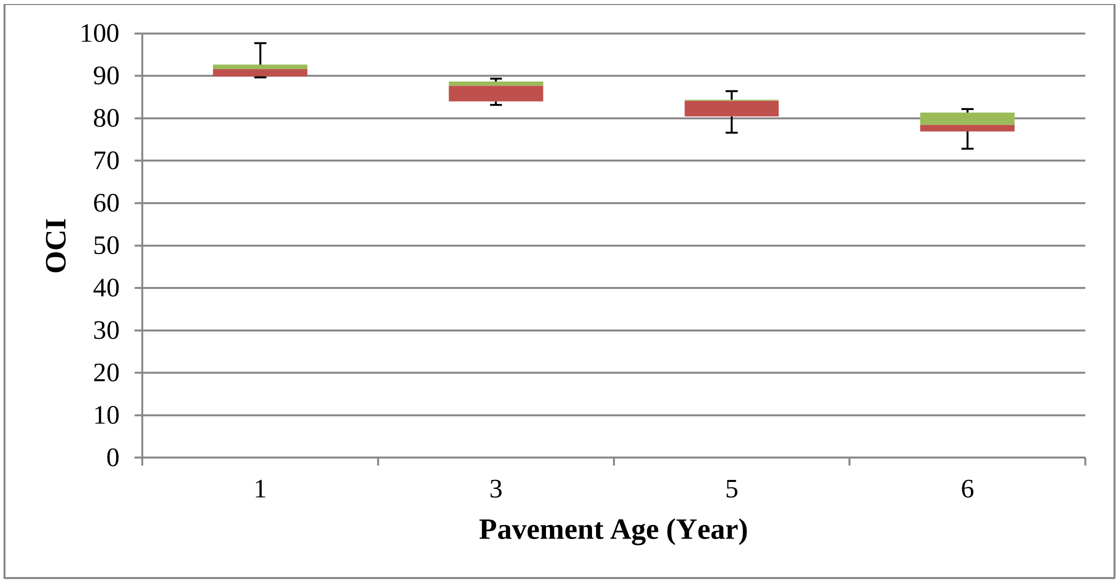


Figure 5.13: Boxplot of Minor Arterial Roads with Expanded Asphalt Treatment

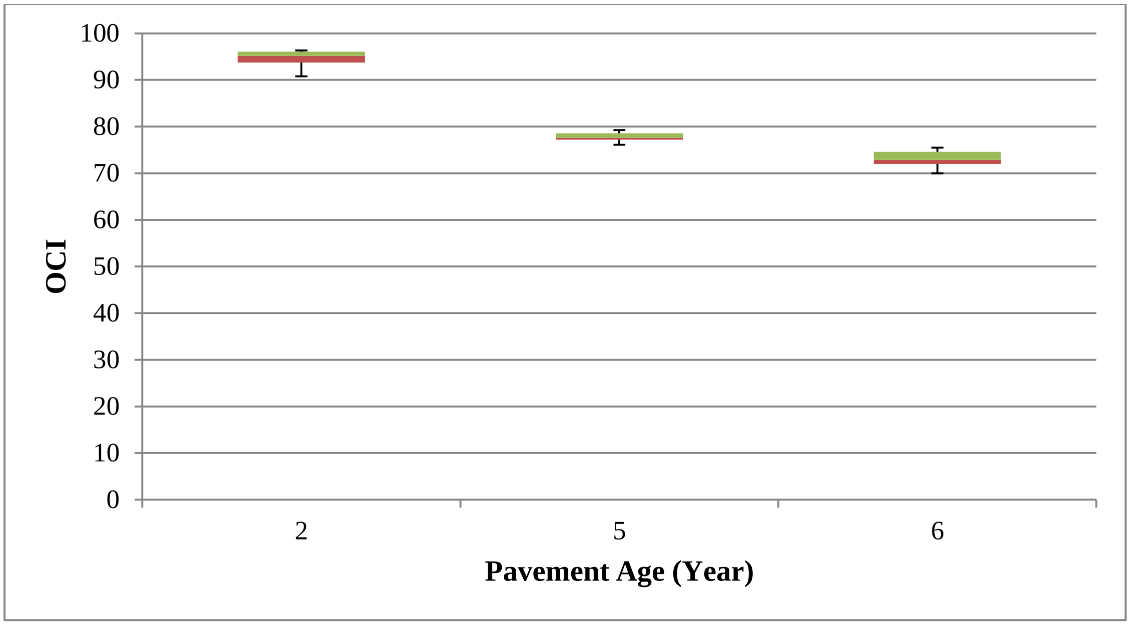


Figure 5.14: Boxplot of Minor Arterial Roads with Microsurfacing Treatment

5.4 Prediction Model for Pavement Performance Deterioration

After calculating the OCI for each road section, using the three methods as explained in section 5.3, the Markov model is used to predict the pavement performance deterioration for various road classifications corresponding to each treatment strategy for the road network. The performance models were developed for a 20 year period and considered an OCI of 50 as the minimum accepted service life for the roads.

The first step in the Markov model is to construct the Transition Probability Matrix (TPM) which summarizes the probability of moving from one candidate state to another state over a defined period of time. The second step involves constructing the state transition matrix for life expectancy of the roads which in this case is considered to be 20 years. Figures 5.15 and 5.16 show a sample of TPM and the road condition based on the Markov model for the collector roads with the expanded asphalt treatment based on the Elhakeem method, respectively (Elhakeem 2005).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
33																
34		**10**	**9**	**8**	**7**	[illegible]	[illegible]	[illegible]	**3**	**2**	**1**	**0**		States		
35	**10**	**0.80**	0.20	0	0	[illegible]	[illegible]	[illegible]	0	0	0	0		10	New	
36	**9**	0	**0.65**	0.35	0	0	0	0	0	0	0	0		9		
37	**8**	0	0	**0.50**	0.50	0	0	0	0	0	0	0		8		
38	**7**	0	0	0	**0.45**	0.55	0	0	0	0	0	0		7		
39	**6**	0	0	0	0	**0.40**	0.60	0	0	0	0	0		6		
40	**5**	0	0	0	0	0	**0.35**	0.65	0	0	0	0		5		
41	**4**	0	0	0	0	0	0	**0.25**	0.75	0	0	0		4		
42	**3**	0	0	0	0	0	0	0	**0.20**	0.80	0	0		3		
43	**2**	0	0	0	0	0	0	0	0	**0.15**	0.85	0		2		
44	**1**	0	0	0	0	0	0	0	0	0	**0.10**	0.90		1		
45	**0**	0	0	0	0	0	0	0	0	0	0	**1.00**		0	Critical	
46																

C35=1-B35

Figure 5.15: TPM Matrix for Collector Roads with Expanded Asphalt Treatment

	BJ	BK	BL	BM	BN
51		Age (Year)	Markov Value	Markov Value Scaled	**Data From Markham**
52		**0**	10.00	100.0	
53		**1**	9.80	98.0	94
54		**2**	9.57	95.7	90
55		**3**	9.31	93.1	
56		**4**	9.00	90.0	89
57		**5**	8.67	86.7	88
58		**6**	8.29	82.9	85
59		**7**	7.89	78.9	81
60		**8**	7.44	74.4	81
61		**9**	6.96	69.6	
62		**10**	6.45	64.5	
63		**11**	5.89	58.9	
64		**12**	5.32	53.2	
65		**13**	4.73	47.3	
66		**14**	4.15	41.5	
67		**15**	3.59	35.9	
68		**16**	3.07	30.7	
69		**17**	2.60	26.0	
70		**18**	2.18	21.8	
71		**19**	1.81	18.1	
72		**20**	1.50	15.0	

BM58=BL58*10

Figure 5.16: Predicted Road Condition Based on Markov Model vs. Actual Condition Based on the City of Markham Data for Collector Roads with Expanded Asphalt Treatment

Figures 5.17, 5.18, 5.19, 5.20, 5.21 and 5.22 illustrate the pavement performance prediction models using the Markov chain methods for the three different methods for the local roads. Appendix D summarizes the similar Figures for the rest of the road classes. The pavement performance prediction models are drawn up to the minimum acceptable service life which is 50.

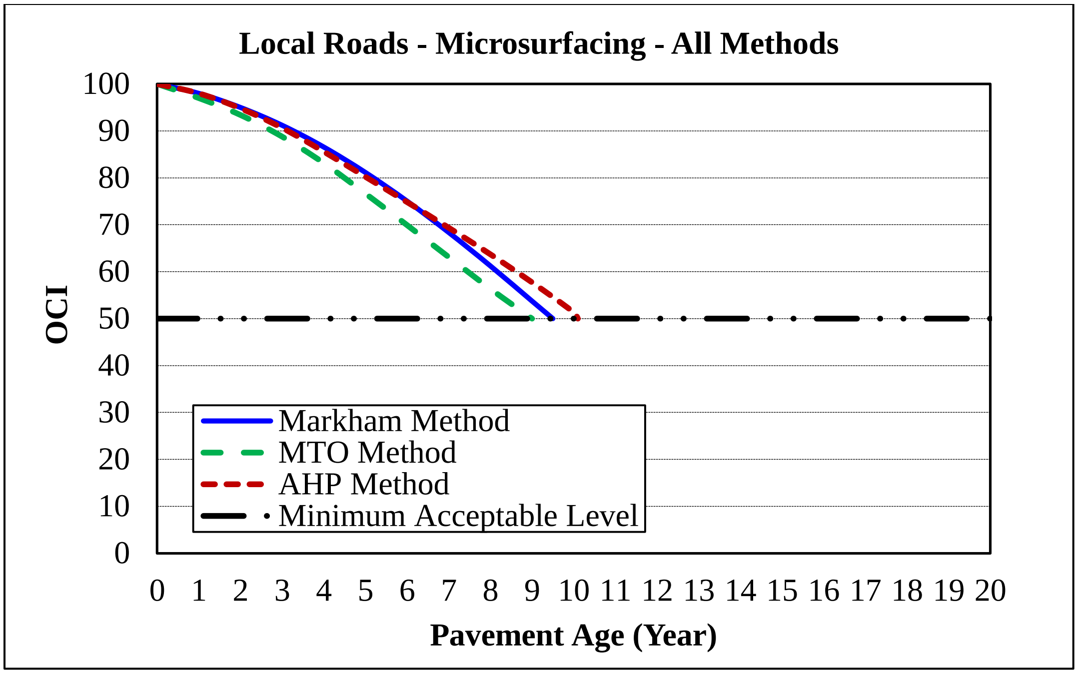


Figure 5.17: Pavement Performance Prediction Model for Local Roads with the Microsurfacing Treatment

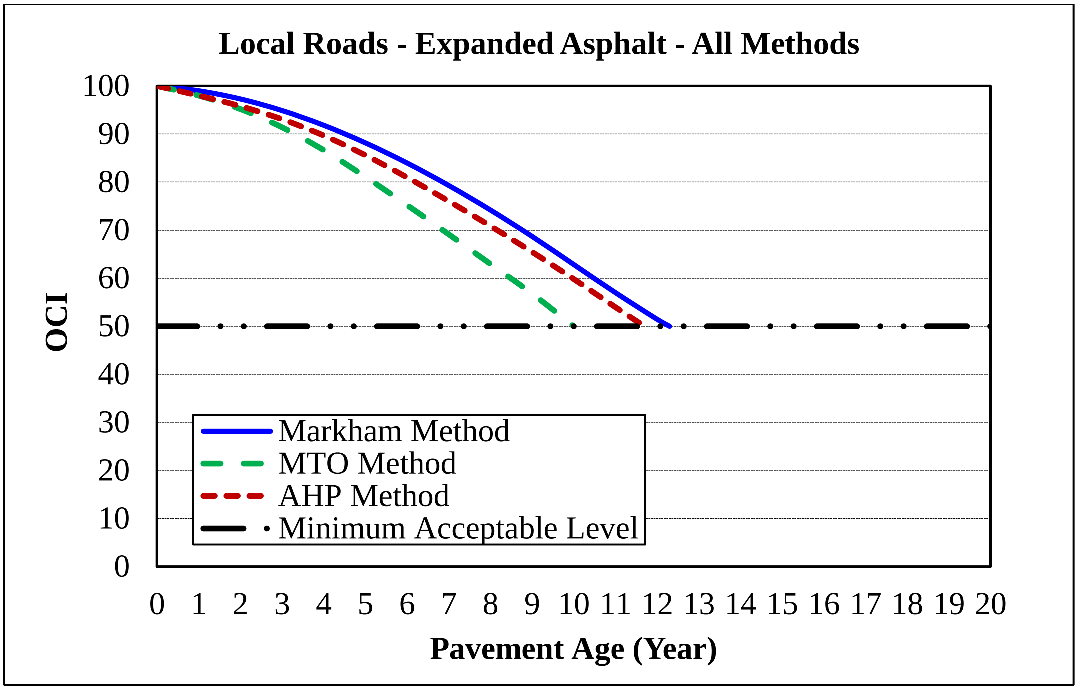


Figure 5.18: Pavement Performance Prediction Model for Local Roads with the Expanded Asphalt Treatment

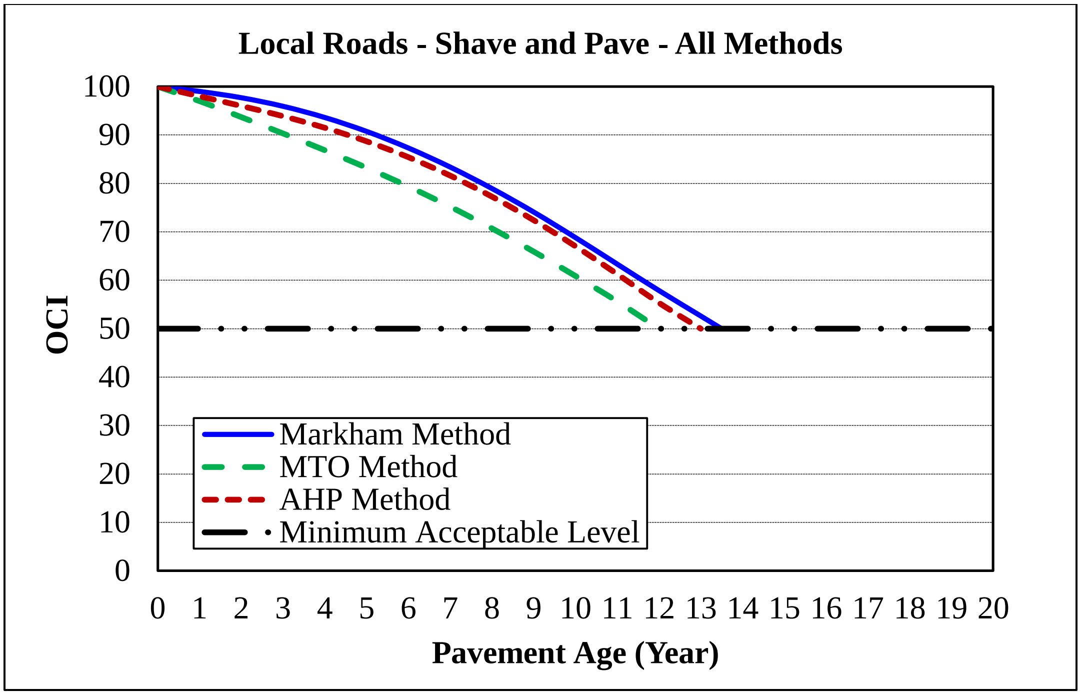


Figure 5.19: Pavement Performance Prediction Model for Local Roads with the Shave and Pave Treatment

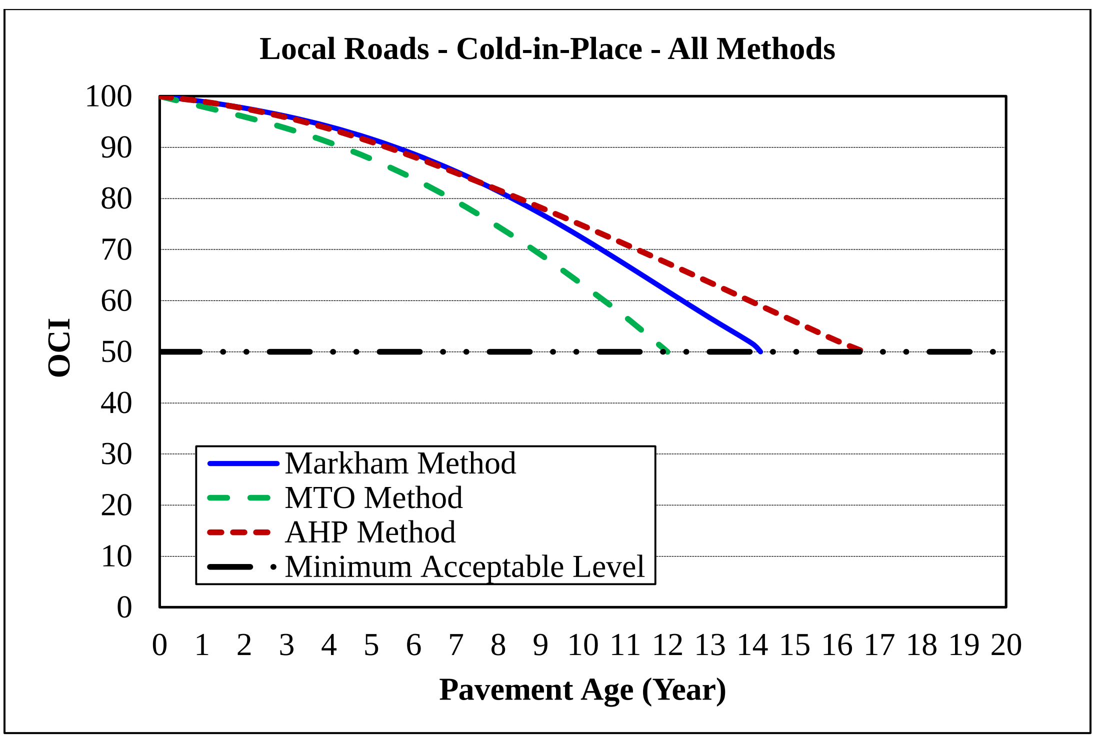


Figure 5.20: Pavement Performance Prediction Model for Local Roads with the Cold-in-Place Treatment

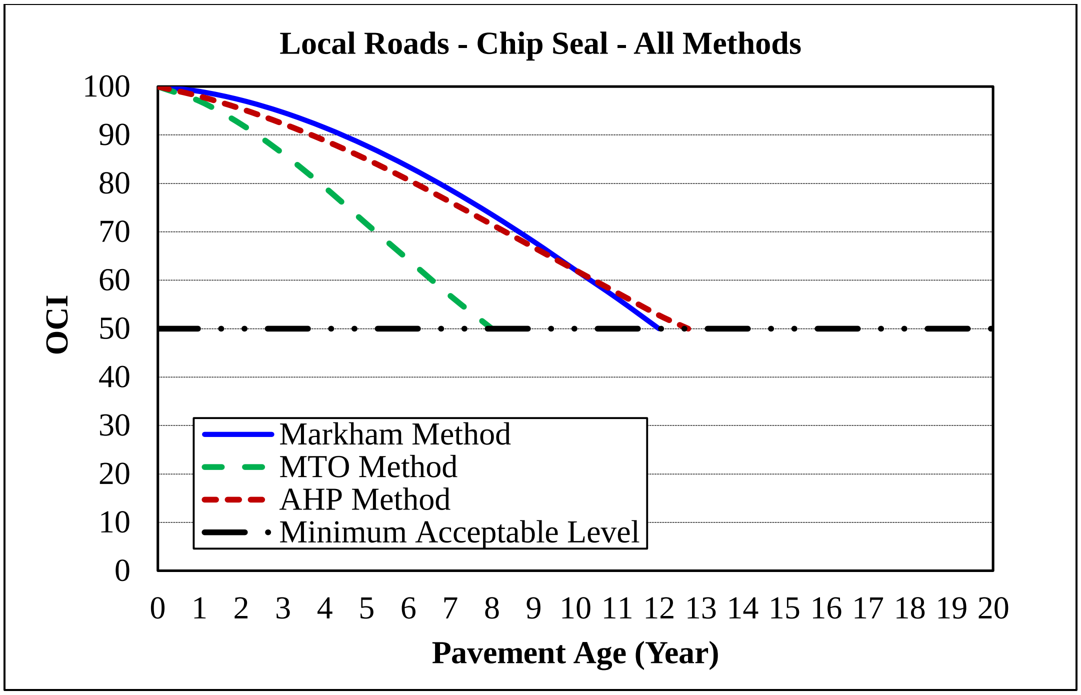


Figure 5.21: Pavement Performance Prediction Model for Local Roads with the Chip Seal Treatment

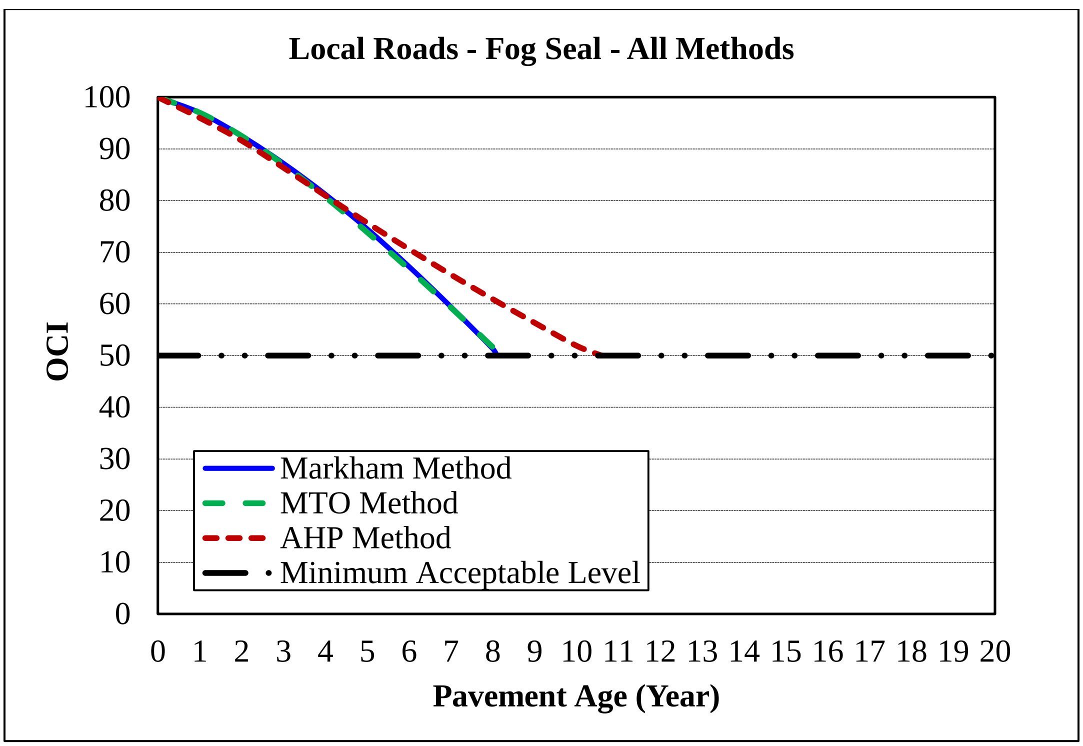


Figure 5.22: Pavement Performance Prediction Model for Local Roads with the Fog Seal Treatment

To examine the variation in service life for the City of Markham method, the MTO method and the AHP method, the variance and standard deviation of service life are calculated for all the road classification corresponding to each treatment strategy as shown in Table 5.10. If the standard deviation value is less than or equal to one then the three methods are considered to be statistically the same. As shown in Table 5.10, for the local roads and the collector roads it was noted that there are variations in expected service life for the three methods. Moreover, Table 5.10 indicates the predicted service life based on the AHP method and the Markham method for the collector roads, minor arterials roads, major arterial roads, and laneways are relatively close. In addition, AHP method provides higher service life for the local roads compare to the other methods.

Table 5.10: Predicted Service Life Comparison for All Three Methods

		Predicted Service Life (Years)				
Road Classification	**Treatment Type**	**Markham Method**	**AHP Method**	**MTO Method**	**Variance**	**Standard Deviation**
Local	Shave and Pave	13.5	13	12	0.6	0.8
	Expanded Asphalt	12	12	10	1.3	1.2
	Microsurfacing	9.5	10	9	0.3	0.5
	Cold-in-Place	14	17	12	6.3	2.5
	Chip Seal	12	13	8	7.0	2.6
	Fog Seal	8	14	8	12.0	3.5
Collector	Shave and Pave	14.5	16	14	1.1	1.0
	Expanded Asphalt	12.5	13	9.5	3.6	1.9
	Microsurfacing	9	9	7.5	0.8	0.9
Minor Arterial	Shave and Pave	14	15.5	15.5	0.8	0.9
	Expanded Asphalt	10	11	10	0.3	0.6
	Microsurfacing	8.5	8.5	8.5	0.0	0.0
	Cold-in-Place	13	12.5	13.5	0.3	0.5
Major Arterial	Shave and Pave	12	12	13	0.3	0.6
	Expanded Asphalt	10	10	10.5	0.1	0.3
	Microsurfacing	9	8.5	10	0.6	0.8
Laneway	Chip Seal	6.5	6.5	6	0.1	0.3

Tables 5.11, 5.12 and 5.13 summarize all the results from the performance prediction models for each road classification and corresponding treatment strategy and the typical observed distresses for each road class based on the 2011 survey for all three methods.

Table 5.11: Summary of Performance Prediction Models and 2011 Survey for Each Road Classification Based on Markham Method

Road Classification	Treatment Type	Performance Prediction Model Utilizing City of Markham Model	R^2	Predicted Service Life (Years)
Local	Shave and Pave	$OCI = 3E\text{-}06\ Age^5 - 0.0005\ Age^4 + 0.0283\ Age^3 - 0.5873\ Age^2 + 0.3299\ Age + 99.974$	0.99	13.5
	Expanded Asphalt	OCI = -1E-07 Age 6 + 2E-05 Age 5 - 0.0016 Age 4 + 0.0596 Age 3 - 0.9437 Age 2 + 1.2574 Age + 98.996	0.99	12
	Microsurfacing	$OCI = -2E\text{-}07\ Age^6 + 4E\text{-}05\ Age^5 - 0.003\ Age^4 + 0.1001\ Age^3 - 1.3871\ Age^2 + 1.1462\ Age + 98.866$	0.99	9.5
	Cold-in-Place	$OCI = 3E\text{-}06\ Age^5 - 0.0005\ Age^4 + 0.0281\ Age^3 - 0.6125\ Age^2 + 0.9865\ Age + 98.99$	0.99	14
	Chip Seal	$OCI = -1E\text{-}07\ Age^6 + 2E\text{-}05\ Age^5 - 0.0017\ Age^4 + 0.0598\ Age^3 - 0.9366\ Age^2 + 1.1044\ Age + 99.115$	0.99	12
	Fog Seal	$OCI = -3E\text{-}07\ Age^6 + 5E\text{-}05\ Age^5 - 0.0035\ Age^4 + 0.1082\ Age^3 - 1.3338\ Age^2 - 0.9889\ Age + 99.998$	0.99	8
Collector	Shave and Pave	$OCI = 3E\text{-}06\ Age^5 - 0.0005\ Age^4 + 0.027\ Age^3 - 0.5977\ Age^2 + 1.0083\ Age + 98.71$	0.99	14.5
	Expanded Asphalt	$OCI = -1E\text{-}07\ Age^6 + 2E\text{-}05\ Age^5 - 0.0016\ Age^4 + 0.059\ Age^3 - 0.9482\ Age^2 + 1.4281\ Age + 98.852$	0.99	12.5
	Microsurfacing	$OCI = -2E\text{-}07\ Age^6 + 4E\text{-}05\ Age^5 - 0.0031\ Age^4 + 0.0983\ Age^3 - 1.2888\ Age^2 - 0.1212\ Age + 99.957$	0.99	9
Minor Arterial	Shave and Pave	$OCI = 3E\text{-}06\ Age^5 - 0.0005\ Age^4 + 0.0284\ Age^3 - 0.6014\ Age^2 + 0.628\ Age + 99.47$	0.99	14
	Expanded Asphalt	$OCI = -2E\text{-}07\ Age^6 + 4E\text{-}05\ Age^5 - 0.003\ Age^4 + 0.1001\ Age^3 - 1.4169\ Age^2 + 1.617\ Age + 98.551$	0.99	10
	Microsurfacing	$OCI = -3E\text{-}07\ Age^6 + 5E\text{-}05\ Age^5 - 0.0036\ Age^4 + 0.1128\ Age^3 - 1.4429\ Age^2 + 0.0026\ Age + 99.499$	0.99	8.5
	Cold-in-Place	$OCI = -9E\text{-}08\ Age^6 + 2E\text{-}05\ Age^5 - 0.0015\ Age^4 + 0.0555\ Age^3 - 0.9322\ Age^2 + 1.7869\ Age + 98.478$	0.99	13
Major Arterial	Shave and Pave	$OCI = -1E\text{-}07\ Age^6 + 2E\text{-}05\ Age^5 - 0.0017\ Age^4 + 0.0598\ Age^3 - 0.9366\ Age^2 + 1.1044\ Age + 99.115$	0.99	12
	Expanded Asphalt	$OCI = -2E\text{-}07\ Age^6 + 4E\text{-}05\ Age^5 - 0.0029\ Age^4 + 0.0983\ Age^3 - 1.4228\ Age^2 + 2.0001\ Age + 98.091$	0.99	10
	Microsurfacing	$OCI = -2E\text{-}07\ Age^6 + 3E\text{-}05\ Age^5 - 0.0023\ Age^4 + 0.0815\ Age^3 - 1.2001\ Age^2 + 1.0863\ Age + 98.101$	0.99	9
Laneway	Chip Seal	$OCI = -3E\text{-}07\ Age^6 + 5E\text{-}05\ Age^5 - 0.0029\ Age^4 + 0.0796\ Age^3 - 0.6677\ Age^2 - 6.9439\ Age + 99.95$	0.99	6.5

Table 5.12: Summary of Performance Prediction Models and 2011 Survey for Each Road Classification Based on MTO Method

Road Classification	Treatment Type	Performance Prediction Model Utilizing MTO Model	R^2	Predicted Service Life (Years)
Local	Shave and Pave	$OCI = 3E-06 Age^{5} - 0.0005 Age^{4} + 0.0294 Age^{3} - 0.5818 Age^{2} - 0.4716 Age + 97.903$	0.99	12
	Expanded Asphalt	$OCI = -1E-07 Age^{6} + 3E-05 Age^{5} - 0.002 Age^{4} + 0.0686 Age^{3} - 0.9945 Age^{2} - 0.1244 Age + 99.353$	0.99	10
	Microsurfacing	$OCI = -2E-07 Age^{6} + 3E-05 Age^{5} - 0.0023 Age^{4} + 0.0771 Age^{3} - 1.0239 Age^{2} - 1.1169 Age + 99.545$	0.99	9
	Cold-in-Place	$OCI = 4E-06 Age^{5} - 0.0007 Age^{4} + 0.0348 Age^{3} - 0.6919 Age^{2} + 0.2934 Age + 99.243$	0.99	12
	Chip Seal	$OCI = -3E-07 Age^{6} + 5E-05 Age^{5} - 0.0032x^{4} + 0.0968 Age^{3} - 1.1407 Age^{2} - 2.2877 Age + 99.68$	0.99	8
	Fog Seal	$OCI = -3E-07 Age^{6} + 5E-05 Age^{5} - 0.0033 Age^{4} + 0.103 Age^{3} - 1.2706 Age^{2} - 1.1958 Age + 99.938$	0.99	8
Collector	Shave and Pave	$OCI = 3E-06 Age^{5} - 0.0004 Age^{4} + 0.0235 Age^{3} - 0.4976 Age^{2} - 0.0899 Age + 99.94$	0.99	14
	Expanded Asphalt	$OCI = -1E-07 Age^{6} + 3E-05 Age^{5} - 0.002 Age^{4} + 0.0674 Age\ x^{3} - 0.9254 Age^{2} - 1.056 Age + 99.946$	0.99	9.5
	Microsurfacing	$OCI = -3E-07 Age^{6} + 5E-05 Age^{5} - 0.0034 Age^{4} + 0.1021 Age^{3} - 1.1679 Age^{2} - 2.6327 Age + 99.968$	0.99	7.5
Minor Arterial	Shave and Pave	$OCI = 1E-08 Age^{6} + 3E-07 Age^{5} - 0.0002 Age^{4} + 0.0178 Age^{3} - 0.4486 Age^{2} + 0.419 Age + 98.949$	0.99	15.5
	Expanded Asphalt	$OCI = -1E-07 Age^{6} + 2E-05 Age^{5} - 0.0015 Age^{4} + 0.0552 Age^{3} - 0.7988 Age^{2} - 1.1315 Age + 99.615$	0.99	10
	Microsurfacing	$OCI = -2E-07 Age^{6} + 3E-05 Age^{5} - 0.0024 Age^{4} + 0.0762 Age^{3} - 0.975 Age^{2} - 1.7543 Age + 99.854$	0.99	8.5
	Cold-in-Place	$OCI = 3E-06 Age^{5} - 0.0005 Age^{4} + 0.0283 Age^{3} - 0.5873 Age^{2} + 0.3299 Age + 99.974$	0.99	13.5
Major Arterial	Shave and Pave	$OCI = 3E-06 Age^{5} - 0.0004 Age^{4} + 0.0222 Age^{3} - 0.4399 Age^{2} - 0.9825 Age + 99.857$	0.99	13
	Expanded Asphalt	$OCI = -2E-07 Age^{6} + 4E-05 Age^{5} - 0.0026 Age^{4} + 0.0915 Age^{3} - 1.3773 Age^{2} + 2.3456 Age + 97.51$	0.99	10.5
	Microsurfacing	$OCI = -2E-07 Age^{6} + 4E-05 Age^{5} - 0.0026 Age^{4} + 0.0915 Age^{3} - 1.3773 Age^{2} + 2.3456 Age + 97.51$	0.99	10
Laneway	Chip Seal	$OCI = -3E-07 Age^{6} + 4E-05 Age^{5} - 0.0026 Age^{4} + 0.0684 Age^{3} - 0.4651 Age^{2} - 8.3745 Age + 99.891$	0.99	6

Table 5.13: Summary of Performance Prediction Models and 2011 Survey for Each Road Classification Based on AHP Method

Road Classification	Treatment Type	Performance Prediction Model Utilizing AHP Model	R^2	Predicted Service Life (Years)
Local	Shave and Pave	$OCI = 4E\text{-}06\ Age^5 - 0.0006\ Age^4 + 0.0344\ Age^3 - 0.7211\ Age^2 + 1.071\ Age + 98.034$	0.99	13
	Expanded Asphalt	$OCI = 4E\text{-}06\ Age^5 - 0.0006\ Age^4 + 0.0333\ Age^3 - 0.6371\ Age^2 - 0.4867\ Age + 99.83$	0.99	12
	Microsurfacing	$OCI = -1E\text{-}07\ Age^6 + 3E\text{-}05\ Age^5 - 0.0021\ Age^4 + 0.0729\ Age^3 - 1.0633\ Age^2 + 0.253\ Age + 98.708$	0.99	10
	Cold-in-Place	$OCI = 1E\text{-}06\ Age^5 - 0.0002\ Age^4 + 0.0141\ Age^3 - 0.3461\ Age^2 - 0.2375\ Age + 99.519$	0.99	17
	Chip Seal	$OCI = 2E\text{-}06\ Age^5 - 0.0004\ Age^4 + 0.0211\ Age^3 - 0.4182\ Age^2 - 1.3664\ Age + 99.831$	0.99	13
	Fog Seal	$OCI = 2E\text{-}06\ Age^5 - 0.0003\ Age^4 + 0.0142\ Age^3 - 0.1994\ Age^2 - 4.0116\ Age + 99.875$	0.99	14
Collector	Shave and Pave	$OCI = 1E\text{-}06\ Age^5 - 0.0002\ Age^4 + 0.0135\ Age^3 - 0.3296\ Age^2 - 0.4137\ Age + 99.564$	0.99	16
	Expanded Asphalt	$OCI = 3E\text{-}06\ Age^5 - 0.0005\ Age^4 + 0.0255\ Age^3 - 0.5004\ Age^2 - 0.7308\ Age + 99.785$	0.99	13
	Microsurfacing	$OCI = -2E\text{-}07\ Age^6 + 4E\text{-}05\ Age^5 - 0.0031\ Age^4 + 0.0983\ Age^3 - 1.2888x^2 - 0.1212x + 99.957$	0.99	9
Minor Arterial	Shave and Pave	$OCI = 1E\text{-}06\ Age^5 - 0.0002\ Age^4 + 0.0142\ Age^3 - 0.326\ Age^2 - 0.7524\ Age + 99.895$	0.99	15.5
	Expanded Asphalt	$OCI = -6E\text{-}08\ Age^6 + 1E\text{-}05\ Age^5 - 0.0012\ Age^4 + 0.0466\ Age^3 - 0.7419\ Age^2 - 0.6693\ Age + 98.944$	0.99	11
	Microsurfacing	$OCI = -3E\text{-}07\ Age^6 + 5E\text{-}05\ Age^5 - 0.0031\ Age^4 + 0.099\ Age^3 - 1.2542\ Age^2 - 0.867\ Age + 99.489$	0.99	8.5
	Cold-in-Place	$OCI = -1E\text{-}07\ Age^6 + 2E\text{-}05\ Age^5 - 0.0016\ Age^4 + 0.0581\ Age^3 - 0.9328\ Age^2 + 1.3261\ Age + 98.849$	0.99	12.5
Major Arterial	Shave and Pave	$OCI = 4E\text{-}06\ Age^5 - 0.0006\ Age^4 + 0.0339\ Age^3 - 0.6539\ Age^2 - 0.3185\ Age + 99.056$	0.99	12
	Expanded Asphalt	$OCI = -2E\text{-}07\ Age^6 + 3E\text{-}05\ Age^5 - 0.0023\ Age^4 + 0.0815\ Age^3 - 1.2001\ Age^2 + 1.0863\ Age + 98.101$	0.99	10
	Microsurfacing	$OCI = -2E\text{-}07\ Age^6 + 3E\text{-}05\ Age^5 - 0.0023\ Age^4 + 0.0815\ Age^3 - 1.2001\ Age^2 + 1.0863\ Age + 98.101$	0.99	8.5
Laneway	Chip Seal	$OCI = -3E\text{-}07\ Age^6 + 5E\text{-}05\ Age^5 - 0.0029\ Age^4 + 0.0796\ Age^3 - 0.6677\ Age^2 - 6.9439\ Age + 99.899$	0.99	6.5

5.5 Economic Evaluation of Rehabilitation and Maintenance Alternatives

The present worth (PW) was used for the case study to evaluate the cost for each rehabilitation and maintenance alternative. Table 5.14 represents the unit cost for each treatment that is used by the City of Markham. Please note the unit cost is incorporated with the labour cost, equipment cost, and material cost.

Table 5.14: Unit Cost for Each Treatment

Treatment Type	Unit Cost
Shave and Pave	\$27.00 m^2
Expanded Asphalt	\$32.00 m^2
Microsurfacing	\$3.37 m^2
Cold-in-Place Recycling	\$15.00 m^2
Chip Seal	\$3.13 m^2
Fog Seal	\$1.46 m^2

Equation 3.9 was used to calculate the PW. To use the PW formula, the analysis period was considered to be five years with the discount rate of 4% (0.04). The future cost (C) for each treatment type was calculated by multiplying the length and width of each road by the unit costs of selected alternative.

5.6 Priority Programing of Rehabilitation and Maintenance Alternatives

The City of Markham's main objective for selecting road and treatment type is to maintain the OCI of 50 or higher for each road within the five year period. The ranking method and optimization method were used for this case study to prioritize the road sections need. The budget limit for each year for the next five years was considered to be \$5,100,000 / year.

5.6.1 Do Nothing Option

The do nothing option is carried out as part of this analysis to evaluate the condition of the road network over the next five years if there is no treatment. To determine the condition of each road over the next five years, the equation obtained from each Markov model was used. Figure 5.23 shows the condition of the road network over the next five years if there is no treatment applied.

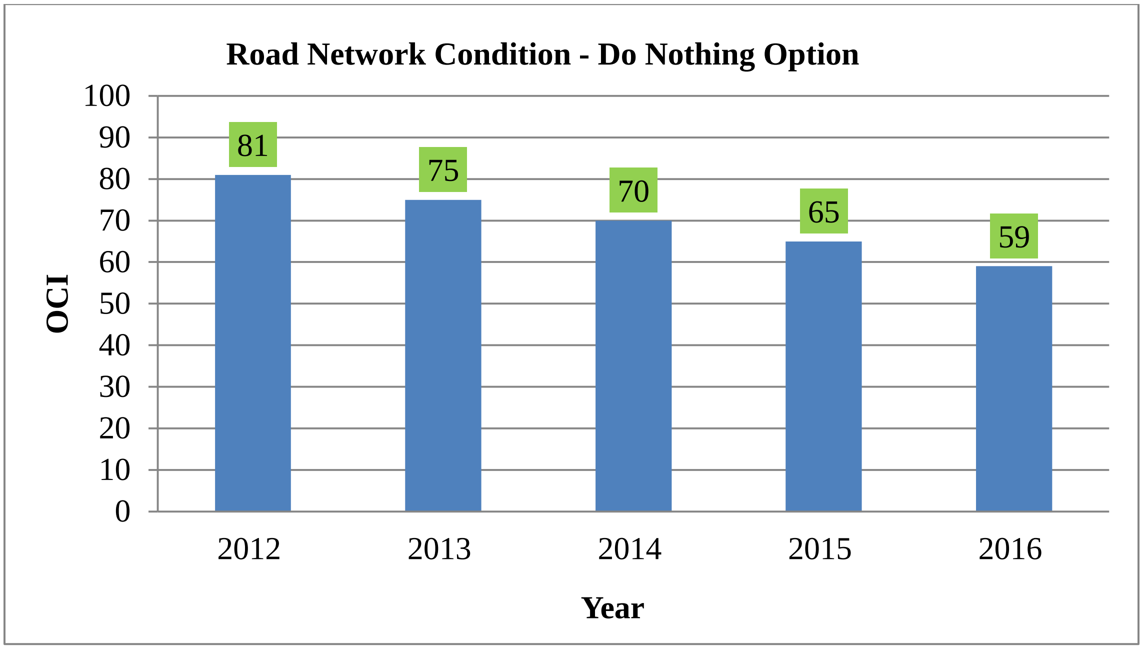
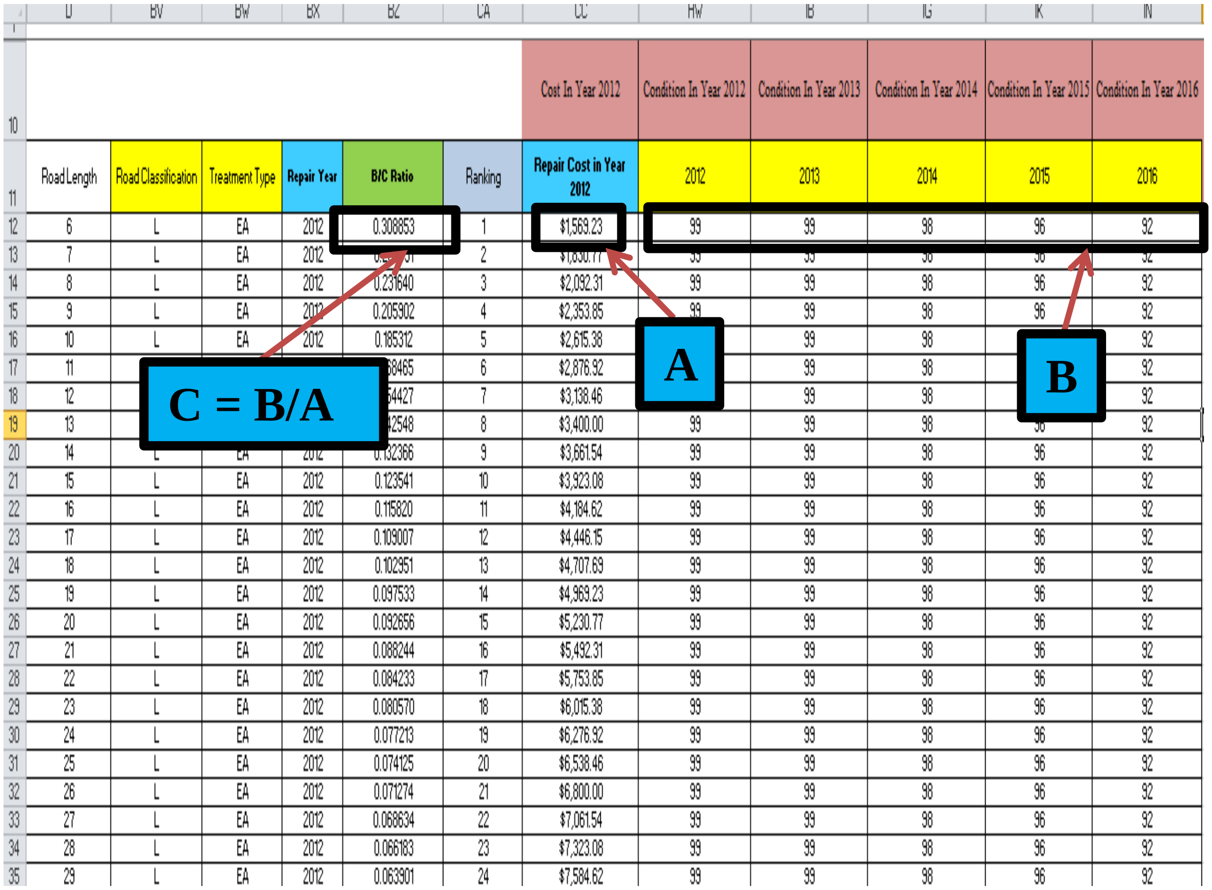


Figure 5.23: Do Nothing Option

As shown in Figure 5.23, the road network condition would degrade over the years if there is no treatment taking place. The average condition for the road network for the do nothing option over the next five years is calculated to be OCI=70.

5.6.2 Simple Ranking Method

The simple ranking method was the first method used to prioritize the road sections needs and used to select the appropriate rehabilitation and maintenance alternatives for this case study. The road network was ranked based on the Benefit Cost ratio (B/C) where benefit is the sum of the average condition of each road for the next five years after applying any treatment and the cost is the PW value of each treatment in the first year. The road network was then ranked based on the descending order of the B/C ratio. The expanded asphalt was selected for all the road classification as a treatment strategy except for the laneways that the chip seal was chosen. Figure 5.24 shows the excel spreadsheet that is used to determine the simple ranking.



	D	BV	BW	BX	BZ	CA	CC	HW	IB	IG	IK	IN
10							Cost In Year 2012	Condition In Year 2012	Condition In Year 2013	Condition In Year 2014	Condition In Year 2015	Condition In Year 2016
11	Road Length	Road Classification	Treatment Type	Repair Year	B/C Ratio	Ranking	Repair Cost in Year 2012	2012	2013	2014	2015	2016
12	6	L	EA	2012	0.308853	1	$1,569.23	99	99	98	96	92
13	7	L	EA	2012	[illegible]	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
14	8	L	EA	2012	0.231640	3	$2,092.31	99	99	98	96	92
15	9	L	EA	2012	0.205902	4	$2,353.85	99	99	98	96	92
16	10	L	EA	2012	0.185312	5	$2,615.38	[illegible]	99	98	[illegible]	92
17	11	[illegible]	[illegible]	[illegible]	[illegible]	6	$2,876.92	[illegible]	99	98	[illegible]	92
18	12	[illegible]	[illegible]	[illegible]	[illegible]	7	$3,138.46	[illegible]	99	98	[illegible]	92
19	13	[illegible]	[illegible]	[illegible]	[illegible]	8	$3,400.00	99	99	98	[illegible]	92
20	14	L	EA	2012	0.132366	9	$3,661.54	99	99	98	96	92
21	15	L	EA	2012	0.123541	10	$3,923.08	99	99	98	96	92
22	16	L	EA	2012	0.115820	11	$4,184.62	99	99	98	96	92
23	17	L	EA	2012	0.109007	12	$4,446.15	99	99	98	96	92
24	18	L	EA	2012	0.102951	13	$4,707.69	99	99	98	96	92
25	19	L	EA	2012	0.097533	14	$4,969.23	99	99	98	96	92
26	20	L	EA	2012	0.092656	15	$5,230.77	99	99	98	96	92
27	21	L	EA	2012	0.088244	16	$5,492.31	99	99	98	96	92
28	22	L	EA	2012	0.084233	17	$5,753.85	99	99	98	96	92
29	23	L	EA	2012	0.080570	18	$6,015.38	99	99	98	96	92
30	24	L	EA	2012	0.077213	19	$6,276.92	99	99	98	96	92
31	25	L	EA	2012	0.074125	20	$6,538.46	99	99	98	96	92
32	26	L	EA	2012	0.071274	21	$6,800.00	99	99	98	96	92
33	27	L	EA	2012	0.068634	22	$7,061.54	99	99	98	96	92
34	28	L	EA	2012	0.066183	23	$7,323.08	99	99	98	96	92
35	29	L	EA	2012	0.063901	24	$7,584.62	99	99	98	96	92

Figure 5.24: Snapshot of Excel for Simple Ranking Method

The budget of $5.1 million per year was used for performing the simple ranking method. As a result, for the first year based on the descending order of B/C ratio, the treatment is scheduled until the total budget of $5.1 million is reached. The procedure is repeated for each year. Table 5.15 shows the area of pavement treated in the network and the PW for the next five years using the simple ranking method.

Table 5.15: Road Network Results Utilizing Simple Ranking Method

Year	2012	2013	2014	2015	2016
Budget Limit	$5,100,000.0	$5,100,000.0	$5,100,000.0	$5,100,000.0	$5,100,000.0
Area of Network Treated (m^2)	223,188	157,545	170,673	168,541	183,802
Percentage of Road Network Treated	17%	12%	13%	13%	14%
Total PW / Year	$5,059,888.6	$5,077,115.4	$5,013,868.3	$5,027,725.7	$5,064,846.3
OCI	84	84	84	85	85

The average condition and the total cost of treatment for the road network using the simple ranking over the next five years are calculated to be 84 and $25,243,444.4, respectively.

5.6.3 Optimization Method

The Evolver software (Evolver 2012) is employed for optimization purposes. Table 5.16 shows the two objective functions and the constraints which were used for the optimization method.

Table 5.16: Objective Functions and Constraints for Optimization Method

Objective Functions	Constraints
Minimize the total cost within a five year period	Minimum acceptable level of an OCI=50 for each section of the road network within a five year period
Maximize the average road network condition within a five year period	Budget limit of $5.1 million per year within a five year period

5.6.3.1 Minimize Total Cost

The first objective function is to find a minimum and optimal cost to maintain the OCI value for each section of the road network about the minimum acceptable level (OCI = 50) within a period of five years. To build the Evolver model, first select the cell with the total cost for the next five years and in the “Optimization Goal” cell select “Minimize”. Second for the “Adjustable Cell Range” select the decision repair years column which is ranged from zero to five, where zero represents no treatment over the next five years, one represents treatment in year 2012 and so on. Finally, for the "Constraints" cell, select the cells containing the updated condition and select the range to be equal or greater than 50 and less than or equal to 100. Figure 5.25 shows the snapshot of the excel spreadsheet with the Evolver model for minimizing total cost.

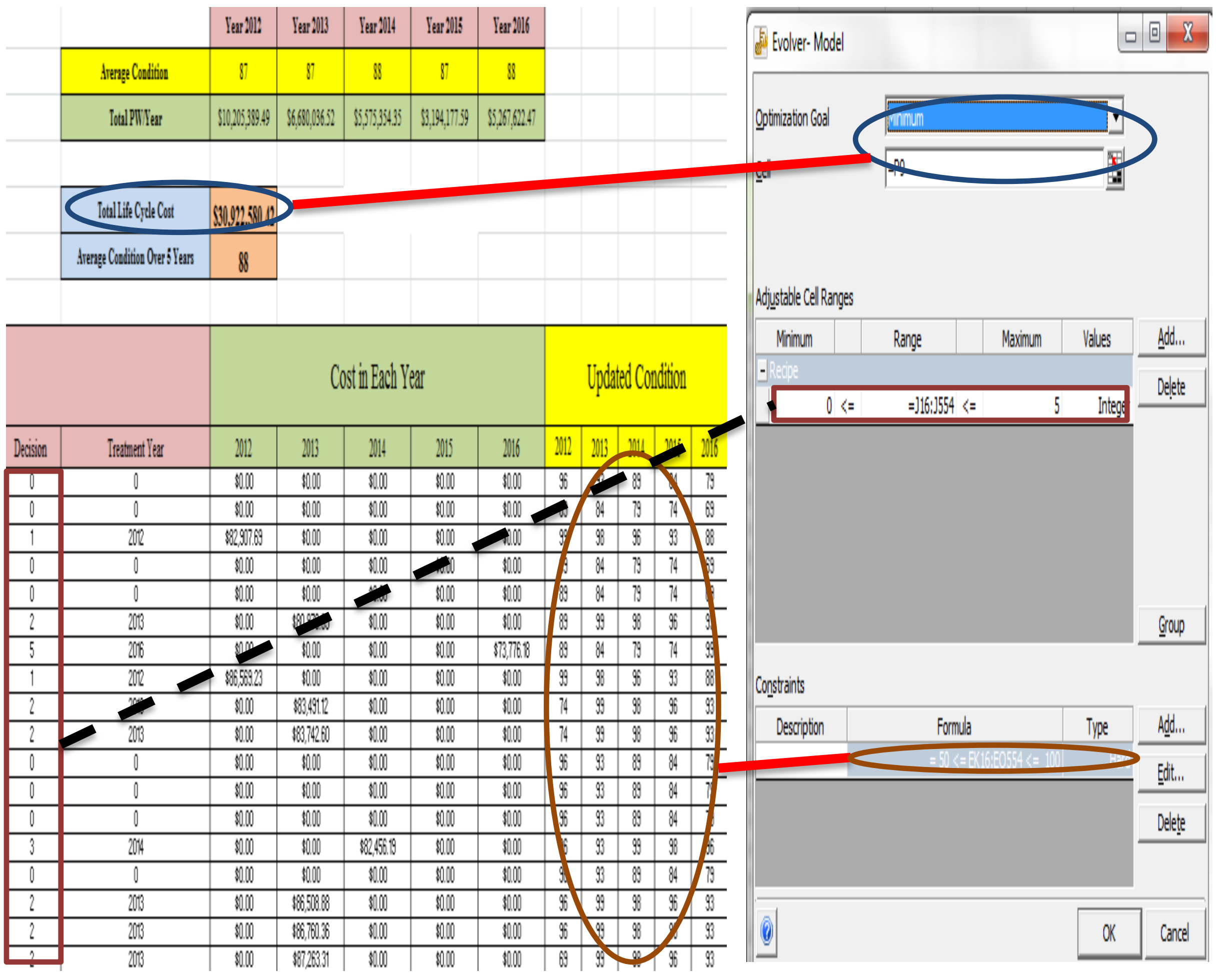


Figure 5.25: Minimize Total Cost

Table 5.17 shows the PW and the area of pavement treated in the network for the next five years using the Evolver by minimizing the total cost.

Table 5.17: Road Network Results Utilizing Evolver by Minimizing the Total Cost

Year	2012	2013	2014	2015	2016
Area of Network Treated (m^2)	324,680	229,104	196,856	109,904	209,232
Percentage of Road Network Treated	25%	17%	15%	8%	16%
Total PW / Year	$10,205,389.5	$6,680,036.5	$5,575,354.3	$3,194,177.6	$5,267,622.5
OCI	87	87	88	87	88

The average condition and the total cost of treatment for the road network using the Evolver by minimizing the total cost over the next five years are calculated to be 88 and $30,922,580.4, respectively.

5.6.3.2 Maximize Average Condition

The second objective function is to predict the performance of the network within a period of five years given a budget constraint of $5.1 million per year. To build the Evolver model, first select the cell with the average condition over the next 5 years and in the “Optimization Goal” cell select the “maximum” option. Second, for the “Adjustable Cell Range” select the decision repair years column. Finally, for the “Constraints” cell, select the cells with the total PW per year and select the range to be less than $5,100,000. Figure 5.26 shows the snapshot of the excel spreadsheet with the Evolver model for the maximizing the average condition.

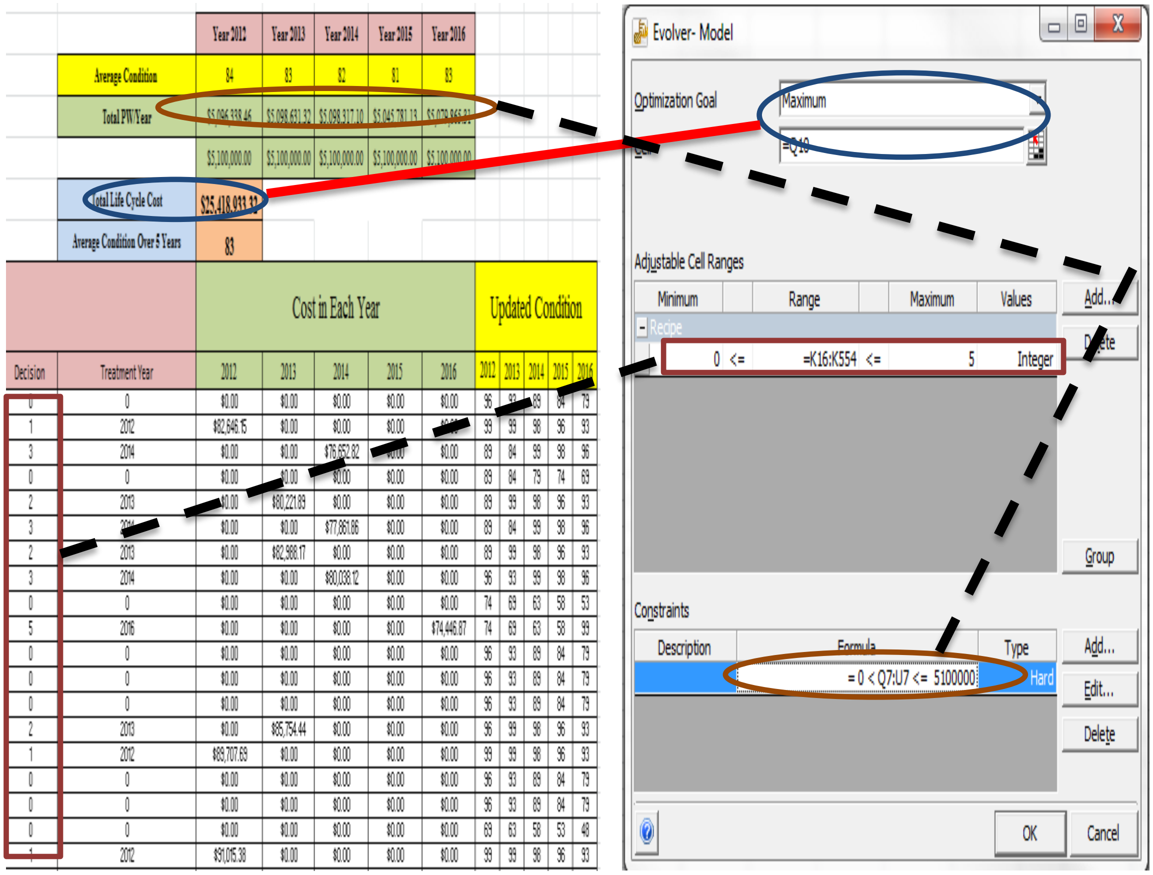


Figure 5.26: Maximize Average Condition

Table 5.18 shows the PW and the area of pavement treated in the network for the next five years using the Evolver by maximizing the average condition.

Table 5.18: Road Network Results Utilizing Evolver by Maximizing the Average Condition

Year	2012	2013	2014	2015	2016
Budget Limit	$5,100,000.0	$5,100,000.0	$5,100,000.0	$5,100,000.0	$5,100,000.0
Area of Network Treated (m^2)	155,888	166,296	185,368	177,720	219,128
Percentage of Road Network Treated	12%	13%	14%	14%	17%
Total PW / Year	$5,059,888.6	$5,077,115.4	$5,013,868.3	$5,027,725.7	$5,064,846.3
OCI	84	83	82	81	83

The average condition and the total cost of treatment for the road network using the Evolver by maximizing the condition over the next five years are calculated to be 83 and $25,418,933.3, respectively.

5.6.3.3 Results Comparison from Priority program

Tables 5.19 and 5.20 show the cost and condition obtained using the simple ranking method and optimization method for the road network within a five year period, respectively.

Table 5.19: Road Network Cost Comparison for all Options

Scenario	Year 2012	Year 2013	Year 2014	Year 2015	Year 2016	Total Cost
Maximize Average Condition	$5,096,338.5	$5,098,631.3	$5,098,317.1	$5,045,781.1	$5,079,865.3	**$25,418,933.3**
Minimize Total Cost	$10,205,389.5	$6,680,036.5	$5,575,354.3	$3,194,177.6	$5,267,622.5	**$30,922,580.4**
Simple Ranking	$5,059,888.6	$5,077,115.4	$5,013,868.3	$5,027,725.7	$5,064,846.3	**$25,243,444.4**

Table 5.20: Road Network Condition Comparison for all Options

Scenario	Year 2012	Year 2013	Year 2014	Year 2015	Year 2016	Average Condition
Maximize Average Condition	84	83	82	81	83	**83**
Minimize Total Cost	87	87	88	87	88	**88**
Simple Ranking	84	84	84	85	85	**84**

Based on the results from Tables 5.19 and 5.20, even though the minimum cost scenario provided the best average road network condition within a five year period, it does not satisfy the budget limit and it is over by 30,922,580.4 – (5*5,100,000) = $5,422,580.4. Thus, the minimize total cost scenario should be eliminated for further analysis. Figure 5.27 shows the percentage of sections of the road network that are below the minimum acceptable level (OCI = 50) within a period of five years. Based on the results from Figure 5.27, it can be concluded that maximizing the average condition scenario provides a lower percentage of sections with the OCI below 50.

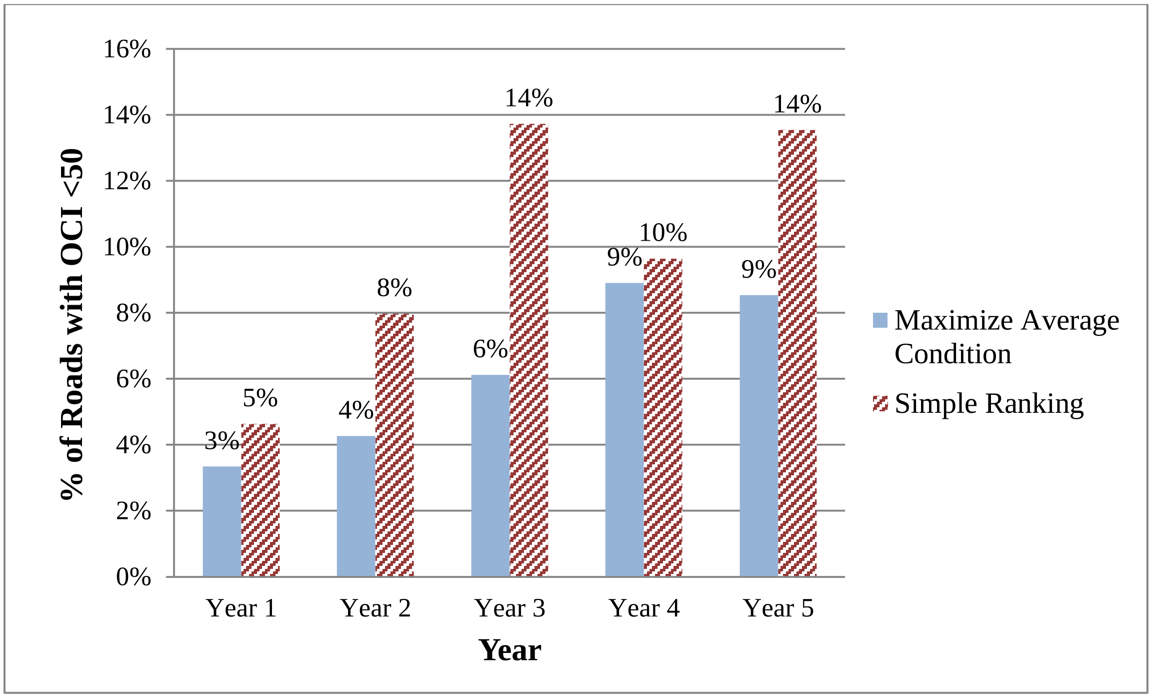


Figure 5.27: Percentage of Roads with OCI < 50 Using Simple Ranking and Evolver

Therefore, it can be concluded that the optimization method provides the ability to produce better results than the simple ranking method.

5.7 Summary

The City of Markham was selected as a case study to examine if this research methodology could be applied to a city. The overall road network condition was calculated based on the three methods, engineering judgement and experience, a combination of AHP method and engineering judgement and experience, and the existing well developed pavement indices. After calculating the OCI, roads were divided into homogenous sections based on the road classification, treatment type, and AADT for analysis. After generating figures for the OCI against the age of the pavement for the road classification corresponding to each treatment strategy, it was found that there is a large range of OCI values corresponding to pavement age. As a result, boxplots are used to show the variation in OCI. Markov modeling was used to develop a prediction model for the pavement performance deterioration. To examine the variation in service life for the City of Markham method, the MTO method and the AHP method, the variance and standard deviation of service life were calculated for all the road classification corresponding to each treatment strategy. The PW value was used for the economic evaluation and the discount rate was considered to be 4%. The simple ranking and Evolver software were used for the prioritization purpose. After comparing the results from the simple ranking and the optimization method, it can be concluded that the optimization method provides the ability to produce better results than the simple ranking method. The overall results from the case study indicated that the steps and requirements which are explained in the research methodology are appropriate for implementation in a local agency.

Chapter 6 Conclusions and Future Work

6.1 Conclusions

The following conclusions are drawn based on the survey results and the case study.

6.1.1 Conclusions from 2011 Survey

- For flexible pavements, the local agencies should collect roughness (IRI), rutting, alligator cracking, ravelling, transverse cracking, pavement edge cracking, map/block cracking, distortion, and patching as the performance data to evaluate pavement condition.
- For rigid pavements, the local agencies should collect spalling, faulting, joint sealant lost, longitudinal mender cracking, edge cracking, transverse cracking, scaling, roughness (IRI), and potholing as the performance data to evaluate pavement condition.
- Local agencies should also consider three severity levels and the percentage of the affected area over the total surveyed area for the density levels.
- The MTO protocols and the ASTM protocols are the most used protocols by the Canadian cities and municipalities as guidelines to collect pavement distress.

6.1.2 Conclusions from Case Study

- A Geographic Information System (GIS) is a good referencing method to represent pavement sections as it can generate maps for the road network in terms of pavement condition and road classification.
- The City of Markham needs to consider collecting more performance data based on the survey results to have a more accurate pavement condition.
- The Equivalent Single Axle Loads (ESALs) should be used to determine the traffic load. Therefore, the agencies should consider collecting the Average Annual Daily Traffic (AADT) and the truck percentage from the AADT.
- In the case when there is a large range in pavement condition corresponding to pavement age, the boxplots can be an effective tool for describing variation.

- A Markov model was developed to predict the pavement performance for the three methods. The results show that predicted service life based on the AHP method and the Markham method for the collector roads, minor arterials roads, major arterial roads, and laneways are relatively close. In addition, the AHP method provides a higher service life for the local roads compare to the other methods.
- The simple ranking and Evolver software were used for the prioritization purpose. After comparing the results from the simple ranking and the optimization, it can be concluded that the optimization method provides the ability to produce better results than the simple ranking method.

The overall results from the case study indicated that the steps and requirements, which are explained in the research methodology, are appropriate for implementation in a local agency.

6.2 Future Work

- Further studies are required to be conducted to explain how local agencies should consider, identify, and incorporate the distresses associated particularly to the utility cuts such as manholes, catchbasins, and valve boxes, curb and gutter, and rail road crossing on the pavement while collecting performance data.
- Further studies need to be done to compare different optimization software in terms of advantages and disadvantages, pricing, and the inputs required from a local agency to be able to adapt the software.

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Appendix A: Ministry of Transportation of Ontario Pavement Condition Assessment for both Flexible Pavement and Rigid Pavement

Flexible Pavement (MTO 1989)

Surface Defects

Loss of Coarse Aggregates. Ravelling (Segregation):

Pavement surface looks as though it is breaking up into small pock-marks as coarse aggregate particles are lost from the surface; or progressive loss of pavement materials (coarse or fine aggregates, or both) from surface downward results in a pock-marked appearance; or pavement surface has the appearance of an open matrix will all coarse aggregates only showing in spots.

Severity

Class	Guidelines
Very Slight	Barely noticeable.
Slight	Noticeable loss of pavement materials.
Moderate	Having pock-marked appearance, fairly well spaced between pock-marks. Shallow disintegration of pavement surface; an open-textured look.
Severe	Having pock-marked appearance, pock-marks are closely spaced. Disintegration with small potholes or veined with slight cracks.
Very Severe	Surface has a ravelled appearance and is disintegrated into large potholes or veined with moderate cracks.

Density

Class	Guidelines
Few	Less than 10% of pavement surface affected. Spotted over localized areas only.
Intermittent	10 to 20% of pavement surface affected. Spotted over localized areas only.
Frequent	20 to 50% of pavement surface affected. May spot evenly over entire length of pavement section or in localized areas only.
Extensive	50 to 80% of pavement surface affected. Spotted evenly over entire length of pavement section.
Throughout	80 to 100% of pavement surface affected. Spotted evenly over entire length of pavement section.

Flushing:

The presence of free asphalt binder on the pavement surface, resulting from upward migration of the binder. Most likely to occur in the wheel tracks during hot weather.

Severity

Class	Guidelines
Very Slight	Very faint coloring (veining).
Slight	Coloring visible (interconnected veining).
Moderate	Distinctive appearance (with excessive asphalt materials already free).
Severe	Free asphaltic materials giving the surface area a wet look.
Very Severe	Free asphaltic materials giving the affected pavement surface area a wet look, and wheel noise comparable to that when driving over a water-wet surface.

Density

Class	Guidelines
Few	Less than 10% of pavement surface affected. Spotted over localized areas only.
Intermittent	10 to 20% of pavement surface affected. Spotted over localized areas only.
Frequent	20 to 50% of pavement surface affected. May spot evenly over entire length of pavement section or in localized areas only.
Extensive	50 to 80% of pavement surface affected. Spotted evenly over entire length of pavement section.
Throughout	80 to 100% of pavement surface affected. Spotted evenly over entire length of pavement section.

Distortion or Permanent Deformation

Ripping and Shoving:

Regular transverse undulations in the surface of the pavement, consisting closely- spaced, alternate valleys and crests (washboard effect); or singular and multiple waves or humps located transversely or longitudinally on the pavement surface.

Severity

Class	Guidelines
Very Slight	Barely noticeable washboard effect.
Slight	Noticeable washboard effect.
Moderate	Bumpy with washboard appearance or ridges and valleys.
Severe	Very bumpy with pronounced appearance washboarding or large humps on pavement surface.
Very Severe	Washboarding or large humps which causes vehicles to drift sideways and may cause loss of control of vehicles.

Density

Class	Guidelines
Few	Less than 10% of pavement surface affected. Spotted over localized areas only.
Intermittent	10 to 20% of pavement surface affected. Spotted over localized areas only.
Frequent	20 to 50% of pavement surface affected. May spot evenly over entire length of pavement section or in localized areas only.
Extensive	50 to 80% of pavement surface affected. Spotted evenly over entire length of pavement section.
Throughout	80 to 100% of pavement surface affected. Spotted evenly over entire length of pavement section.

Wheel Track Rutting:

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.

Severity

Class	**Guidelines**
Very Slight	Barely noticeable, less than 6 mm (1.3 m baseline).
Slight	6 to 13 mm with or without single longitudinal cracks.
Moderate	14 to 19 mm with or without single or multiple longitudinal cracks. Double rutting begins to develop.
Severe	20 to 50 mm with or without longitudinal cracks, or double rutting developed.
Very Severe	Greater than 50 mm single or double rutting with or without multiple longitudinal cracks or alligator cracks.

Density

Class	**Guidelines**
Few	Less than 10% of wheel track affected.
Intermittent	10 to 20% of wheel track affected.
Frequent	20 to 50% of wheel track affected.
Extensive	50 to 80% of wheel track affected.
Throughout	80 to 100% of wheel track affected.

Distortion:

Any deviation (other than described for ripping, shoving and rutting) of the pavement surface from its original shape. Generally, distortions result from settlement, slope failure, volume changes due to moisture changes or frost heaving, and from residual effects of frost heaving accumulating after each winter.

Severity

Class	**Guidelines**
Very Slight	Barely noticeable swaying of vehicle while in motion.
Slight	Barely noticeable pitch and roll, and jarring bump or drop of vehicle while in motion.
Moderate	Noticeable pitch and roll, and harsh bump or jarring drop of vehicle while in motion.
Severe	Continuous pitch and roll, and hard jarring bump or drop of vehicle while in motion; driver always has to anticipate distortion ahead
Very Severe	Continuous distortion, making driver feel it is necessary to reduce speed from the posted speed.

Density

Class	Guidelines
Few	Less than 10% of pavement surface affected. Spotted over localized areas only.
Intermittent	10 to 20% of pavement surface affected. Spotted over localized areas only.
Frequent	20 to 50% of pavement surface affected. May spot evenly over entire length of pavement section or in localized areas only.
Extensive	50 to 80% of pavement surface affected. Spotted evenly over entire length of pavement section.
Throughout	80 to 100% of pavement surface affected. Spotted evenly over entire length of pavement section.

Cracking

Longitudinal Wheel-Track Cracking:

Cracks which follow a course approximately parallel to the centre line of the pavement and are situated at or near the centre of the wheel tracks.

Severity

Class	Guidelines
Very Slight	Single crack less than 3 mm.
Slight	Single crack from 3mm to 12 mm.
Moderate	Single or multiple cracks. Single cracks from 13 to 19 mm. multiple cracks even if less than 13 mm.
Severe	Single or multiple cracks. Single crack 20 to 25 mm, with initial sign of spallig. Multiple cracks even if less than 20 mm but greater than 13 mm, with initial sign of spalling.
Very Severe	Single or multiple cracks. Single crack greater than 25 mm, with or without initial spallig. Multiple cracks even if less than 25 mm but greater than 20 mm, with or without spalling.

Density

Class	Guidelines
Few	Less than 10% of pavement surface affected. Spotted over localized areas only.
Intermittent	10 to 20% of pavement surface affected. Spotted over localized areas only.
Frequent	20 to 50% of pavement surface affected. May spot evenly over entire length of pavement section or in localized areas only.
Extensive	50 to 80% of pavement surface affected. Spotted evenly over entire length of pavement section.
Throughout	80 to 100% of pavement surface affected. Spotted evenly over entire length of pavement section.

Longitudinal Meander and Mid-Lane Crack:

Cracks, usually quit long, which wanders from edge to edge of the pavement, or crack which is usually straight and parallel to the centre line, at or near the middle of the lane. These types of cracks are usually single cracks, but occasionally secondary cracks do develop parallel to them.

Severity

Class	Guidelines
Very Slight	Single crack less than 3 mm.
Slight	Single crack from 3mm to 12 mm.
Moderate	Single or multiple cracks. Single cracks from 13 to 19 mm. multiple cracks even if less than 13 mm.
Severe	Single or multiple cracks. Single crack 20 to 25 mm, with initial sign of spallig. Multiple cracks even if less than 20 mm but greater than 13 mm, with initial sign of spalling.
Very Severe	Single or multiple cracks. Single crack greater than 25 mm, with or without spallig. Multiple cracks even if less than 25 mm but greater than 20 mm, with or without spalling.

Density

Class	Guidelines
Few	Less than 10% of pavement surface affected. Spotted over localized areas only.
Intermittent	10 to 20% of pavement surface affected. Spotted over localized areas only.
Frequent	20 to 50% of pavement surface affected. May spot evenly over entire length of pavement section or in localized areas only.
Extensive	50 to 80% of pavement surface affected. Spotted evenly over entire length of pavement section.
Throughout	80 to 100% of pavement surface affected. Spotted evenly over entire length of pavement section.

Centre Line Crack:

Cracks which run along or near the road centre line.

Severity

Class	Guidelines
Very Slight	Single crack less than 3 mm.
Slight	Single crack from 3mm to 12 mm.
Moderate	Single or multiple cracks. Single cracks from 13 to 19 mm. multiple cracks even if less than 13 mm.
Severe	Single or multiple cracks. Single crack 20 to 25 mm, with initial sign of spallig. Multiple cracks even if less than 20 mm but greater than 13 mm, with initial sign of spalling.
Very Severe	Single or multiple cracks. Single crack greater than 25 mm, with or without spallig. Multiple cracks even if less than 25 mm but greater than 20 mm, with or without spalling.

Density

Class	Guidelines
Few	Less than 10% of pavement surface affected. Spotted over localized areas only.
Intermittent	10 to 20% of pavement surface affected. Spotted over localized areas only.
Frequent	20 to 50% of pavement surface affected. May spot evenly over entire length of pavement section or in localized areas only.
Extensive	50 to 80% of pavement surface affected. Spotted evenly over entire length of pavement section.
Throughout	80 to 100% of pavement surface affected. Spotted evenly over entire length of pavement section.

Pavement Edge Crack:

Cracks which are parallel to and within 30 cm of the pavement edge, and are either a continuous "straight" crack or consists of crescent-shaped cracks in a wave formation. On some thin asphalt surfaces, pavement edge cracking progressively encroaches onto the outer-wheel tracks through the middle of the lane, and may even progress right across to the centre line.

Severity

Class	Guidelines
Very Slight	Single longitudinal crack or single wave-formation crack less than 3 mm wide and no more than 150 mm from pavement edge.
Slight	Single crack or two parallel cracks 3 mm to 12 mm wide and less than 300 mm from pavement edge.
Moderate	Extending over 300 mm but less than 600 mm from pavement edge. Multiple cracks begin to interweave with connecting cracks.
Severe	Extending over 600 mm but less than 1500 mm from pavement edge. Outmost area near edge cracks begins to develop connecting cracks to give appearance of alligatoring.
Very Severe	Progressive multiple cracks extended over 1500 mm from pavement edge. Outermost area near edge is alligatored.

Density

Class	Guidelines
Few	Less than 10% of pavement surface affected. Spotted over localized areas only.
Intermittent	10 to 20% of pavement surface affected. Spotted over localized areas only.
Frequent	20 to 50% of pavement surface affected. May spot evenly over entire length of pavement section or in localized areas only.
Extensive	50 to 80% of pavement surface affected. Spotted evenly over entire length of pavement section.
Throughout	80 to 100% of pavement surface affected. Spotted evenly over entire length of pavement section.

Transverse Crack:

Cracks which follow a course approximately at right angles to the pavement centre line. Full transverse cracks tend to be regularly spaced along the length of the road, while half transverse and part transverse occur at shorter, intermediate distances.

Severity

Class	Guidelines
Very Slight	Single crack less than 3 mm.
Slight	Single crack from 3mm to 12 mm.
Moderate	Single or multiple cracks. Single cracks from 13 to 19 mm. multiple cracks even if less than 13 mm.
Severe	Single or multiple cracks. Single crack 20 to 25 mm, with initial sign of spallig. Multiple cracks even if less than 20 mm but greater than 13 mm. Cracks have developed cupping or lipping distortion.
Very Severe	Greater than 25 mm single crack, or multiple cracks even if crack opening is less than 25 mm but greater than 20 mm. cracks are distorted with cupping and lipping, and spalling of the cracked edge.

Density

Class	Guidelines
Few	Less than 10% of pavement surface affected. Spotted over localized areas only.
Intermittent	10 to 20% of pavement surface affected. Spotted over localized areas only.
Frequent	20 to 50% of pavement surface affected. May spot evenly over entire length of pavement section or in localized areas only.
Extensive	50 to 80% of pavement surface affected. Spotted evenly over entire length of pavement section.
Throughout	80 to 100% of pavement surface affected. Spotted evenly over entire length of pavement section.

Map Crack:

Interconnected cracks forming a series of large polygons which resemble a map. The cracking appears to combine transverse and longitudinal cracks. This form of distress is also called random cracking.

Severity

Class	Guidelines
Very Slight	Single crack less than 3 mm and of short length, developed randomly between transverse cracks.
Slight	Single crack from 3mm to 12 mm, well spaced but interconnected to form map-like appearance between transverse cracks.
Moderate	Interconnected cracks begin to develop multiple cracks. First sign of spalling. Single crack width 13 mm to 19 mm.
Severe	Multiple interconnected cracks, some with spalling. Single crack width 20 mm to 25 mm.
Very Severe	Multiple interconnected cracks, many with spalling or even potholes. Single cracks width more than 25 mm.

Density

Class	Guidelines
Few	Less than 10% of pavement surface affected. Spotted over localized areas only.
Intermittent	10 to 20% of pavement surface affected. Spotted over localized areas only.
Frequent	20 to 50% of pavement surface affected. May spot evenly over entire length of pavement section or in localized areas only.
Extensive	50 to 80% of pavement surface affected. Spotted evenly over entire length of pavement section.
Throughout	80 to 100% of pavement surface affected. Spotted evenly over entire length of pavement section.

Alligator Crack:

Cracks which form a network of polygon blocks resembling the skin of an alligator. The block size, which can range from a few millimetres to about a metre, is indicative of the level (depth) at which failure is taking place.

Severity

Class	Guidelines
Very Slight	Multiple cracks begin to develop short interconnecting cracks. Distortion less than 13 mm.
Slight	Alligator pattern established with corners of polygon blocks fracturing. Distortion less than 13mm.
Moderate	Alligator pattern established with spalling of polygon blocks. Distortion 13 mm to 25 mm.
Severe	Polygon blocks begin to lift. Small potholes. Distortion 26 mm to 50 mm.
Very Severe	Polygon blocks lifting, with different sizes of potholes. Distortion greater than 50 mm.

Density

Class	Guidelines
Few	Less than 10% of pavement surface affected. Spotted over localized areas only.
Intermittent	10 to 20% of pavement surface affected. Spotted over localized areas only.
Frequent	20 to 50% of pavement surface affected. May spot evenly over entire length of pavement section or in localized areas only.
Extensive	50 to 80% of pavement surface affected. Spotted evenly over entire length of pavement section.
Throughout	80 to 100% of pavement surface affected. Spotted evenly over entire length of pavement section.

Rigid Pavement (MTO 1995)

Surface Defects

Ravelling and Coarse Aggregates Loss:

Coarse aggregate particles (less than 6 mm) have been removed from pavement surface, or fine aggregate has been lost from the surface matrix.

Severity

Class	Guidelines
Very Slight	Barely noticeable.
Slight	Noticeable loss of pavement materials.
Moderate	Pavement has a pockmarked appearance, with pockmarks closely spaced.. Shallow disintegration of pavement surface; an open-textured look.
Severe	Having pock-marked appearance, pock-marks are closely spaced. Disintegration with small and shallow potholes.
Very Severe	Surface has a ravelled and disintegrated appearance with large, shallow potholes

Density

Class	Guidelines
Few	Less than 10% of pavement surface affected. Spotted over localized areas only.
Intermittent	10 to 20% of pavement surface affected. Spotted over localized areas only.
Frequent	20 to 50% of pavement surface affected. May spot evenly over entire length of pavement section or in localized areas only.
Extensive	50 to 80% of pavement surface affected. Spotted evenly over entire length of pavement section.
Throughout	80 to 100% of pavement surface affected. Spotted evenly over entire length of pavement section.

Note: Density is same for all the disteresses.

Polishing:

Polished appearance of pavement surface due to glazing of coarse aggregate particles in mix.

Severity

Class	Guidelines
Very Slight	Barely noticeable.
Slight	Noticeable dull finish.
Moderate	Distinctive dull finish.
Severe	Glossy mirror finish .
Very Severe	Surface has a highly polished appearance.

Scaling:

Peeling away of the concrete pavement surface. Scaling may occur anywhere over the pavement surface.

Severity

Class	Guidelines
Very Slight	Barely noticeable.
Slight	Noticeable.
Moderate	An open-texture look, as with ravelling, but very shallow.
Severe	Disintegration in closely spaced, shallow patches.
Very Severe	Disintegration in shallow large patches.

Potholing:

Bowl-shaped depressions or holes in the pavement surface, unrelated to cracking or other surface defects.

Severity

Class	**Guidelines**
Very Slight	Barely noticeable. Pothole resembles a pop-out of coarse aggregate.
Slight	Disintegration of surrounding materials.
Moderate	Potholes much wider (<75 mm) than a pop-out of coarse aggregate and deeper (<75 mm)
Severe	Potholes 75-100 mm wide and 75-100 mm deep.
Very Severe	Potholes over 150 mm wide and over 150 mm deep. Interferes with rideability

Joint and Crack Spalling:

The breaking or chipping of the pavement at joints and cracks, usually resulting in fragments with feathered edge or potholes.

Severity

Class	**Guidelines**
Very Slight	Small crack(s) with very small surface.
Slight	Small crack(s) within 75 mm of the joint or crack, with a few small pieces missing or loosened from the fractured area.
Moderate	Spalling extends more than 75 mm of the joint or crack, with many small pieces missing or loosened from the fractured area.
Severe	Spalling extends more than 75 mm of the joint or crack, with large pieces missing or loosened from the fractured area. Temporary patching may have been placed.
Very Severe	Large potholes are at places along the joint or crack, perhaps causing tire damage.

Surface deformations

Faulting (Stepping):

Differential vertical displacement of abutting slabs at joints or cracks, creating a ‘step’ deformation in the pavement surface. In the case of faulting of transverse joints or cracks, usually the ‘upstream’ or ‘approach’ slab is higher than the ‘downstream’ or ‘leave’ slab.

Severity

Class	Guidelines
Very Slight	Barely noticeable (<3 mm)
Slight	3-6 mm
Moderate	7-12 mm
Severe	13-19 mm
Very Severe	>19 mm

Distortion (Sagging or Slab Warping)

A longitudinal deviation of the pavement surface from its original profile. The change in elevation is generally in the order of more than 2.5 cm, with a wave length of more than 3 m.

Severity

Class	Guidelines
Very Slight	Barely noticeable.
Slight	Barely noticeable pitch and roll, and a jarring bump or drop of vehicle.
Moderate	Noticeable pitch and roll, and a harsh bump or jarring drop of vehicle.
Severe	A continuous pitch and roll, and a harsh jarring bump or drop of vehicle. The driver always must anticipate distortion ahead.
Very Severe	Continuous distortion, making the driver feel it necessary to reduce speed from the posted speed limit.

Joint Deficiencies

Joint Sealant Loss:

Transverse or longitudinal joint sealant is squeezed out or pulled out of the joint.

Severity

Class	Guidelines
Very Slight	Barely popped out or breaking.
Slight	Sealant broken and beginning to pull out (up to 30 cm)
Moderate	Sealant broken and pulled out by up to 50% of its length.
Severe	Sealant broken and pulled out by up to 80% of its length.
Very Severe	Sealant is completely broken and pulled out by more than 80% of its length. It is ineffective as a sealant.

Transverse Joint Creep:

One lane's transverse joint moves ahead or behind the one in the adjacent lane.

Severity

Class	Guidelines
Very Slight	Joints barely out of line.
Slight	Joints noticeably out of line($\leq$ 19 mm).
Moderate	Joints 19-25 mm out of line.
Severe	Joints 26-50 mm out of line.
Very Severe	Joints > 50 mm out of line.

Longitudinal Joint Separation:

Separation of two adjacent lanes along the longitudinal joint.

Severity

Class	Guidelines
Moderate	Up to 25 mm.
Severe	Greater than 25 mm and up to 50 mm.
Very Severe	Greater than 50 mm.

Note: severity is recognized only from the moderate level upward.

Joint Failures (Blow-ups):

Excessive breakdowns or localized upward movement (blow-up) of slab adjacent to joint. Joint failures are most likely to occur during the hot summer.

Severity

Class	**Guidelines**
Severe	Pavement fractures into blocks, with multiple cracks and missing pieces along both sides of the joint. Distortion is noticeable.
Very Severe	Pavement fractures into large blocks with multiple cracks and missing pieces along both sides of the joint, extending a considerable distance (2-3m) from the joint. Distortion is very noticeable.

Cracking

Longitudinal and Meandering:

Cracks which follow a course approximately parallel to the centreline of the pavement and are generally quite straight; or cracks which wander serpent-like across the traffic lane, usually starting at one transverse joint and ending at another.

Severity

Class	**Guidelines**
Very Slight	<3 mm wide.
Slight	3-12 mm wide.
Moderate	13-19 mm wide (with or without spalling and faulting)
Severe	20-25 mm wide (with spalling and faulting)
Very Severe	>25 mm wide (with spalling and faulting)

Diagonal, Corner, and Edge Crescent:

Diagonal and corner cracks form a triangle between a longitudinal edge or joint and a transverse joint or crack. In the case of corner cracking, the size of the triangle is generally about 30 – 60 cm on a side. In the case of diagonal cracking from lane to lane following a course diagonal to the centreline, the triangle is much larger.

Severity

Class	Guidelines
Very Slight	<3 mm wide.
Slight	3-12 mm wide.
Moderate	13-19 mm wide (with or without spalling and faulting)
Severe	20-25 mm wide (with spalling and faulting)
Very Severe	>25 mm wide (with spalling and faulting)

'D' Cracking

Closely spaced, fine, crescent-shaped in the concrete surface, usually parallel to a joint or major crack and usually curving across slab corners. This type of cracking is very similar in appearance to corner cracking.

Severity

Class	Guidelines
Very Slight	<3 mm wide.
Slight	3-12 mm wide.
Moderate	13-19 mm wide (with or without spalling and faulting)
Severe	20-25 mm wide (with spalling and faulting)
Very Severe	>25 mm wide (with spalling and faulting)

Transverse Cracking

Generally a single crack which follows a course approximately at right angles to the pavement centreline. It is generally a single crack.

Severity

Class	**Guidelines**
Very Slight	<3 mm wide.
Slight	3-12 mm wide.
Moderate	13-19 mm wide (with or without spalling and faulting)
Severe	20-25 mm wide (with spalling and faulting)
Very Severe	>25 mm wide (with spalling and faulting)

Appendix B: Current Condition of Each Road Classification Corresponding to Each Treatment Strategy

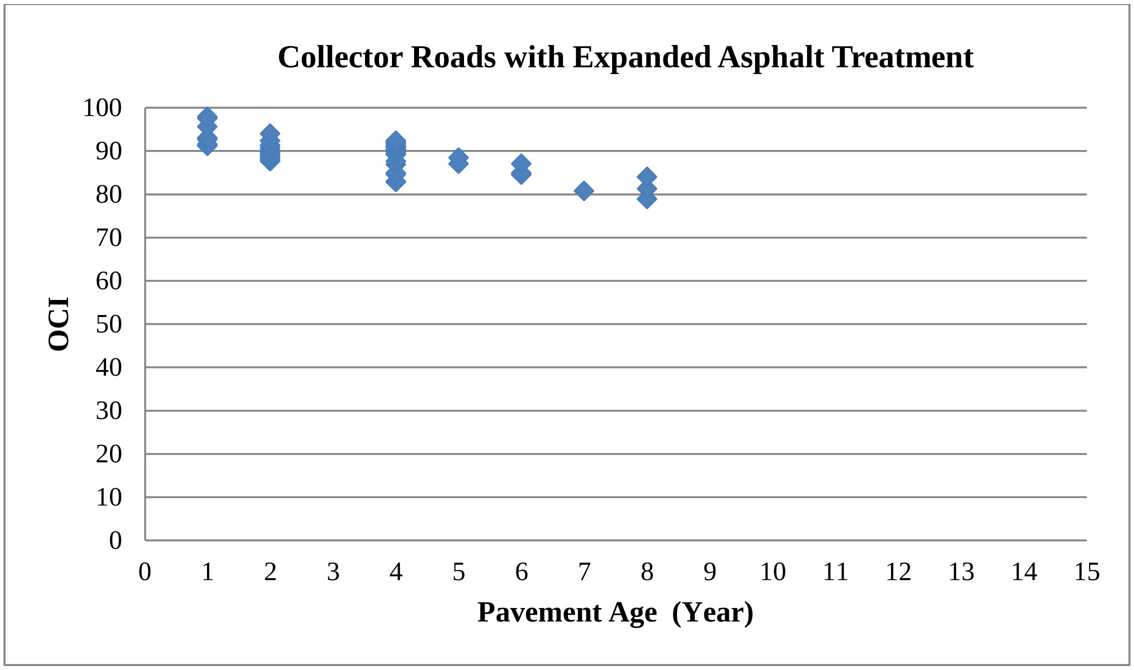

Figure B1: Collector Roads with Expanded Asphalt Treatment

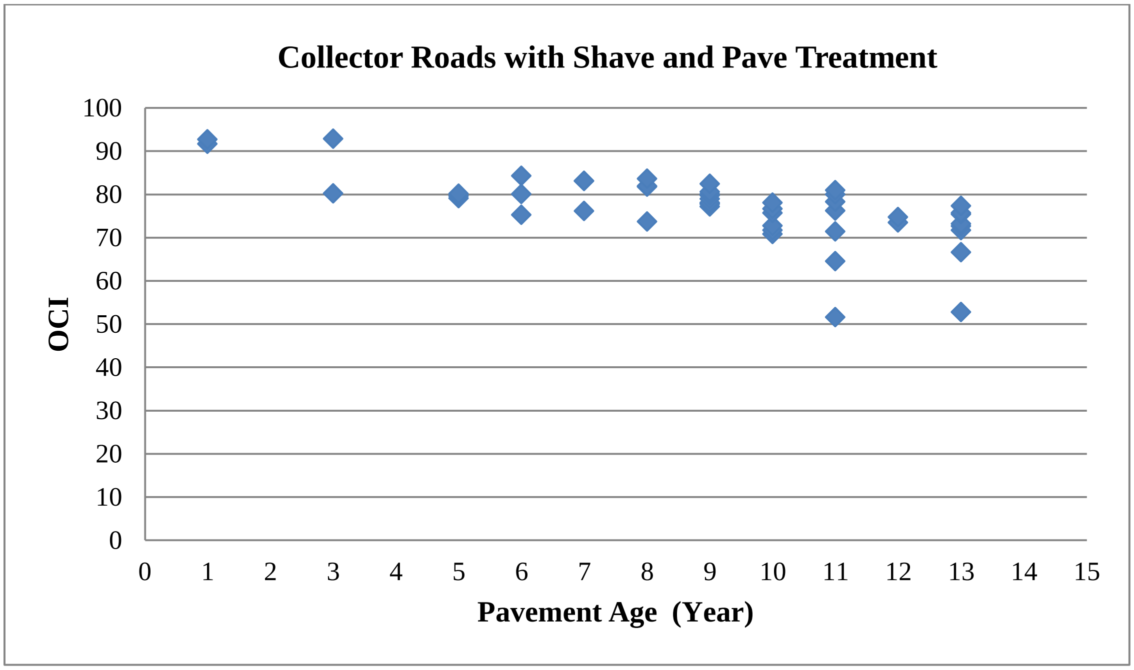

Figure B2: Collector Roads with Shave and Pave Treatment

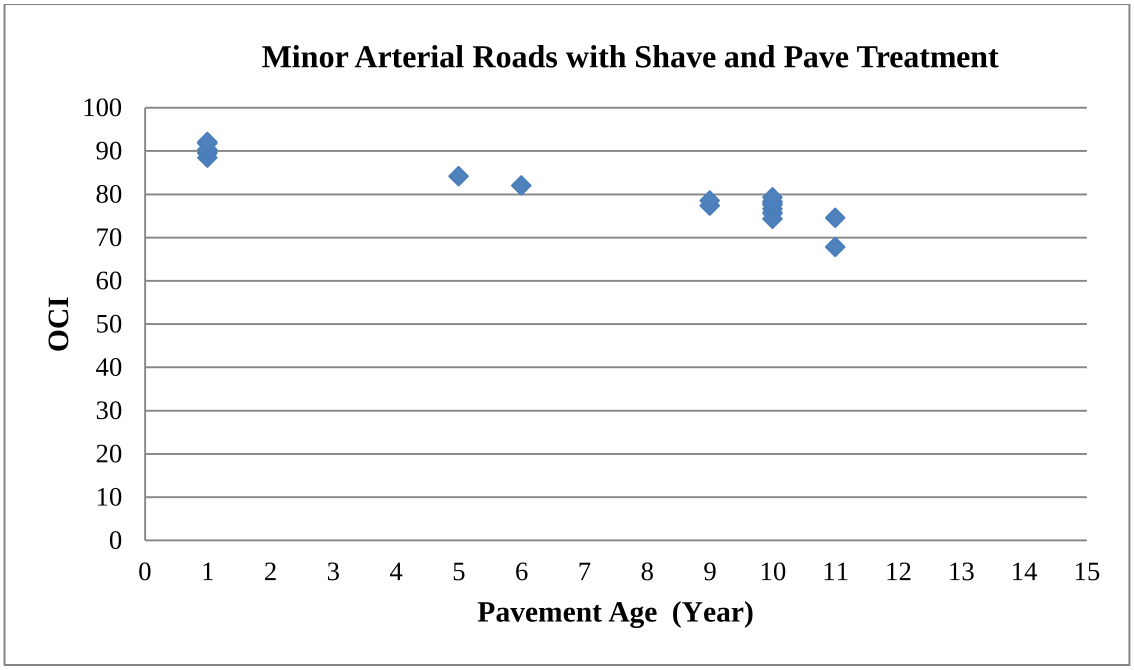

Figure B3: Minor Arterial Roads with Shave and Pave Treatment

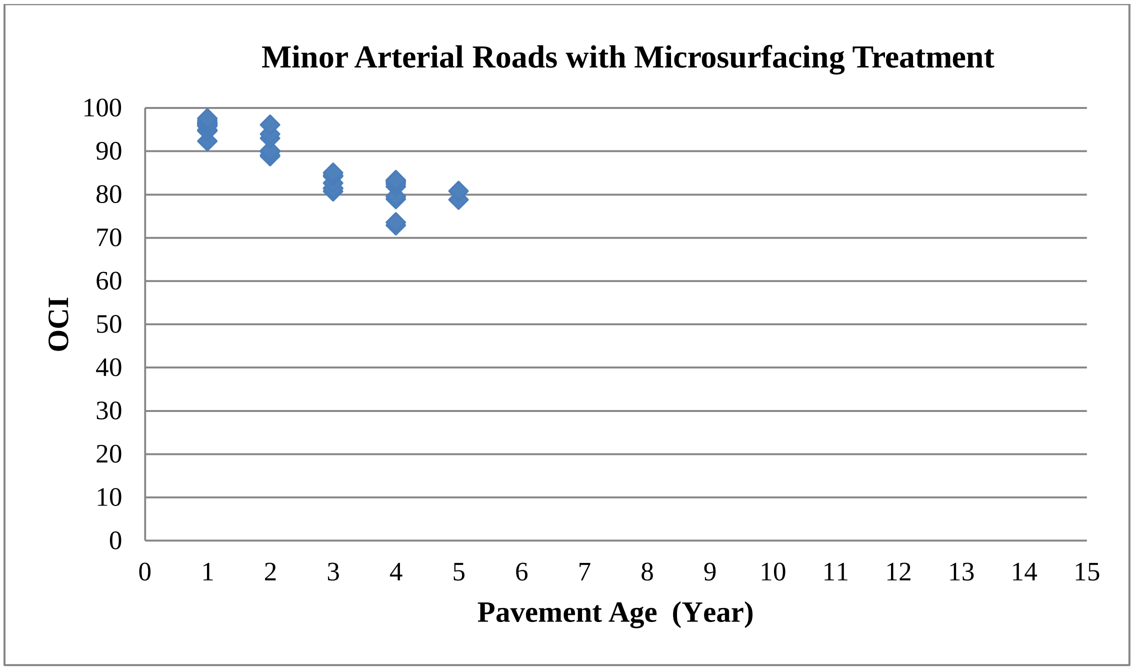

Figure B4: Minor Arterial Roads with Microsurfacing Treatment

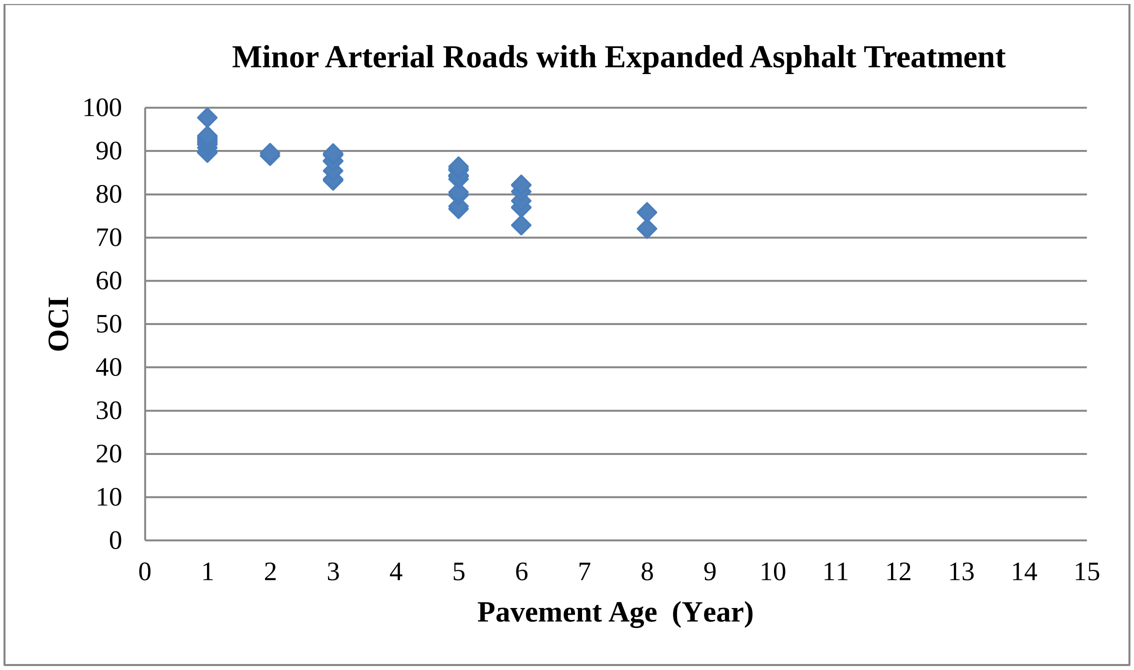

Figure B5: Minor Arterial Roads with Expanded Asphalt Treatment

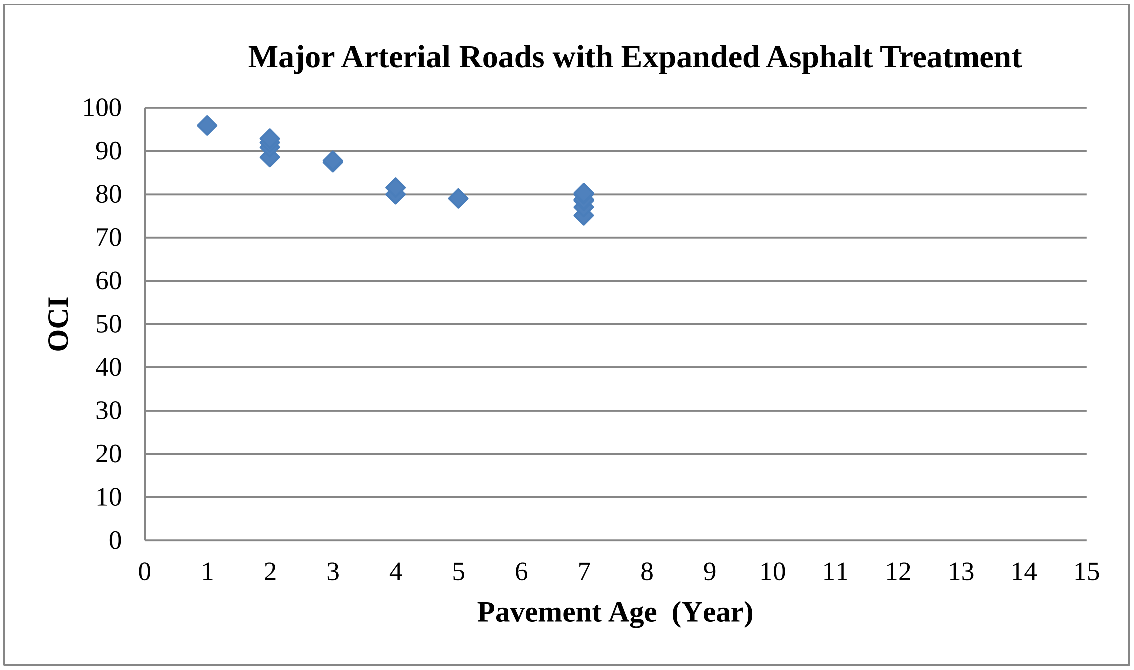

Figure B6: Major Arterial Roads with Expanded Asphalt Treatment

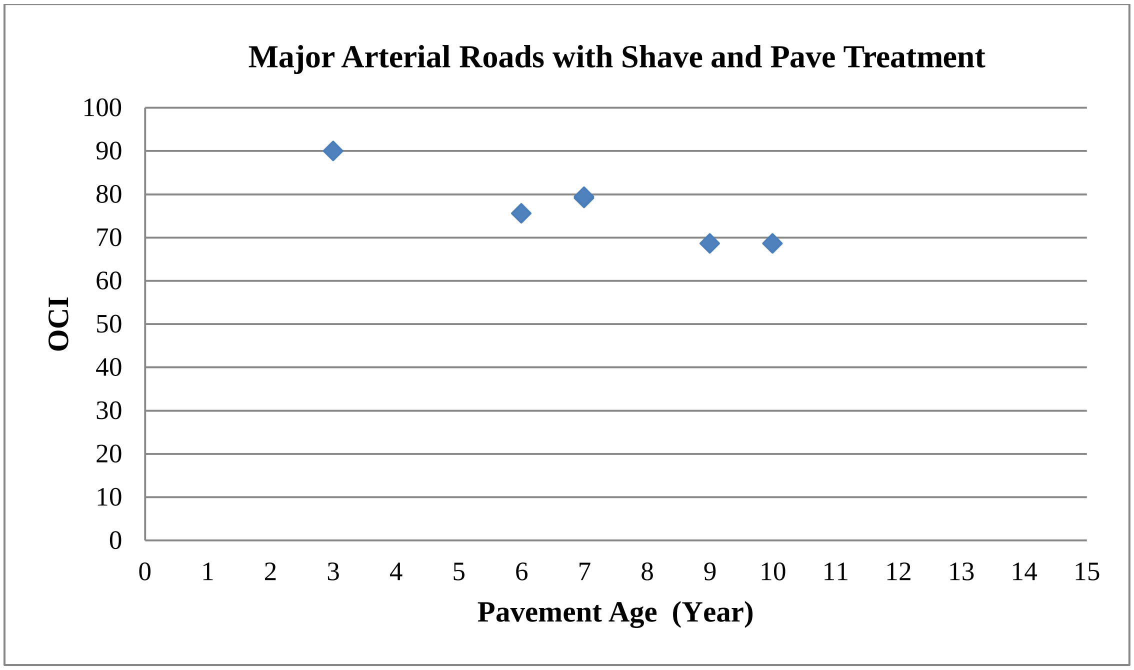

Figure B7: Major Arterial Roads with Shave and Pave Treatment

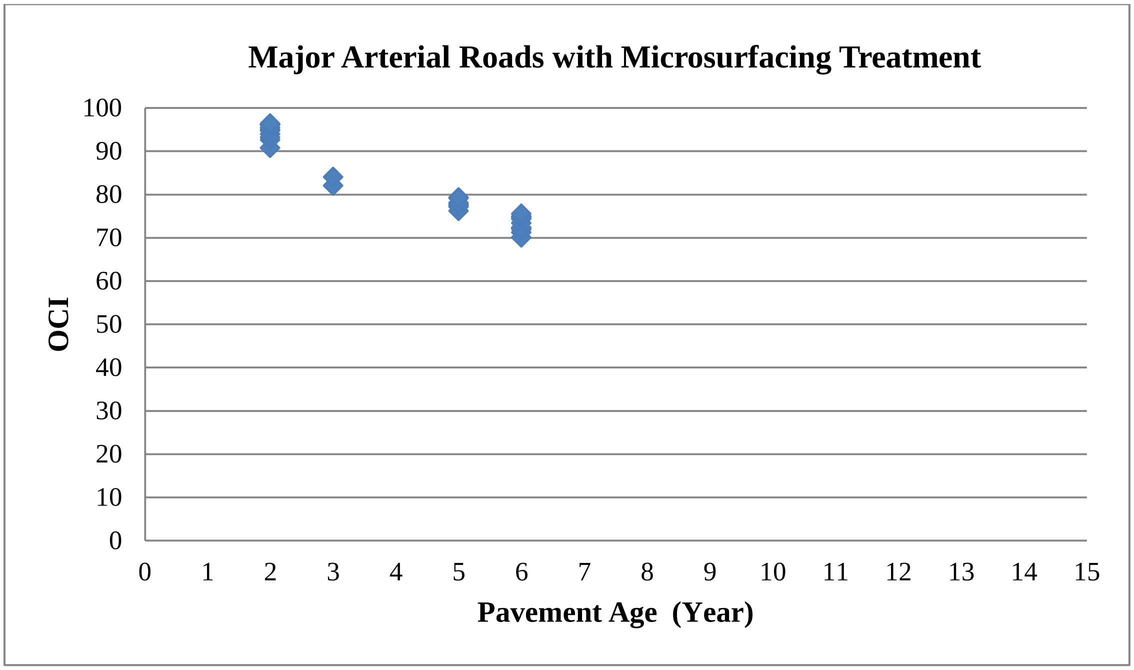

Figure B8: Major Arterial Roads with Microsurfacing Treatment

Appendix C: Current Condition of Each Road Classification Corresponding to Each Treatment Strategy Including AADT Information

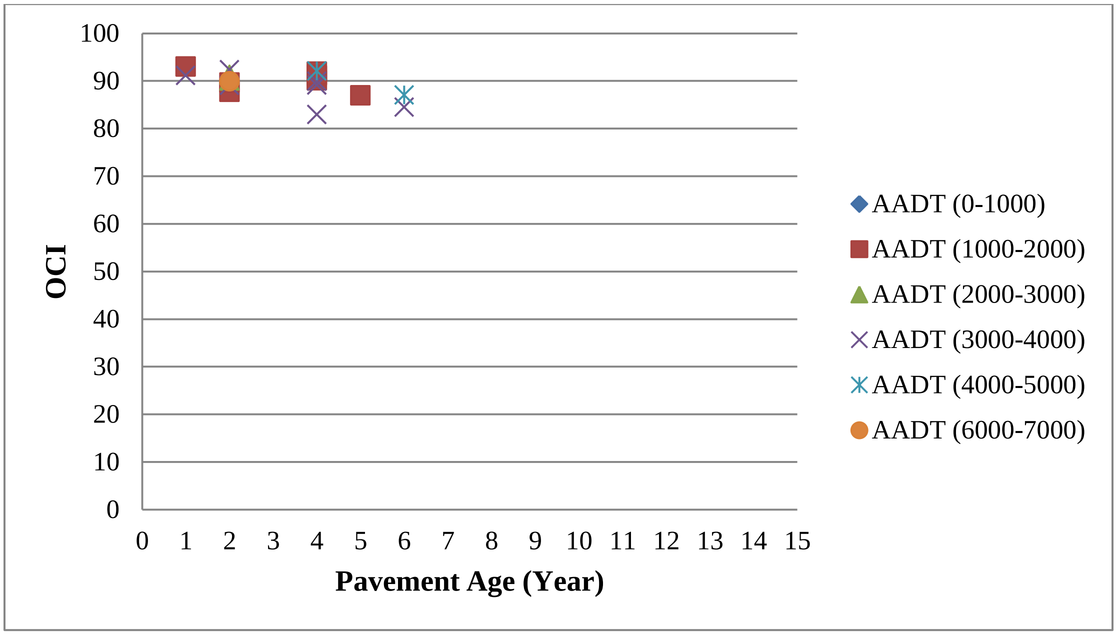

Figure C1: Collector Roads with Expanded Asphalt Treatment for Different AADT

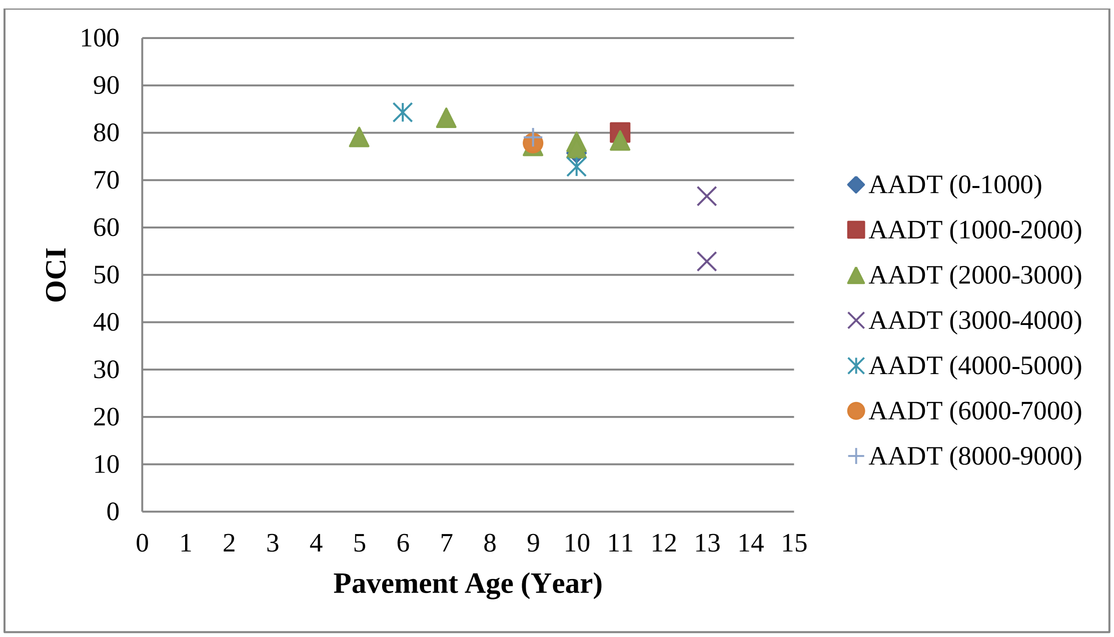

Figure C2: Collector Roads with Shave and Pave Treatment for Different AADT

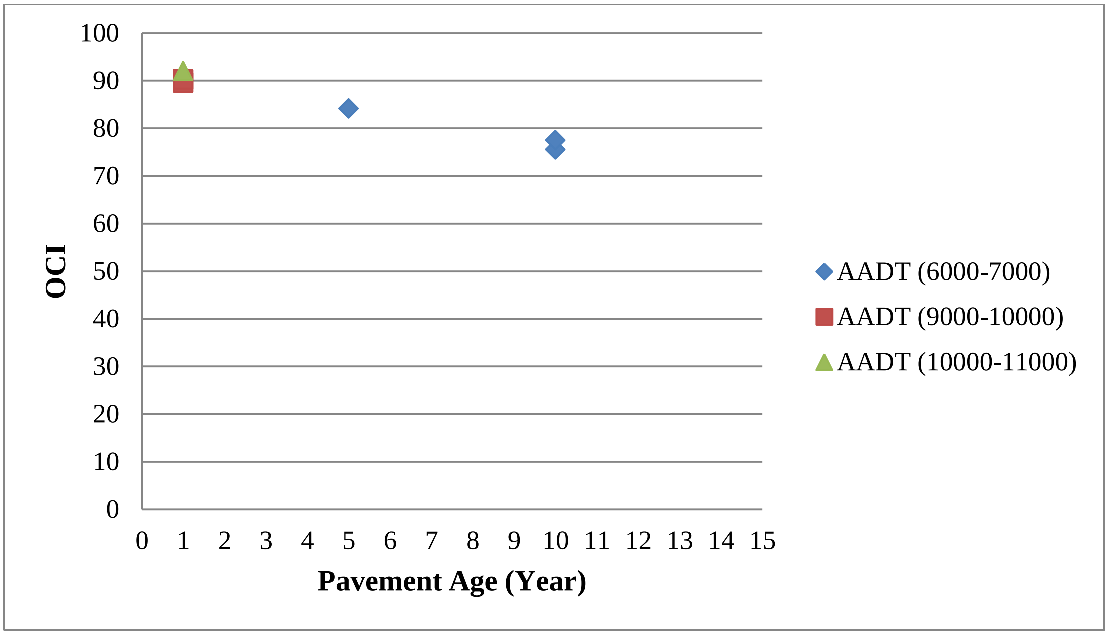

Figure C3: Minor Arterial Roads with Shave and Pave Treatment for Different AADT

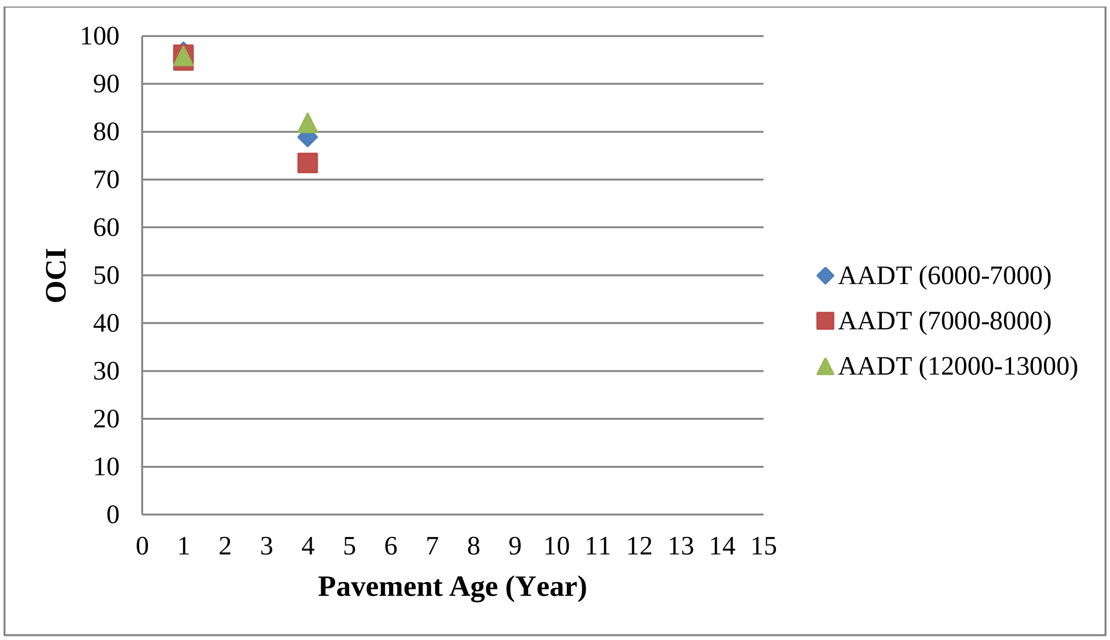

Figure C4: Minor Arterial Roads with Microsurfacing Treatment for Different AADT

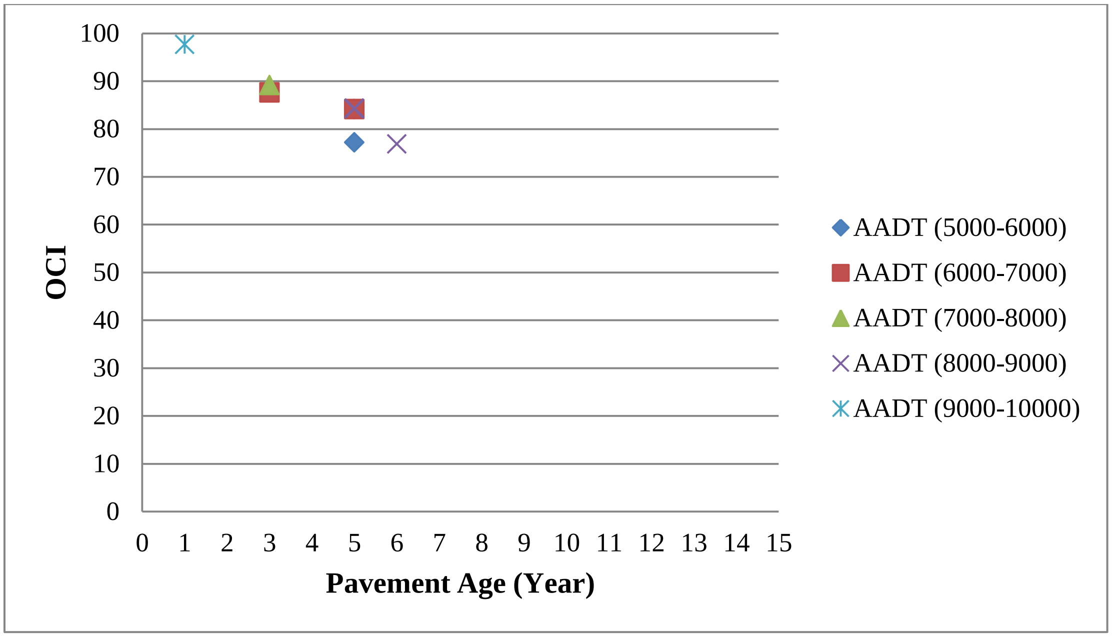

Figure C5: Minor Arterial Roads with Expanded Asphalt Treatment for Different AADT

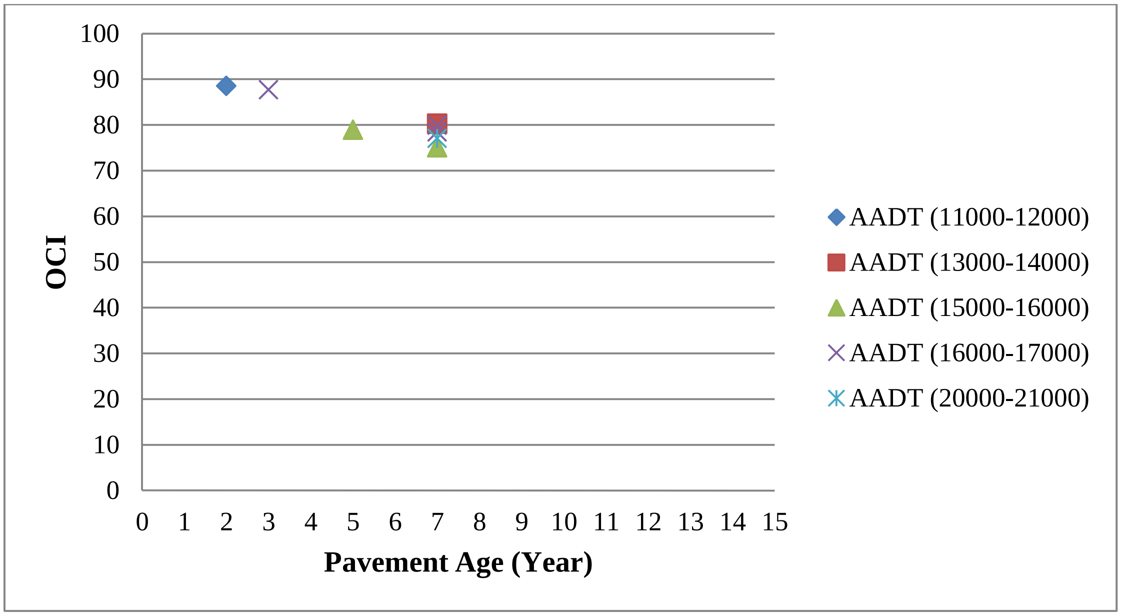

Figure C6: Major Arterial Roads with Expanded Asphalt Treatment for Different AADT

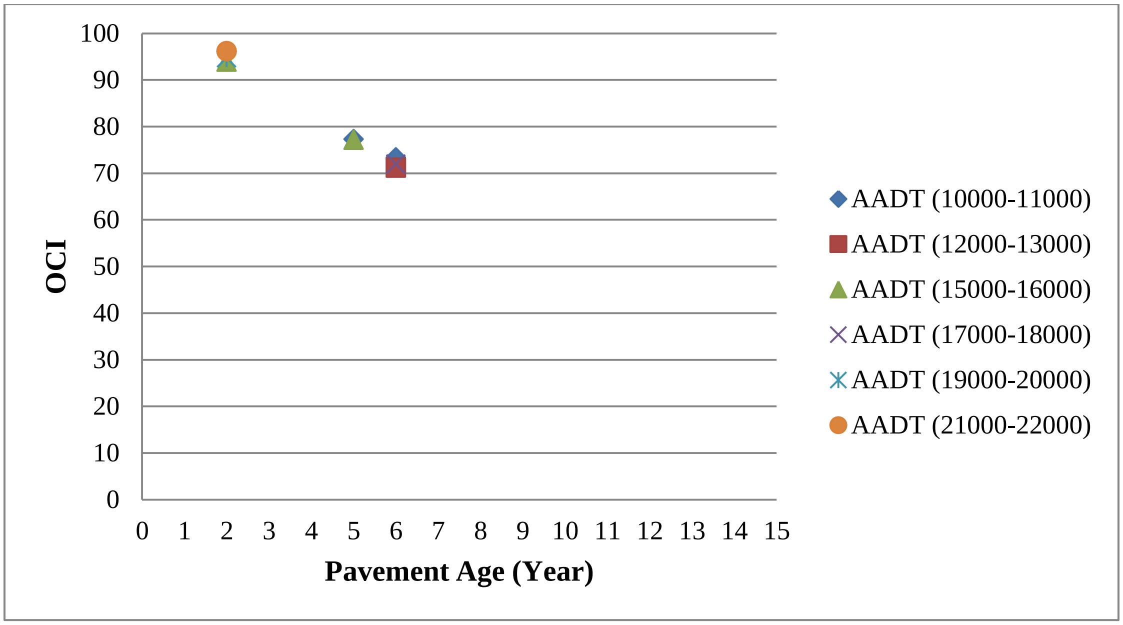

Figure C7: Major Arterial Roads with Microsurfacing Treatment for Different AADT

Appendix D: Pavement Performance Prediction Models for Each Road Classification Corresponding to Each Treatment Strategy

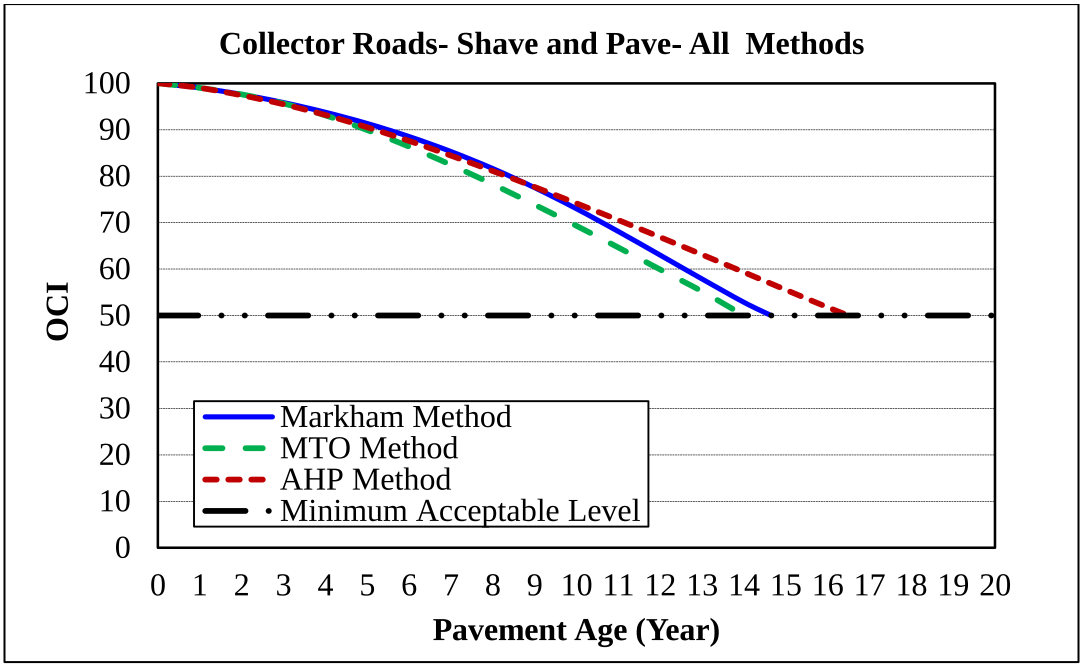

Figure D1: Pavement Performance Prediction Model for Collector Roads with the Shave and Pave Treatment

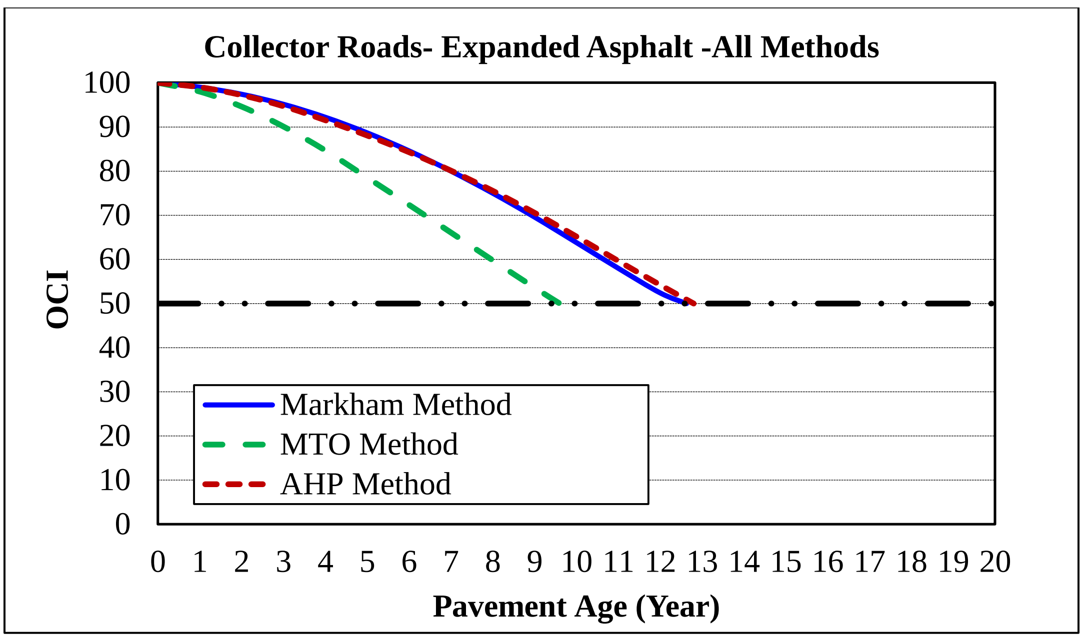

Figure D2: Pavement Performance Prediction Model for Collector Roads with the Expanded Asphalt Treatment

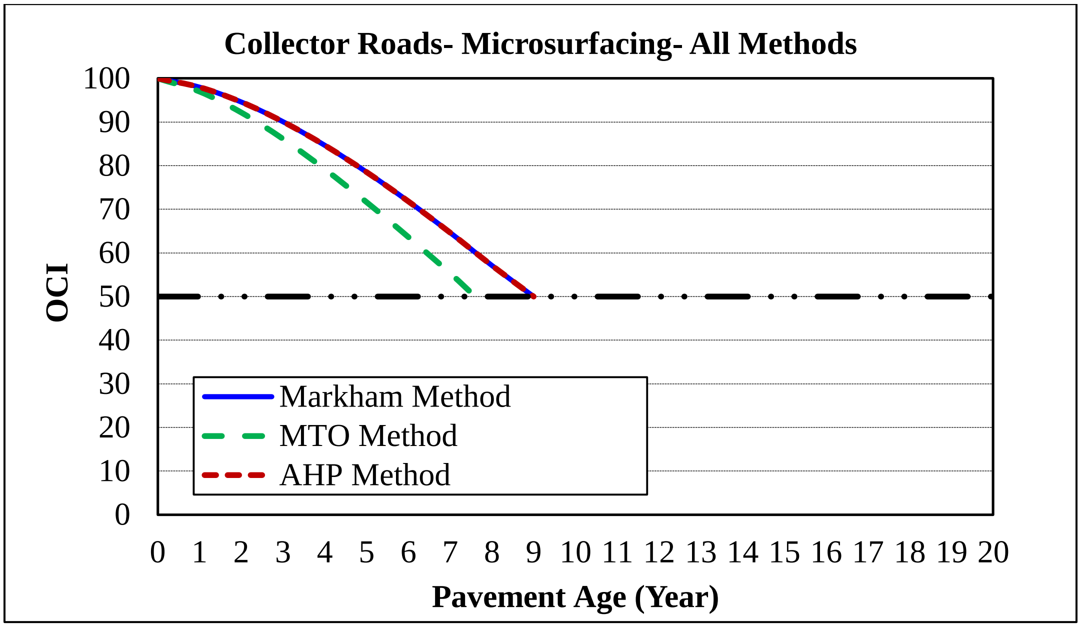

Figure D3: Pavement Performance Prediction Model for Collector Roads with the Microsurfacing Treatment

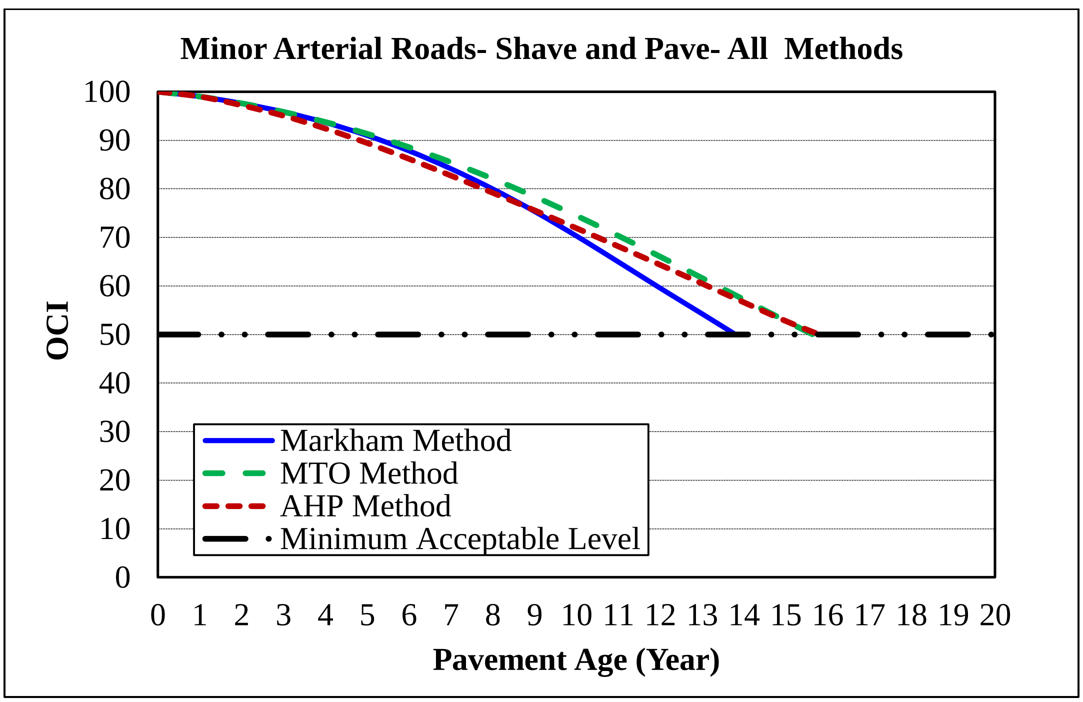

Figure D4: Pavement Performance Prediction Model for Minor Arterial Roads with the Shave and Pave Treatment

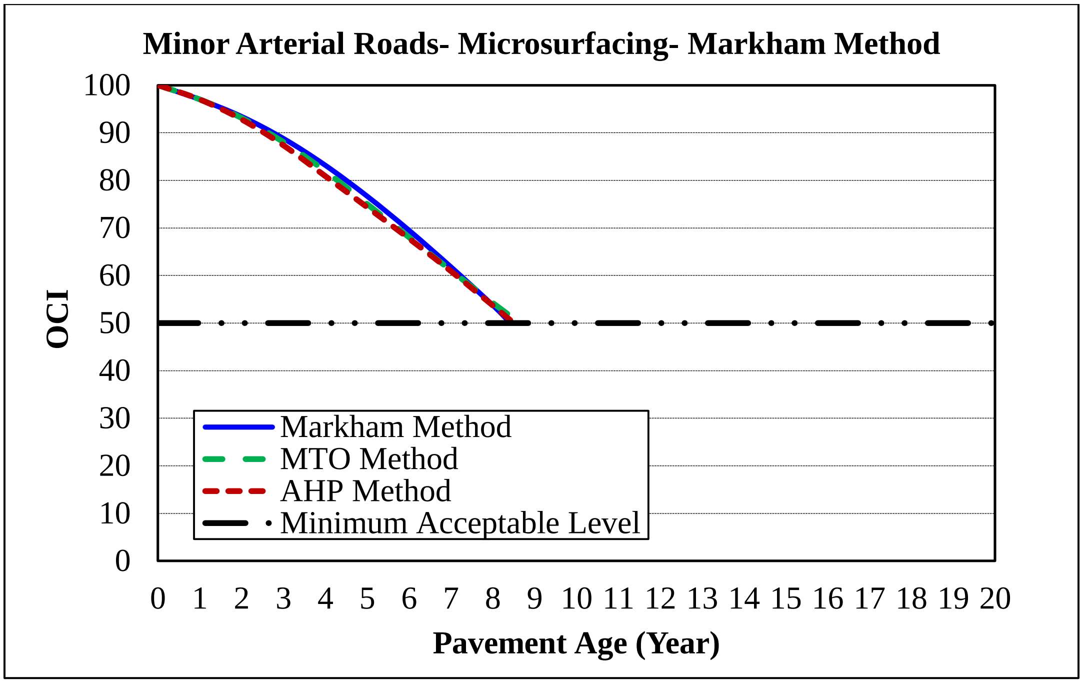

Figure D5: Pavement Performance Prediction Model for Minor Arterial Roads with the Microsurfacing Treatment

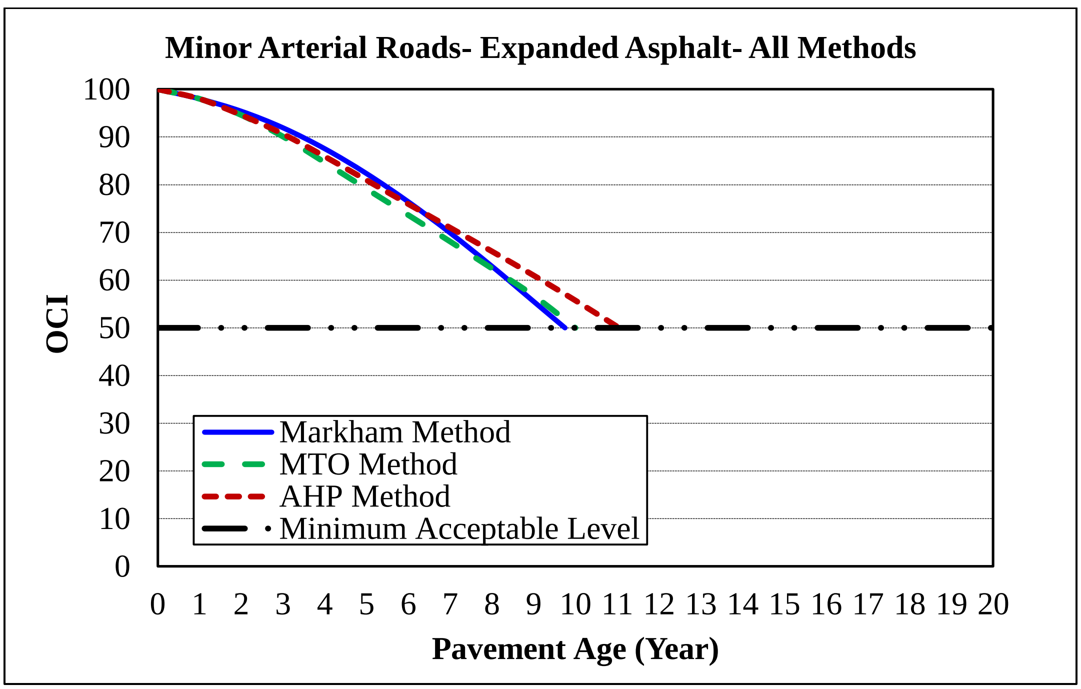

Figure D6: Pavement Performance Prediction Model for Minor Arterial Roads with the Expanded Asphalt Treatment

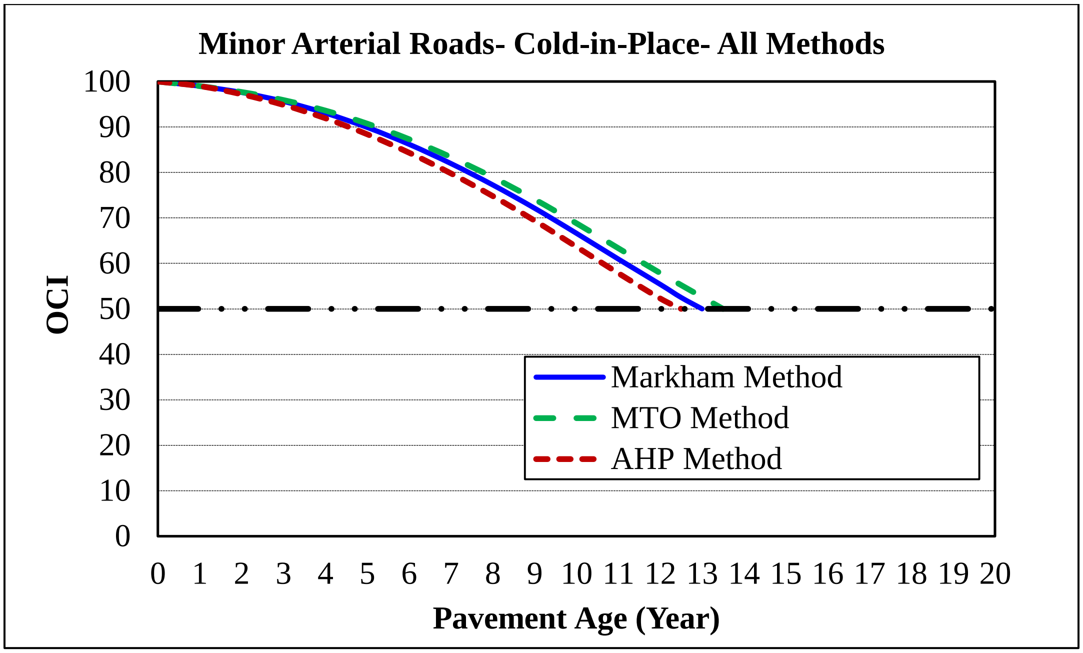

Figure D7: Pavement Performance Prediction Model for Minor Arterial Roads with the Cold-in-Place Treatment

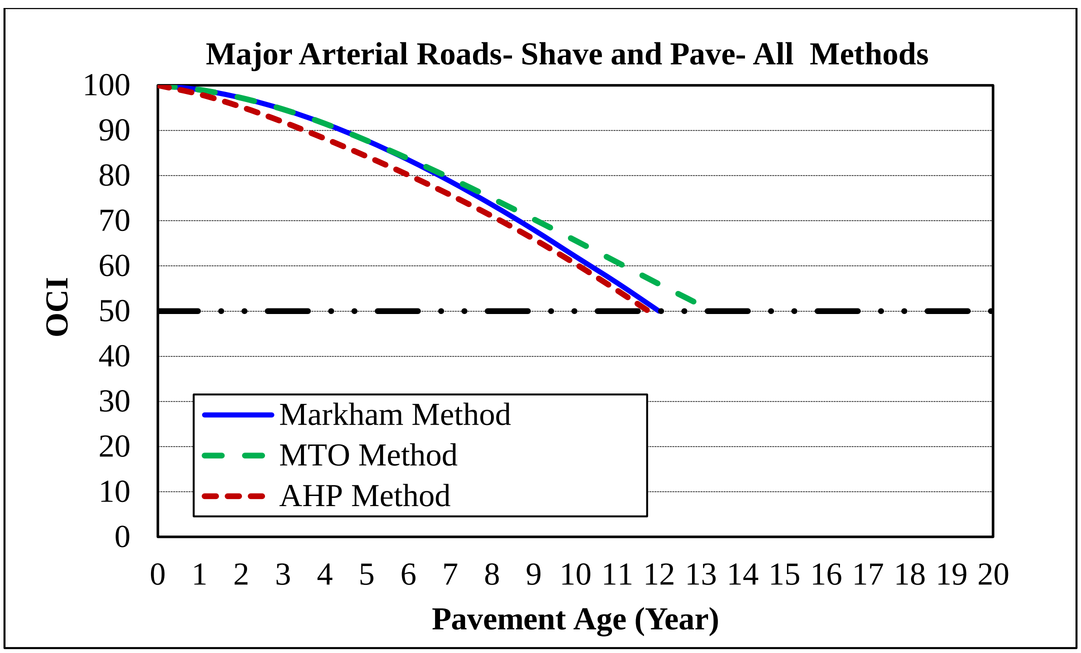

Figure D8: Pavement Performance Prediction Model for Major Arterial Roads with the Shave and Pave Treatment

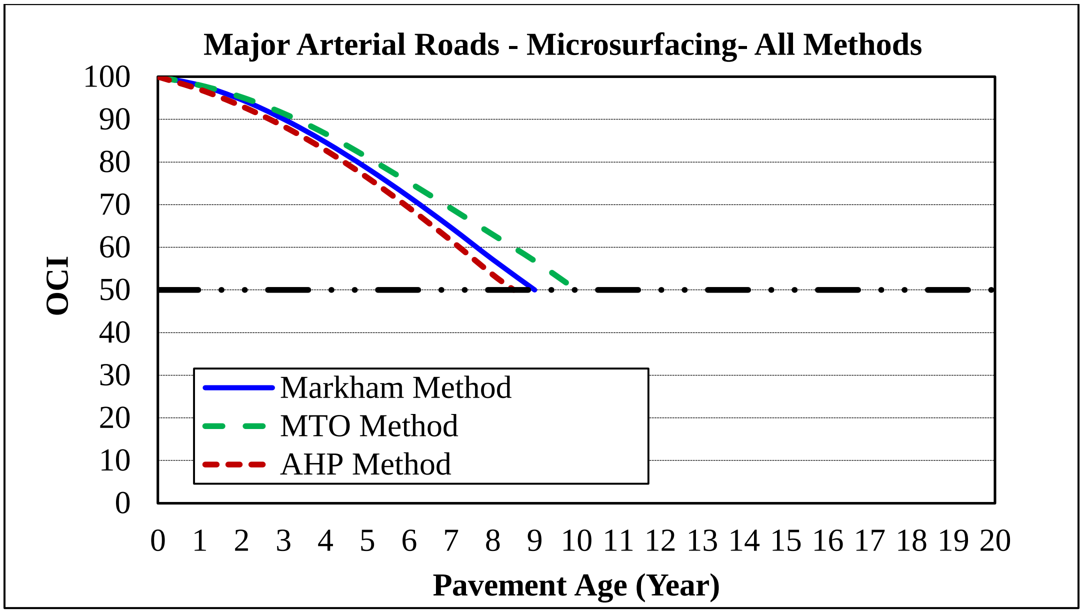

Figure D9: Pavement Performance Prediction Model for Major Arterial Roads with the Microsurfacing Treatment

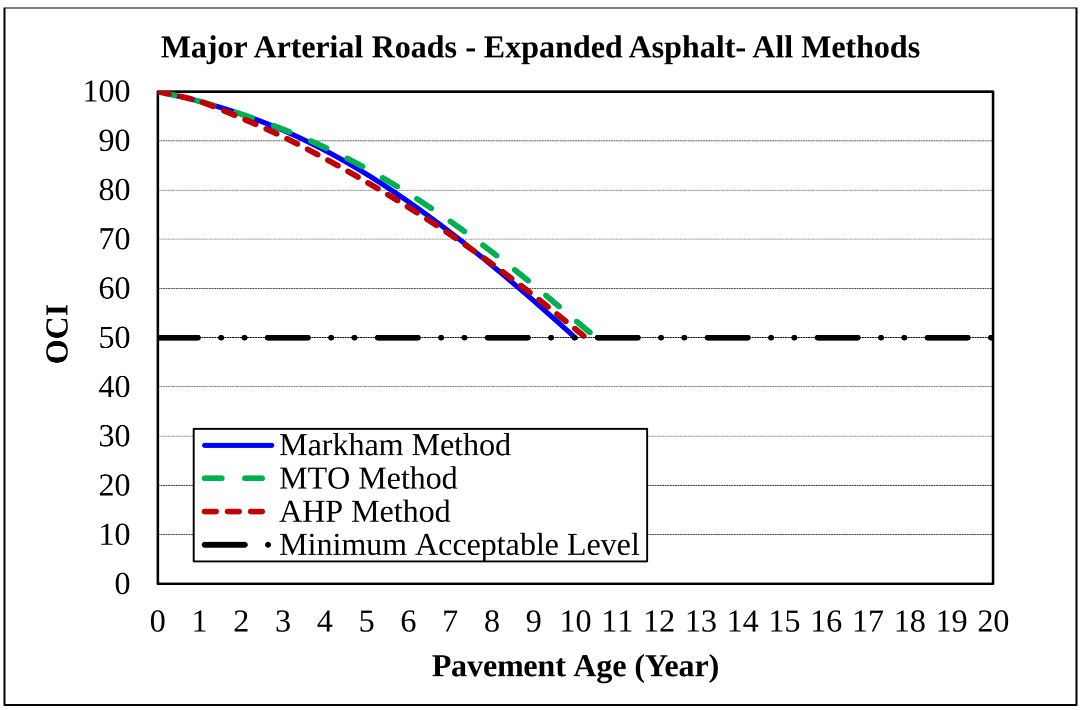

Figure D10: Pavement Performance Prediction Model for Major Arterial Roads with the Expanded Asphalt Treatment

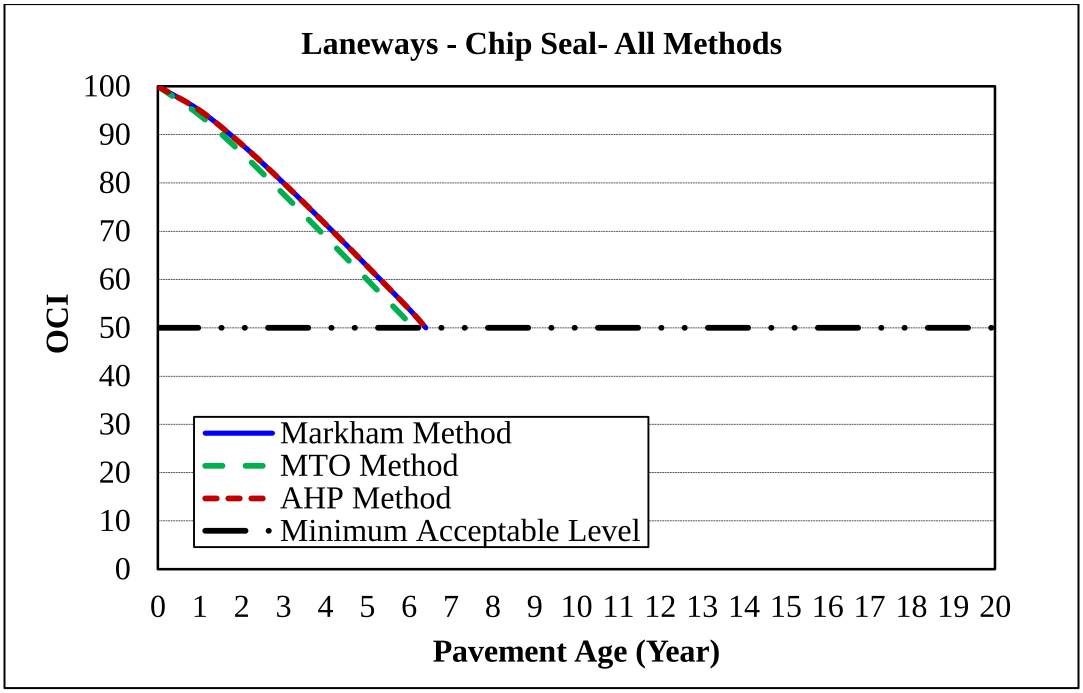

Figure D11: Pavement Performance Prediction Model for Laneways with the Chip Seal Treatment