NOTE TO USERS

This reproduction is the best copy available.

UMI®

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

FLEXIBLE PAVEMENT PERFORMANCE EVALUATION IN ONTARIO: AN OVERVIEW

By

Muzaffar Hassan
B.E. (Civil)
University of Engineering and Technology Lahore
Pakistan 1991

A Project

Presented to Ryerson University

in Partial Fulfillment of the

Requirement for the Degree of

Master of Engineering

in the Program of Civil Engineering

Toronto, Ontario, Canada, 2004

© Muzaffar Hassan

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

UMI Number: EC52955

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI®

UMI Microform EC52955

Copyright 2008 by ProQuest LLC.

All rights reserved. This microform edition is protected against unauthorized copying under Title 17, United States Code.

ProQuest LLC
789 E. Eisenhower Parkway
PO Box 1346
Ann Arbor, MI 48106-1346

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this project. I authorize Ryerson University to lend this project to other institutions or individuals for the purpose of scholarly research.

Muzaffar Hassan
Department of Civil Engineering
Ryerson University

I further authorize Ryerson University to reproduce this project by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

Muzaffar Hassan
Department of Civil Engineering
Ryerson University

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Ryerson University

School of Graduate Studies

The undersigned certify that they have read and recommend to the School of Graduate Studies for acceptance, a project entitled "Flexible Pavement Performance Evaluation in Ontario: An Overview" submitted in partial fulfillment of the requirements for the degree of Master of Engineering.

	Dr. Said M. Easa, Supervisor Department of Civil Engineering
	Dr. Paul Poh, Co-Supervisor Department of Architecture Engineering
	Date

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Flexible Pavement Performance Evaluation in Ontario: An Overview

Muzaffar Hassan
Master of Engineering, 2004
Department of Civil Engineering
Ryerson University

ABSTRACT

Measuring pavement performance is a major component of the pavement management system. It assists in decision-making for finding the optimum strategies to provide, evaluate, and maintain serviceability in an acceptable condition cost effectively. The Ontario Ministry of Transportation (MTO) has been systematically rating pavement performance since the mid-1960s. Pavement condition survey involves measurement of two physical parameters: ride quality of pavement surfaces, and the extent and severity of pavement distress manifestations. The pavement ride quality can be measured with an acceptable level of consistency and repeatability through automation. However, achieving consistency in the evaluation of pavement distress manifestations is a challenging task because the automation that could accurately and consistently detect, quantify and record surface distresses is not fully developed in spite of rapid advances in video imagery and non-contact sensing devices.

This report evaluates the progress made over the past three decades in the key areas of Distress Manifestation Index, Riding Comfort Rating, Pavement Condition Index and second generation Pavement Management System software (PMS2). A review of the Ministry's network-level pavement performance database is presented, emphasizing

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

pavement condition surveys, prediction models and main factors influencing assessment of long-term pavement performance. Several key issues related to the quality control and quality assurance of the pavement roughness are discussed with reference to the verification techniques used by the MTO. Based on the literature review, future recommendations for possible improvements of the prediction models and techniques used for the evaluation of pavement performance are presented in order to obtain more consistent values.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ACKNOWLEDGMENTS

I would like to thank my project supervisors Dr. Said M. Easa and Co-supervisor Dr. Paul Poh for their outstanding supervision and guidance. Their support, advice and constructive criticism through my graduating have been invaluable. I am also grateful to my brothers, sister, dear wife and children for their continued support, prayer and love. I am also grateful to my all colleagues at Ryerson University for their moral and technical support. Deepest gratitude to my wife and kids, who had to sacrifice their needs and time and supported me in finishing my studies. Finally, I am grateful to the Grace of God for the countless blessings I have received.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

DEDICATION

Dedicated to my loving parents.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

TABLE OF CONTENTS

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

LIST OF TABLES

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

LIST OF FIGURES

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 1: PAVEMENT PERFORMANCE

1.1 Background

Currently, Ontario Ministry of Transportation (MTO) has 18,646 kilometers of provincial highways comprising 3,654 km of freeways, 4,324 km of collectors, 6,120 km of arterials, and 4,648 km of local and secondary roads. Based on surveys conducted in 2000, 14,259 km (or 76.5%) are hot mix asphalt pavements, 3,318 km (or 17.8%) are asphalt surface treated pavements, and the remainder are Portland cement concrete and gravel-surfaced pavements. Table 1.1 presents a summary of the Ministry's highway network information in terms of road functional class and pavement type. It is evident that flexible pavements are the majority (17,577 km or 94.3%) of the highways in the provincial network (Ningyuan et al. 2002).

Geographically, the provincial highways are distributed in the five MTO jurisdictional regions (Table 1.2). Each region has its own environmental and traffic conditions as well as economic character. The distribution of road class and pavement type is, therefore, different from region to region. For example, Central region is characterized by significant percentage of high volume freeways with asphalt concrete pavements, while Northwestern region has a significant percentage of low volume local and secondary roads with asphalt surface treated pavements. It should be noted that most of the freeways are located in Southern Ontario (Central, Eastern and Southwestern regions) whereas the majority of the local and secondary roads are located in the Northern and Northwestern regions.

As far as pavement structure is concerned, most of surface treated pavements are distributed within Northern and Northwestern regions while Portland cement concrete

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

pavements are predominately located in Central region around the urban centres. There are no composite and exposed concrete pavements in the Northern and Northwestern regions and no surface treated pavements exist in the Central and Southwestern regions (Ningyuan et al. 2002). For the purpose of pavement management, all highways in each region are sectioned on the basis of uniformity in pavement structure, road function, subgrade condition, traffic loads and other principles used in pavement management.

Table 1.1 MTO Road Network as Surveyed in 2000 (Ningyuan et al. 2002)

Road Class	Length(km)	Percentage	Pavement Type	Length (km)	Percentage
Arterial	6120	32.8	Hot Mix Asphalt	14259	76.5
Collector	4324	23.2	Composite	444	2.4
Freeway	3654	19.6	Portland Cement Concrete	121	0.7
Local	2890	15.5	Surface Treated	3318	17.8
Secondary	1658	8.9	Gravel Surface	505	2.6

Table 1.2 Length of Each Class of Pavement by MTO Regions Surveyed in 2000 (Ningyuan et al. 2002)

Pavement Type	Total Centre line Length (km) by MTO Regions				
	Central	Southwestern	Eastern	Northern	Northwestern
Hot Mix Asphalt	1216	2788	2788	3646	3821
Surface Treated	0	0	39	1541	1738
Portland Cement Concrete	46	30	45	0	0
Composite	315	114	14	0	0
Gravel Surface	0	0	0	142	363

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

As a result, there are a total of 1,700 road sections used to define the provincial road network. The length of each pavement section ranges from the shortest at 400 meters to the longest at 78 kilometers. Detailed descriptions of each pavement section and dynamic data collected in the field are stored in MTO's second generation Pavement Management System (PMS2) database. The data is collected for each pavement section: road section geometry, environmental and traffic data, pavement structure and materials, construction history, and pavement performance. At present, the Ministry invests about $200 million annually to ensure that the highway network is maintained above the target serviceability level required for each classified road.

For preservation of the road network in terms of preventive and corrective maintenance activities, the Ministry has established a set of standardized maintenance and rehabilitation alternatives corresponding to treatment strategies for various pavement distresses. All of the standardized M&R treatments are input in the form of decision trees within the PMS2 (Kazmierowski et al. 2001) database for utilization in pavement network rehabilitation programming, which involves life-cycle cost analysis of pavement design and economic analysis.

1.2 Pavement Management System

The definition provided in Pavement Management Guide (RTAC 1977) is still entirely applicable and is quoted as: "The basic purpose of the pavement management system is to achieve the best value possible for the available public funds and to provide safe, comfortable and economic transportation. This is accomplished by comparing the investment alternate at both network and project levels, coordinating design, construction, maintenance and evaluation activities and making efficient use of existing practice and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

knowledge".

The definition described in Pavement Management Guide (AASHTO 2001) is quoted as: "The function of a pavement management system is to improve the efficiency of decision-making, expand its scope, provide feedback on the consequences of decisions, facilitate the co-ordination of activities within the Ministry and ensure the consistency of decisions made at different management levels within the same organization". Since its introduction in the late 1960s and early 1970s pavement management system has evolved continuously in terms of its scope, methodology, and application.

The pavement management system has two basic working levels, network and project. The primary function of the network-level is to develop a priority program, schedule of rehabilitation and maintenance, within budget constraint. Here are the key components (TAC 1997):

1. Sectioning, data acquisition, (field data on roughness, surface distress, structural adequacy, surface friction, geometrics, traffic, costs, and other data) and data processing.
2. Criteria for the minimum acceptable serviceability, maximum surface distress, minimum structural adequacy, etc.
3. Application of deterioration prediction models.
4. Determination of present and future needs, evaluation of the options and budget requirement.
5. Identification of alternatives, development of priority programs and schedule of work (rehabilitation, maintenance, new construction).

The project-level pavement management system deals with the details of work coming on-stream from the network-level decision. Here are the key components (TAC 1997):

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

1. Sub-sectioning, detailed field/lab and other data of scheduled projects, data processing.
2. Predicting deterioration and economic analysis within project alternatives.
3. Selecting the best alternative, detailed quantities, costs, and schedules.
4. Implementation construction and periodic maintenance.

1.3 Pavement Performance Evaluation

The definition described in Pavement Design and Rehabilitation Manual (MTO 1990) is quoted as: "The procedure of going to the field and measuring and / or observing the current state of various pavement characteristics systematically, periodically, and recording them for future use". The purpose of pavement evaluation is to provide a basis for identifying current and future fiscal needs in network-level pavement management system and to provide the detailed analysis at the project-level to select a suitable rehabilitation or maintenance treatment. Pavement performance evaluation relies on two principle features:

1. Surface distress manifestations, and
2. Ride quality.

The model for Distress Manifestations (DM) was developed by Phang et al. (1979) to define the surface distress manifestations in a numerical value by defining the severity, extent, and weighting values for twenty-seven surface distresses. The model for Distress Manifestation Index (DMI_I) was developed by Hajek et al. (1986). Presently, MTO is using revised Distress Manifestation Index (DMI) in its PMS2 (Ningyuan et al. 2001). Surface distress surveys are performed manually by regional pavement evaluation officers or technicians driving on the pavement sections. Each individual pavement

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

surface distress is visually inspected by aggregating the severity, and extent.

Fig. 1.1 summarizes the average DMI values for each region based on data collected in 2000 (Ningyuan et al. 2002). Pavements in the Central region are generally in very good condition, with the average DMI value being higher than 9.2. The surface of the pavement in Eastern and Southern regions are in good condition with the average DMI values just below the 8.5 level. The Northern region has the lowest average DMI value, because of the large amount of local roads.

The definition of the ride quality described by Phang et al. (1979) is quoted as: "The degree of pavement surface undulation which affects the ride comfort of the motorist." It is rated on a Riding Comfort Rating (RCR) scale of 0 to 10 where 10 represents a perfectly smooth surface, and 0 is a very rough road. It can be measured subjectively by riding the pavement by specialized raters (Phang et al. 1979) and objectively by using different mechanical and electrical devices.

Pavement roughness is one of the most important indicator of the pavement performance and directly reflects pavement serviceability to the road users. The concept of pavement serviceability was devised in the AASHTO Road Test as a measure of the pavement performance (AASHTO 1962). The American Society for Materials and Testing (ASTM E1777-96) assigns roughness the highest priority among performance related data for pavement management, both at the project and network levels. Thus, the most important factor in characterizing the serviceability of a pavement is the roughness of the traveled surface. Roughness measurement in terms of International Roughness Index (IRI) has become the primary parameter used to measure pavement surface condition.

In recent years, some American states and Canadian provinces have used IRI in

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

their business plan as an objective measure of their pavement network conditions. For example, MTO uses IRI as a performance measure for describing and monitoring the pavement condition of its network-level pavement management system (Hajek et al. 1998). The U.S. Federal Highways Administration (FHWA) uses IRI as a performance measure for describing and monitoring the pavement condition of its National Highway System (NHS).

Recent research has demonstrated an approach for adopting the IRI calculated from the high precision profilometers for the effective quality assurance and evaluation of the roughness on paving projects. By its definition, IRI (ASTM E867-96) is a summary statistic, representing an aggregation of the profile elevation data. Measurement of pavement roughness in terms of IRI can be performed using different measuring devices, but the result of individual measurement on the same pavement section may vary significantly from one another due to the facts of using different measuring devices, different longitudinal profiles and different measuring speeds (Ningyuan et al. 2001).

Thus, given an IRI and the relative information, a highway agency can objectively assess how the condition of its pavement network responds to pavement investments like maintenance and rehabilitation program or a budget plan. The IRI measurement at network-level has become a routine practice for many road agencies in recent years. At the network-level, roughness is measured on an annual or biannual basis as a part of pavement evaluation. .

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

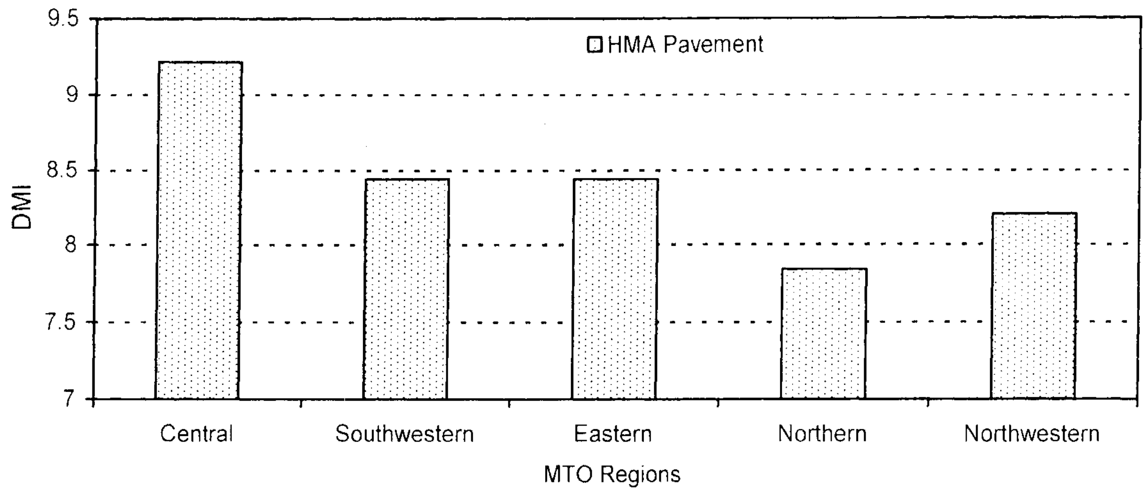

Figure 1.1 Surface Condition (DMI) Summary of Hot Mix Asphalt Pavements of MTO Regions (Ningyuan et al. 2002)

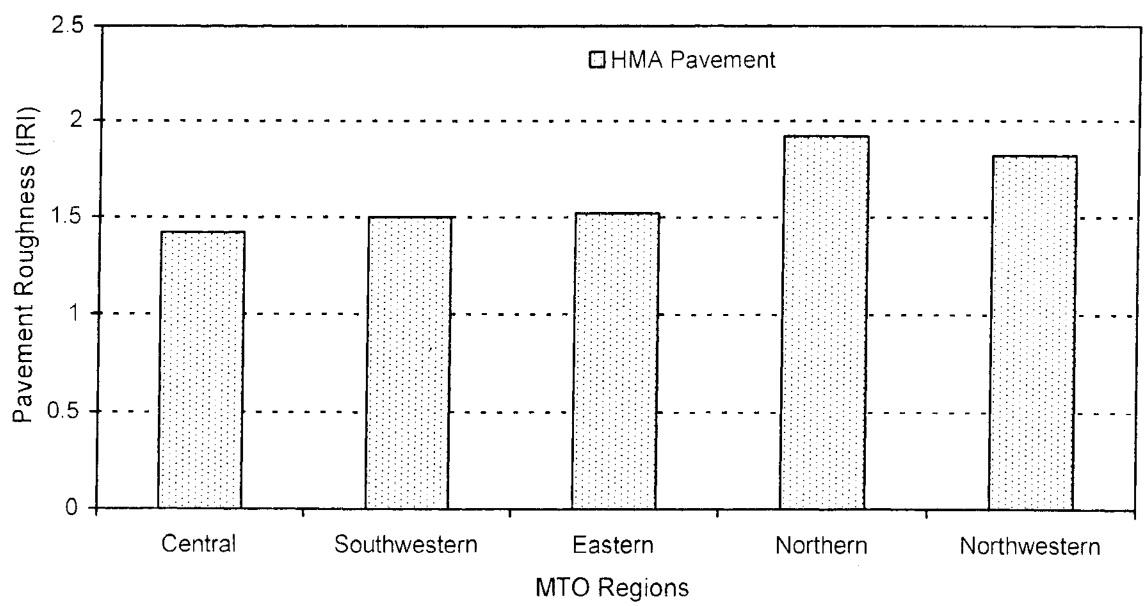

Figure 1.2 Summary of Average Roughness (IRI) of Hot Mix Asphalt (HMA) Pavements of MTO Regions (Ningyuan et al. 2002)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

On the other hand, the IRI measurement at the project-level is required primarily for accepting or adjusting the price of a paving contractor's product. Therefore, there is a need to standardize the pavement roughness evaluation both at the project and network-levels. The most commonly used methods and equipments to measure the roughness have been categorized according to scale of accuracy and reliability developed as a part of the IRI experiments by Sayers et al. (1986).

Historically, many highway agencies have gathered roughness measurement using response type devices and converted their existing data into IRI through the use of correlation techniques. Pavement ride quality by region is shown in Fig. 1.2, indicates that the pavements in Southern Ontario are generally smoother than those in Northern Ontario based on data collected in 2000. Overall, the pavement roughness in the provincial network is at a good level of serviceability according to the scale of IRI (Fig. 5.1).

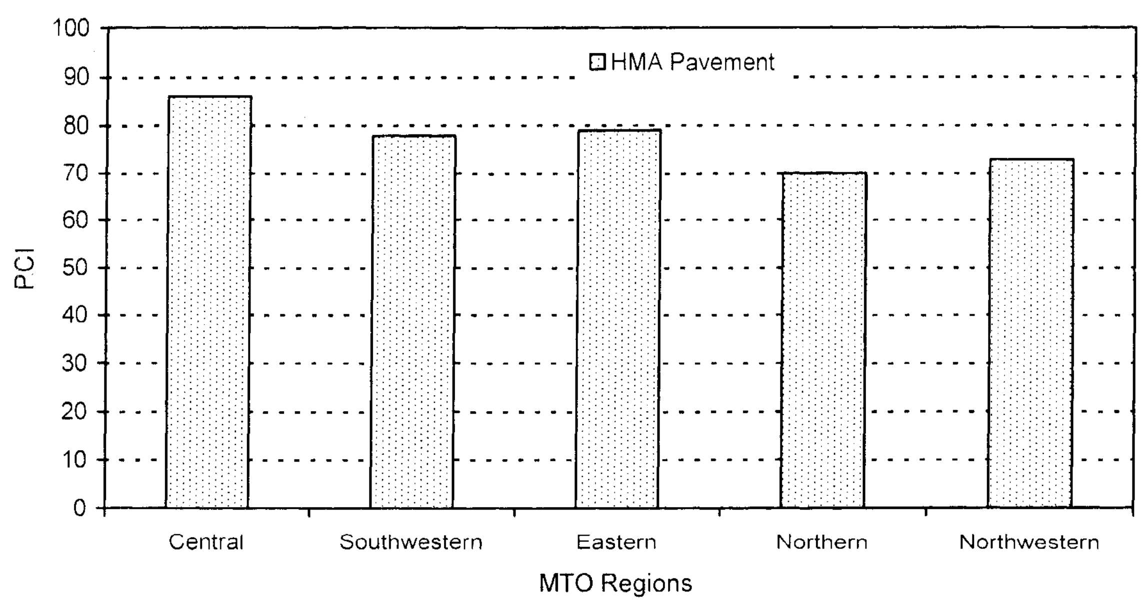

Figure 1.3 Average PCI of Hot Mix Asphalt (HMA) Pavements of the MTO Regions (Ningyuan et al. 2002)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

1.4 Summary of the Literature Review

Table 1.3 provides the summary of the literature review for flexible pavement performance evaluation methodology used by the MTO. It should be noted that the numbers in brackets following each category in the subject column provide the section within the report that can be referenced for the supporting information.

Table 1.3 Summary of the Literature Review

No	Author	Subject	Importance	Be superseded
1	Chong et al. (1975)	Manual	Description of 27 Distresses.	Yes by Chong et al. (1982)
		RCR (4.2)	Subjective Measure (0-10)	No
		PCR (6.2)	Subjective Measure (0-100)	No
2	Phang et al. (1979)	DI (6.3)	Parameter (0-100)	Yes by PCI (Hajek et al. 1986)
		RCR (4.4)	Mays Ride Meter (0-10)	Yes by PURD Hajek et al. (1986)
		DM (3.2)	With 27 Distresses (0-320)	Yes by Hajek et al. (1986)
3	Chong et al. (1982)	Manual	Description of 27 Distresses	Yes by Chong et al. (1989)
4	Hajek et al. (1986)	PCI (6.4)	Parameter (0-100)	No but Coefficient
		RCR (4.4)	PURD (0-10)	Yes by Hajek et al. (1998)
		DMI (3.3)	With 15 Distresses (0-205)	Yes by Ningyuan et al. (2002)
5	Chong et al. (1989)	Manual (2.3)	Description of 15 Distresses	No
6	Hajek et al. (1998)	RCI (5.2)	Switch to IRI	No
7	Ningyuan et al. (2002)	Prediction Models(6.5.1)	RCI, DMI, PCI	No
		DMI (3.3.2)	With 15 Distresses (0-10)	No
8	Sayers et al. (1995)	IRI	Integration of Ordinary Differential Equations	Different Methods like Euler Integration
9	Kazmierowski et al. (2001)	IRI (5.2.6)	Quality Assurance	No
		Model	Transfer Function to Get Class I IRI	No
10	Kazmierowski et al. (2001)	PMS2(6.6)	PMS2 Software	No
10	Joseph et al. (1984)	RMSVA (4.4.1.1)	Algorithm	Yes by Kazmierowski et al. (2001)
10	Queiroz (1981)	S V(4.4.1)	Model	Yes by Joseph et al. (1984)
11	Loughnan and Evers (1980)	RAM (4.4.1)	Model	Yes Queiroz (1981)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

1.5 Objective and Scope of the Project

The purpose of this project is to carry out a literature and methodology review for the pavement performance evaluation in Ontario. The main objective of this study is to review the Ministry's network pavement performance history, in terms of pavement condition surveys, performance prediction models and the main factors influencing the assessment of long-term pavement performance. Specifically, each element of the pavement performance evaluation are addressed: condition of pavement by word description, distress severity and density, weighting value, PCI, DMI, and RCR measurement based on Portable Universal Roughness Devices (PURD) and International Roughness Index (IRI). Consequences of measuring the IRI using different equipment, models to convert the roughness measurement to RCR and quality assurance of IRI are discussed. The study emphasizes the following aspects of pavement performance evaluation:

1. Diagnosis of pavement condition and performance trends of the provincial road network.
2. Discussion of pavement performance prediction models based on historical performance data.
3. Review of the quality assurance process developed for measure of pavement performance.

Based on the literature review, the recommendations for the improvement of the existing techniques used to manage the pavement performance evaluation are presented.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

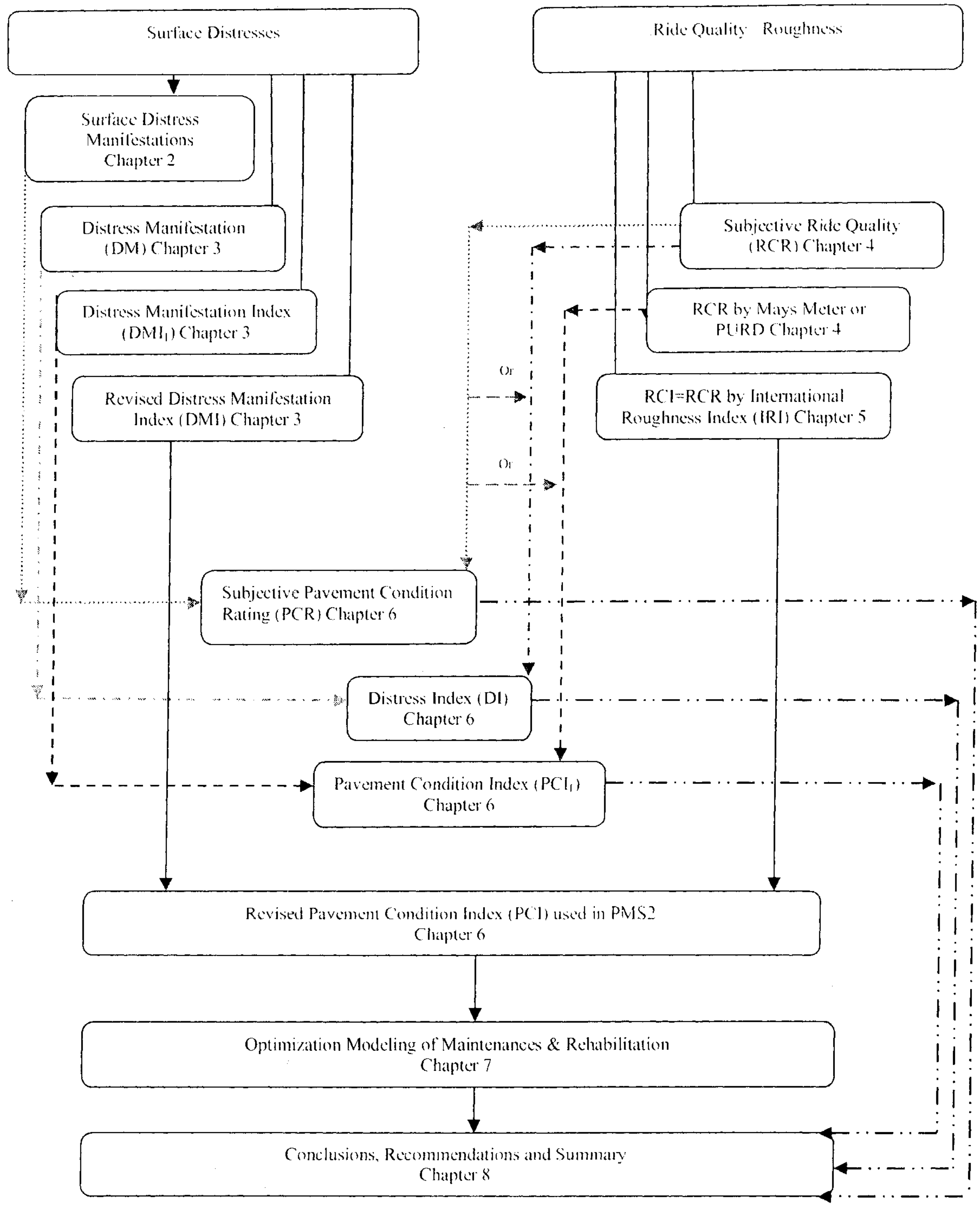

Figure 1.4 Activities of the Project

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 2: SURFACE DISTRESS MANIFESTATIONS

2.1 Introduction

This chapter explains the methodology, how the surface distress data is collected to calculate the pavement evaluation indexes. It is done by literature review and examining the methodologies from the MTO manuals (Chong et at 1975, 1982, 1989). Distress manifestations are visible signs of the pavement structural condition. The assessment method (Chong et al. 1989) answers four simple questions:

1. What is the problem?
2. What causes the problem?
3. How bad is the problem?
4. How big is the problem?

First, the distress type is identified by comparing with catalog photos (Chong et al. 1989) of various distresses which are accompanied by the word descriptions of physical appearances and brief summaries of why it happens. Next, the question of 'how bad' is answered by describing the distress severity in one of these very simple terms: very slightly, slightly, moderate, severe, and very severe. The correct answer may be chosen by simply comparing the problem to the catalog photos and descriptions. A catalog of photos showing the different stages of 'how bad' distresses are, is contained in a manual (Chong et al. 1989).

Lastly, 'how big is the problem' is answered by describing the density of occurrence of the distress by using one of these words: few, intermittent, frequent, extensive, and throughout. These words refer to the percentage of length or area of the road section which is being rated. For example, the rater may encounter a situation where

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

there are some incidences of distress located within a short distance of each other and within the evaluation section, this distance represents between 10 to 20% of the pavement surface area. Thus the 'density' is said to be "intermittent" (Fig. 2.1).

2.2 Assessment of Surface Distress Manifestations

The rater drives along the shoulders at a slow speed (not exceeding 40 km/h) and observes the cracks and other distresses, making frequent stops to examine and measure the particular distresses. At the end, he summarizes his impression by placing check marks in the appropriate boxes of a condition rating check list form (Table 3.2).

2.3 Guidelines for Surface Distress Manifestations

The definitions, causes and guidelines for surface distress manifestations are defined below (Chong et al. 1989).

2.3.1. Ravelling and Loss of Coarse Aggregates

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 the surface. Following are the possible causes:

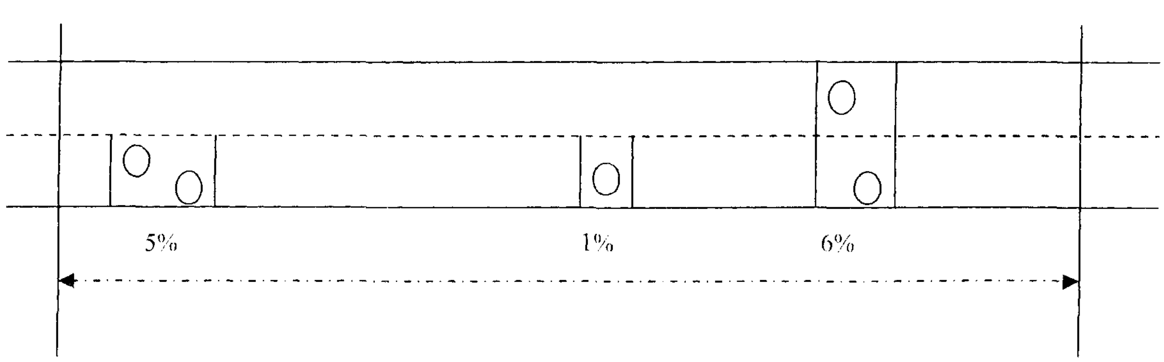

Figure 2.1 Intermittent Occurrence of Distress (Chong et al. 1989)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

1. Lack of bond between particles and mortar due to inadequate coating.
2. Fracture of the particles through load or natural causes, allowing the loosened pieces to be picked out by traffic action.
3. Disintegration of particles, such as chert, which are highly absorptive and disintegrate upon repeated freezing and thawing.
4. Delamination of chert or shale particles.
5. Clay coated aggregate particles.

2.3.1.1 Severity

Following are the guidelines to describe the severity of ravelling and loss of coarse aggregates (Chong et al. 1989).

Uniform Description	Guidelines (based on observation of appearance)
Very Slight	Barely noticeable.
Slight	Noticeable loss of pavement materials.
Moderate	Having pock-marked appearance, pock- marks are fairly well spaced.
Severe	Having pock-marked appearance, pock- marks are closely spaced.
Very Severe	Surface has a ravelled appearance and is disintegrated into large potholes or veined with moderate cracks.

2.3.2 Flushing

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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

to high asphalt content relative to void content in mineral aggregate.

2.3.2.1 Severity

Following are the guidelines to describe the severity of flushing (Chong et al. 1989).

Uniform Description	Guidelines (based on observation of appearance)
Very slight	Very faint colouring (veining).
Slight	Colouring visible (interconnected veining).
Moderate	Distinctive appearance (with excessive asphaltic materials already free).
Severe	Free asphaltic material giving the pavement surface area a wet look.
Very Severe	Free asphaltic material giving the affected pavement surface area a wet look and wheel noise comparable to that when driving over a water wet surface.

2.3.3 Rippling and Shoving

Regular transverse undulations in the surface of the pavement consist of closely spaced, alternate valleys and crests. Following are the possible causes:

1. Faulty paver behaviour with some mixes.
2. Heavy traffic on steep downgrade or upgrade, or pavement with too thick tack coat or too thick soft waterproofing membranes on the bridge decks.
3. Low stability in asphalt mix.
4. Stopping at intersection stop lights.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

2.3.3.1 Severity

Following are the guidelines to describe the severity of rippling and shoving (Chong et al. 1989).

Uniform Description	Guidelines (based on observation of appearance)
Very slight	Barely noticeable washboard effect.
Slight	Noticeable washboard effect.
Moderate	Rough ride
Severe Very	Very rough ride
Very Severe	Washboarding or large humps which cause vehicles to drift sideways and may cause loss of control of vehicles.

2.3.4 Wheel Track Rutting

Longitudinal depressions, which can take the form of single rut or double ruts, left in the wheel tracks after repeated load application. Wheel track rutting results from densification and permanent deformation under the load, combined with displacement of pavement material. Deep ruts are often accompanied by longitudinal cracking in the wheel tracks. Following are the possible causes:

1. Poorly-compacted structural layers.
2. Unstable granular bases or subbases created by positive pore water pressures under loads at the time of near-saturation.

2.3.4.1 Severity

Following are the guidelines to describe the severity of rutting (Chong et al. 1989).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Uniform Description	Guidelines (based on observation of appearance)
Very slight	Barely noticeable, less than 6mm.
Slight	6 to13mm with or without single longitudinal crack.
Moderate	14 to 19mm with or without single or multiple longitudinal cracks. Double rutting begins to develop.
Severe	20 to 50mm with or without longitudinal cracks, or double rutting developed.
Very Severe	Greater than 50mm single or double rutting with or without multiple longitudinal cracks or alligator cracks.

2.3.5 Distortion

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

2.3.5.2 Severity

Following are the guidelines to describe the severity of distortion (Chong et al. 1989).

Uniform Description	Guidelines (based on observation of appearance)
Very slight	Barely noticeable swaying of vehicle while in motion.
Slight	Barely noticeable pitch and roll, and jarring bump.
Moderate	Noticeable pitch and roll, and harsh bumps.
Severe	Continuous pitch and roll, and hard jarring bump.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Very Severe	Continuous distortion makes the driver to feel it is necessary to reduce speed.

2.3.6 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, and may be due to overloaded vehicles at the weakest pavement period, in the early spring (Chong et al. 1989).

2.3.6.1 Severity

Following are the guidelines to describe the severity of longitudinal wheel-track cracking (Chong et al. 1989).

Uniform Description	Guidelines (based on observation of appearance)
Very Slight	Single crack less than 3mm.
Slight	Single crack 3 to 12mm.
Moderate	Single crack 13 to 19mm. Multiple cracks even if less than 13mm.
Severe	Single or multiple cracks. Single crack 20 to 25mm with initial sign of spalling. Multiple cracks even if less than 20mm but greater than 13mm, with initial sign of spalling.
Very Severe	Single crack greater than 25mm with or without spalling. Multiple cracks even if less than 25mm but greater than 20mm, with or without initial sign of spalling.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

2.3.7 Longitudinal Meander and Mid-Lane Crack

Crack, usually quite 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. Following are possible causes:

1. Frost action-greater heave at pavement centre than at edges.
2. Poor construction practices.
3. Faulty construction equipment, resulting in weak plane which then fails, due to thermal shrinkage.

2.3.7.1 Severity

Following are the guidelines to describe the severity of longitudinal meander and mid-lane crack (Chong et al. 1989).

Uniform Description	Guidelines (based on observation of appearance)
Very Slight	Single crack less than 3mm.
Slight	Single crack 3 to 12mm.
Moderate	Single or multiple cracks. Single crack 13 to 19mm. Multiple cracks even if less than 13mm.
Severe	Single crack 20 to 25mm, with initial sign of spalling. Multiple cracks even if less than 20mm but greater than 13mm, with initial sign of spalling.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Very Severe	Single or multiple cracks. Single crack greater than 25mm, with or without spalling. Multiple cracks even if less than 25mm but greater than 20mm, with or without spalling.

2.3.8 Centre Line Crack

Crack which runs along or near the road centre line. Following are the possible causes:

1. Poor longitudinal joint construction.
2. Variable granular depths due to constructing lanes separately.
3. Moisture changes (swelling/shrinkage)

2.3.8.1 Severity

Following are the guidelines to describe the severity of centre line crack. (Chong et al. 1989).

Uniform Description	Guidelines (based on observation of appearance)
Very Slight	Single crack less than 3mm.
Slight	Single crack 3 to12mm.
Moderate	Single or multiple cracks. Single crack 13 to 19mm. Multiple cracks even if less than 13mm.
Severe	Single or multiple cracks. Single crack 20 to 25mm with initial sign of spalling. Multiple cracks even if less than 20mm but greater than 13mm with initial sign of spalling.
Very Severe	Single or multiple cracks. Single crack greater than 25mm, with or without spalling. Multiple cracks even less than 25 but greater than 20mm, with or without spalling.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

2.3.9 Pavement Edge Crack

Crack (or cracks) which is parallel to and within 30cm of the pavement edge, and is either a fairly continuous 'straight' crack or consists of crescent-shaped cracks in a wave formation. Following are the possible causes:

1. Frost action.
2. Insufficient bearing support and/or excessive traffic loading at the pavement edge.
3. Poor drainage at the pavement edge and shoulder.
4. Inadequate pavement width and traffic too close to pavement edge.

2.3.9.1 Severity

Following are the guidelines to describe the severity of pavement edge crack (Chong et al. 1989).

Uniform Description	Guidelines (based on observation of appearance)
Very Slight	Single longitudinal crack or single wave-formation crack less than 3mm and no more than 150mm from the pavement edge.
Slight	Single crack or two parallel cracks 3 to 12mm wide and less than 300mm from pavement edge.
Moderate	Extending over 300mm but less than 600mm from pavement edge. Multiple cracks begin to interweave with connecting cracks.
Severe	Extending over 600mm but less than 1500mm from pavement edge.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Very Severe	Progressive multiple cracks extend over 1500mm from pavement edge. Outermost area near edge is alligatored.

2.3.10 Transverse Crack

Crack which follows 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. Following are the possible causes:

1. Natural shrinkage caused by very low temperatures.
2. High temperature susceptibility of asphalt cement binder in asphalt mixes.
3. Frost action.

2.3.10.1. Severity

Following are the guidelines to describe the severity of transverse crack (Chong et al. 1989).

Uniform Description	Guidelines (based on observation of appearance)
Very Slight	Single crack less than 3mm.
Slight	Single crack 3 to 12mm.
Moderate	13 to 19mm single crack or multiple cracks even if crack opening is less than 13mm. Cracks starting to develop cupping or lipping.
Severe	20 to 25mm single crack or multiple cracks even if crack opening is less than 20mm but greater than 13mm. Cracks have developed cupping or lipping distortion.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Very Severe	Greater than 25mm single crack or multiple cracks even if crack opening is less than 25mm but greater than 20mm. Cracks are distorted with cupping and lipping, and spalling of the cracked edges.

2.3.11 Alligator Crack

Cracks which form a network of polygon block resembling the skin of an alligator. The block size can range from a few millimeters to about a meter. Following are the possible causes:

1. Insufficient bearing support.
2. Poor base drainage, and stiff or brittle asphalt mixes at cold temperatures.

2.3.11.1 Severity

Following are the guidelines to describe the severity of alligator crack (Chong et al. 1989).

Uniform Description	Guidelines (based on observation of appearance)
Very Slight	Multiple cracks begin to develop short interconnecting cracks. Distortion less than 13mm.
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 to 25mm.
Severe	Polygon blocks begin to lift. Small potholes. Distortion 26 to 50mm.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Very Severe	Polygon blocks lifting with different sizes of potholes. Distortion greater than 50mm.

2.4 Densities for Distress Manifestations

Following are the guidelines to describe the density of all above mentioned pavement surface distresses (Chong et al. 1989).

Uniform Description	Guidelines (based on percent of surface area in the pavement section being affected by the defect)
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	21 to 50% of pavement surface affected. May spot evenly over length of pavement section or over localized area only.
Extensive	51 to 80% of pavement surface affected. Spotted evenly over length of pavement section
Throughout	81 to 100% of pavement surface affected. Spotted evenly over length of pavement section.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 3: SURFACE DISTRESSES RATING

3.1 Introduction

The first manual (Chong et al. 1975) for condition rating of flexible pavements described only the severity and density of the distresses by word description. Later it was realized that the severities and densities of the distresses should be weighted to get a numerical value. The model for Distress Manifestation (DM) was developed by Phang et al. (1979) and the model for Distress Manifestation Index (DMI_I) was developed by Hajek et al. (1986) to evaluate the distress manifestations. The currently used model in PMS2 for revised Distress Manifestation Index (DMI) is described in Ningyuan et al. (2001). The scope of this chapter is to explain, how the visible distresses are converted into a numerical value to describe or rate the surface distresses.

3.2 Distress Manifestations (DM)

A systematic method for classifying and assessing the visible consequences of various distresses was described by Phang et al. (1979). Distress Manifestations (DM) classified the distress manifestations into 27 categories (Table 3.1), which were rated by severity and density. DM was calculated for each section of the road network by the model presented in Eq. 3.1.

$$\text{Distress Manifestations} = DM = \sum_{i=1}^{27} W_i (S_i + D_i) \qquad (3.1)$$

The DM was an overall characteristic describing the pavement surface condition on a scale of 0 to 320 where 0 for excellent pavement condition (no distress), and 320 for very poor pavement condition (maximum distresses).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

W_i = Weighting value for a particular type of crack or other form of pavement distress (Table 3.1).

S_i= Weighting value for severity of crack or other form of distress (Table 3.1).

D_i= Weighting value for density of occurrence of the particular crack type or other form of distress (Table 3.1).

3.2.1 Procedure for Determining Distress Manifestation (DM)

The basic procedure for classifying and rating pavement distresses was described by Phang et al. (1979). The value of DM was calculated based on measurements taken from the field survey. The evaluation was done by using the flexible pavement condition evaluation form (Table 3.1). Eventually, the DM was calculated by substituting weighting values (Table 3.1) in Eq. 3.1.

3.3 Distress Manifestation Index (DMI_1)

A systematic method for classifying and assessing the visible consequences of the various distresses was described by Hajek et al. (1986). It was designed to supersede the previously used DM. Distress Manifestation Index (DMI_1) classified distress manifestations into 15 categories, which were rated by the severity and the density. The model developed for the calculation of the DMI_1 has a similar structure to that used for calculating the DM (Phang et al. 1979), but the distresses were reduced to fifteen.

$$\text{Distress Manifestation Index } (DMI_1) = \sum_{i=1}^{15} W_i (S_i + D_i) \tag{3.2}$$

DMI_1 was an overall characteristic for describing the pavement distress manifestations on a scale of 0 to 205 where 0 for excellent pavement condition (no distress), and 205

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(maximum distresses) for very poor pavement.

W_i = Weighting value for a particular type of crack or other form of pavement (Table 3.2).

S_i= Weighting value for severity of crack or other form of distress (Table 3.2).

D_i= Weighting value for density of occurrence of the particular crack type or other form of distress (Table 3.2).

3.3.1 Procedure for Determining Distress Manifestation Index (DMI_1)

The basic procedure for classifying and rating pavement distresses described by Phang et al. (1979) was remained same, however only 15 separate distress categories were evaluated. The evaluation was done by using the flexible pavement condition evaluation form (Table 3.2) (Hajek et al. 1986). DMI_1 was calculated by substituting the field recorded data and the distress weighting values in Eq. 3.2. The DMI_1 was an integral part of the Pavement Condition Index (PCI_1) but it was used independently as the measurement of visible pavement distresses. The DMI_1 was used as a proxy for assessing pavement structural adequacy and identifying pavement sections that required a corrective action due to the specific distress condition (Hajek et al. 1986). The weighting values (W_i) were chosen using expert's opinion and calibration techniques.

For example, centerline alligator cracking has a W_i = 2, (Table 3.2) while longitudinal wheel track alligator cracking has a W_i =3. In other words, cracking in the wheel-track was considered to contribute 33% more to the DMI_1 than cracking along the centerline. The weighting values were not intended to capture pavement roughness components already accounted for the Riding Comfort Rating (RCR) (Chong et al. 1975). The weighting values of the 15 distresses given in Table 3.2 were also tested to ensure that the DMI_1 was equal to the previously used DM based on 27 distresses. All DM

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

recorded during the period from 1978 to 1985 have been converted to DMI_l. The R^2 of the linear relationship between the DM and the DMI_l was 0.938.

3.3.2 Revised Distress Manifestation Index (DMI)

It is same as DMI_l but its scale is revised from 0 to 10 where 10 represents flawless pavement (no distress), and 0 for very poor pavement (maximum distresses) (Ningyuan et al. 2001). It is currently used by the MTO in its PMS2.

$$\text{Revised Distress Manifestation Index (DMI)} = 10 * \frac{208 - \sum_{i=1}^{15} W_i (S_i + D_i)}{208} \tag{3.3}$$

W_i = Weighting value for a particular type of crack or other form of pavement distress (Table 3.2).

S_i= Weighting value for severity of crack or other form of distress (Table 3.2).

D_i= Weighting value for density of occurrence of the particular crack type or other form of distress (Table 3.2).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 3.1 Flexible Pavement Condition Evaluation or Checklist Form (Phang et al. 1979)

RIDING COMFORT RATING (AT 80 km/h)	EXCELLENT	GOOD	FAIR	POOR	VERY POOR
	10	8	6	4	2

				SEVERITY OF DISTRESS (S_i)					DENSITY OF DISTRESS (D_i)					
				VERY SLIGHT	SLIGHT	MODERATE	SEVERE	VERY SEVERE	FEW	INTERMITTENT	FREQUENT	EXTENSIVE	THROUGHOUT	
PAVEMENT DISTRESSES			Weight / No	0.5	1	2	3	4	0.5	1	2	3	4	W_i
SURFACE DEFECTS	COARSE AGG. LOSS		1											0.5
	RAVELLING		2											0.5
	FLUSHING		3											0.5
SURFACE DEFORMATION	RIPPLING		4											0.5
	SHOVING		5											0.5
	WHEEL-TRACK RUTTING		6											3.0
	DISTORTION		7											3.0
CRACKING	LONGITUDINAL WHEEL-TRACK	SINGLE	8											1.0
		MULTIPLE	9											1.5
		ALLIGATOR	10											3.0
	MID-LANE	SINGLE	11											0.5
		MULTIPLE	12											1.0
	CENTRE LINE	SINGLE	13											0.5
		MULTIPLE	14											1.0
		ALLIGATOR	15											2.0
	MEANDER	SINGLE	16											0.5
		MULTIPLE	17											1.0
	PAVEMENT EDGE	SINGLE	18											1.5
		MULTIPLE	19											1.0
		ALLIGATOR	20											1.5
	TRANSVERSE	PARTIAL	21											0.5
		HALF	22											0.5
		FULL	23											1.5
		MULTIPLE	24											2.0
		ALLIGATOR	25											3.0
	RANDOM		26											0.5
	SLIPPAGE		27											0.5

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 3.2 Flexible Pavement Condition Evaluation or Checklist Form (Hajek et al. 1986)

RIDING COMFORT RATING (AT 80 km h)	EXCELLENT	GOOD	FAIR	POOR	VERY POOR
	10	8	6	4	2

				SEVERITY OF DISTRESS (S_i)					DENSITY OF DISTRESS (D_i)					
				VERY SLIGHT	SLIGHT	MODERATE	SEVERE	VERY SEVERE	FEW	INTERMITTENT	FREQUENT	EXTENSIVE	THROUGHOUT	
PAVEMENT DISTRESSES			No. \ Weight	05	1	2	3	4	0.5	1	2	3	4	W_i
SURFACE DEFECTS	RAVELLING AND COARSE AGG. LOSS		1											3.0
	FLUSHING		2											0.5
SURFACE DEFORMATION	RIPPLING AND SHOVING		3											1.0
	WHEEL -TRACK RUTTING		4											3.0
	DISTORTION		5											3.0
CRACKING	LONGITUDINAL WHEEL -TRACK	S & M	6											1.0
		ALLIGATOR	7											3.0
	CENTRE LINE	S & M	8											0.5
		ALLIGATOR	9											2.0
	PAVEMENT EDGE	S &M	10											0.5
		ALLIGATOR	11											1.5
	TRANSVERSE	H. F & M	12											1.0
		ALLIGATOR	13											3.0
	LONGITUDINAL MEANDER AND MID-LANE		14											1.0
	RANDOM		15											0.5

S & M - Single and Multiple
H. F & M - Half, Full and Multiple

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 4: RIDE QUALITY RATING

4.1 Introduction

Ontario's pavement condition assessment method relies on the examination of two principal features: one is the riding quality and the other is distress manifestation. This chapter explains how the ride quality is measured presently and how it was measured in past in Ontario. The ride quality is the measurement of roughness on a Riding Comfort Rating (RCR) scale ranging from 0 to 10 where 10 represents a perfectly smooth surface, and 0 is very rough road. Roughness is defined as a distortion of the pavement surface that contributes to an undesirable or uncomfortable ride.

Pavement roughness is one of the most important indicator of the pavement performance that directly reflects the pavement serviceability to the road users. The RCR is a perceived measure of roadway roughness as experienced by the public. As a perceived measurement, RCR has been traditionally evaluated subjectively. However, the present mechanical and laser devices are enabled to give an objective, repeatable and reliable measurement. The RCR for the purpose of revised Pavement Condition Index (PCI) currently used by the MTO is established objectively from International Roughness Index (IRI).

4.2 Subjective Measurement of Riding Comfort Rating (RCR)

The riding quality or roughness of the pavement used by the MTO in the past was rated subjectively. The Riding Comfort Rating (RCR) assessment was carried out by the rater in a passenger car traveling at a standard speed of 80 km/h. The rater was usually the driver and the vehicle was normally one with which he was very familiar (Phang et al.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

1979). The rater marked the pavement on a scale ranging from 0 to 10 or any one from excellent, good, fair, poor, and very poor by comparing the summary description (Table 4.1). In recent years, systems have been developed that minimize the effects of human judgment and bias in surface condition rating, because these effects may lead to inconsistencies in the priority list that is used in funds allocation. The pavement ride quality can be measured with an acceptable level of consistency and repeatability through automation.

4.3 Introduction to Objective Measurement of Riding Comfort Rating (RCR)

Since 1986 to 1996, the MTO used Response Type Road Roughness Measurement System (RTRRMS) called Portable Universal Roughness Device (PURD) (MTO 1990) for periodic monitoring of pavement roughness for network-level pavement management. The PURD is manufactured by the Roadware Inc., that measures roughness in terms of Root Mean Square Vertical Acceleration (RMSVA) of a trailer axle.

The roughness measurement obtained by this device is referred to as PURD. In order to obtain RCR value objectively, the roughness was measured in the past by PURD and then converted to the RCR through a transfer function. With the switch to the International Roughness Index (IRI), it is necessary to convert IRI values back to the RCR (Hajek et al. 1998).

4.4 Roughness Study for Mays and PURD to Develop Models for Objective RCR.

Extensive pavement roughness measurements were carried out on the highway networks

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

of three districts of the MTO, Huntsville, Kingston and Stratford, in 1984. Both Mays and PURD measurement devices were used (Hajek et al. 1986). The three districts were selected with the intention of obtaining a province-wide representative sample of distress manifestations and roughness conditions associated with a variety of pavement structures, traffic, and the environmental exposures.

All asphalt concrete pavements on King's Highways in the three districts (about 3270 center line km) were included in the study. Two-lane highways were measured in one direction only, but divided highways were measured in both directions. The average roughness measurements were obtained for each highway section. The RCR was also determined subjectively by different raters in each district. All raters were experienced and familiar with their respective districts. The highway sections were considered to have a uniform pavement performance. The section length was ranged from 0.3 to 25.7 km with an average of 9.9 km. The total numbers of highway sections included in the study were 310.

4.4.1 Transfer Functions for RCR from Mays and PURD

The search for the best transfer function (Hajek et al. 1986) was done by formulating many promising mathematical models, relating the mechanically measured roughness with the subjective Riding Comfort Rating (RCR) and evaluating using the least square regression technique. The results for the two typical models formulation were a linear and a semi-logarithmic, summarized in Table 4.2 (Hajek et al. 1986) in terms of R^2. The results suggest that roughness measured by PURD correlate marginally better with the subjective RCR than the roughness measured by Mays Ride Meter. Also for the PURD,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4.1 Ride Comfort Rating (RCR) Guide (Chong et al. 1975)

RCR	Uniform Description of Ride Comfort Rating (RCR) at 80 km/h	Guidelines
8-10	Excellent	Very smooth ride.
6-8	Good	Smooth ride with just a few bumps or depressions.
4-6	Fair	Still comfortable ride with intermittent bumps or depressions.
2-4	Poor	Uncomfortable ride with frequent bumps or depressions
0-2	Very Poor	Uncomfortable ride with constant bumps or depressions resulting in rattle and shake of rating vehicle. Cannot maintain posted speed and must steer constantly to avoid bumps or depressions. Dangerous at 80 km/h.

Table 4.2 Evaluation of Roughness Transfer Functions (Hajek et al. 1986)

Roughness Device	MTO Districts	No. of Observations	R^2 (1)	
			Linear (2)	Semi Log (3)
PURD 1985-1996	Huntsville Kingston Stratford All three District Combined	55 132 123 310	0.410 0.452 0.424 0.403	0.439 0.469 0.439 0.413
MAYS	Huntsville Kingston Stratford All three District Combined	55 132 123 310	0.454 0.530 0.390 0.401	0.450 0.512 0.400 0.378

1 Squared multiple correlation coefficient
2 Linear form= C_0+C_1 (device response)
3 Semi logarithmic form = $C_0+C_1 * \log_{10}$ (device response)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

the semi-logarithmic model formulation is marginally better than the linear one. For the Mays Ride Meter, the linear model formulation appears to be marginally better. Based on the results of the roughness study, the following transfer functions were recommended (Hajek et al. 1986):

a) Portable Universal Roughness Device (PURD I)

$$\text{Riding Comfort Rating (RCR)} = 14.85 - 6.18 * \log_{10}(\text{PURD I}) \tag{4.1}$$

$$\text{PURD I} = \frac{\sum_{i=1}^{n} SV}{n} \tag{4.2}$$

n= Numbers of 50m segments contained in the highway network.

SV=Slope Variance computed from profile elevations on 50m long segments (Joseph et al. 1984). Slope Variance (SV) is a method of profile analysis (Queiroz 1981)

$$SV = \frac{\sum_{i=1}^{n} \theta_i^2 - \frac{1}{N}\left(\sum_{i}^{n} \theta_i\right)^2}{n-1} \tag{4.2a}$$

b) Mays Ride Meter

$$\text{Riding Comfort Rating (RCR)} = 9.38 - 0.0177(\text{MAYs}) \tag{4.3}$$

$$\text{MAYs} = \frac{\sum_{i=1}^{n} RAM}{n} \tag{4.4}$$

RAM = Relative axle movement as defined in Loughnan and Evers (1980) obtained for 0.8 km long segment.

n = numbers of 0.8 km long segments contained in the highway network.

In order to achieve the long-term stability in measuring the objective RCR, the roughness measuring equipment must be carefully calibrated and any unavoidable change in its mechanical components must be noted to assess their influence. The use of the two

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

roughness measurement devices and their respective transfer functions will yield on the average, the same objective RCR as assigned subjectively. However, for the individual pavement section, there may be considerable difference between the objectively and subjectively assigned RCR. Furthermore, there is also a difference between the RCR obtained by different roughness measurement devices. For example, R^2 for a linear model relating Mays and PURD was 0.80 (Hajek et al. 1986).

This indicates that 20% of the variance between the two models was not explained by the model. The unexplained variance can be caused by the difference in the measured physical responses, difference in the equipment (e.g., tire type, weight and suspension of trailers), and by the other factors. At any rate, in order to obtain the reliable and historically stable roughness measurements, only one type of roughness measurement device should be used for establishing the RCR. It should be noted that the function relating to the new PURD is in Root Mean Square Vertical Acceleration (RMSVA).

$$\text{Riding Comfort Rating (RCR)} = 27.6 - 7.51 \log(\text{PURD})$$

$$= 27.6 - 7.51 \log(\text{RMSVA}) \qquad (4.5)$$

4.4.1.1 Root Mean Square Vertical Acceleration (RMSVA)

Root Mean Square Vertical Acceleration (RMSVA) was initially proposed by McKenzie and Srinarawat (1978) to summarize profilometer data. It is defined as the root mean square ratio of the change of adjacent profile slopes to the distance between the spaced points. The slope is defined as the ratio of the elevation change to the corresponding horizontal distance of the selected interval (Fig 4.1). Algorithm for RMSVA is as follows (Joseph et al. 1984).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Slope at A = $\frac{Y_A - Y_B}{\Delta s} = |\theta_1|$ since θ_1 is small

Slope at B = $\frac{Y_C - Y_B}{\Delta s} = |\theta_2|$.

Change of Slope = $\theta_2 - \theta_1 = \Delta\theta = \frac{Y_C - Y_B + Y_A - Y_B}{\Delta s}$

Ratio of slope to the distance is given by,

$\frac{\Delta\theta}{\Delta s} = \frac{(Y_C - Y_B) - (Y_B - Y_A)}{\Delta s^2}$, $\frac{\Delta\theta}{\Delta s}$ is the estimate of second derivative.

Δs = sample length

$$\text{Thus RMSVA} = \left[\sum_{i=2}^{n-1}\frac{\left(\frac{\Delta\theta}{\Delta s}\right)^2}{n-2}\right]^{\frac{1}{2}} \tag{4.6}$$

$$= \sum_{i=2}^{n-1}\left[\frac{\{(Y_{i+1} - Y_i) - (Y_i - Y_{i-1})\}^2 / \Delta s^4}{n-2}\right]$$, where n= numbers of profile elevations

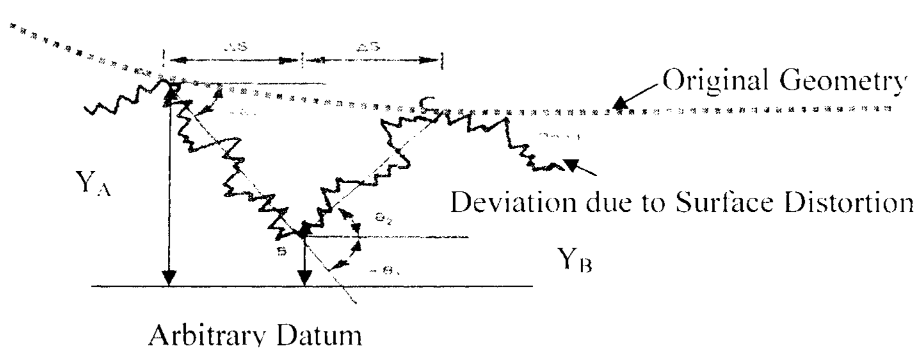

Figure 4.1 Representation of Pavement Profile for Root Mean Square Vertical Acceleration (RMSVA) Analysis (Joseph et al. 1984)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 5: INTERNATIONAL ROUGHNESS INDEX (IRI)

5.1 Introduction

Since 1997, MTO has used International Roughness Index (IRI) to measure roughness (Hajek et al. 1998). It is computed from a longitudinal profile measurement using quarter car simulation at a speed of 80 km/h (ASTM 1997) The IRI is a measurement scale for pavement roughness based on the response of a generic motor vehicle to a single longitudinal profile of the road surface. The IRI was developed (Hajek et al. 1998) in 1986 using the results of the international road roughness experiments held in Brazil in 1982 (Sayers 1995). Since then, the IRI has become a well recognized standard for measuring road roughness. The source code for calculating the IRI is described in Sayers (1995).

Details on the calculation of the IRI are given in Sayers (1995) and Sayers et al. (1986). Sayers (1995) also contains discussion on some of the unresolved IRI measurement issues which include location of the profile in the traveled lane, width of the profile (optical system can measure a path about 150mm wide rather than a line), length of profile, and the influence of cracks. It should be noted that some agencies report IRI values which are not obtained from the actual pavement profile measurements but from Root Mean Square Vertical Acceleration (RMSVA) measurements are converted to IRI values through a calibration procedure.

5.1.1 Advantages of Using International Roughness Index (IRI)

A standardized roughness measurement procedure has many advantages for a highway agency as summarized by Hajek et al. (1998).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

1. General Applicability of Results: The profile-based IRI is a geographically transferable and time-stable standard for the measurement of road roughness. The results of the studies undertaken by one jurisdiction and reported in the standard IRI units can be directly transferable and usable by other agencies. This applies to the studies in the areas such as pavement roughness comparison and pavement performance modeling.

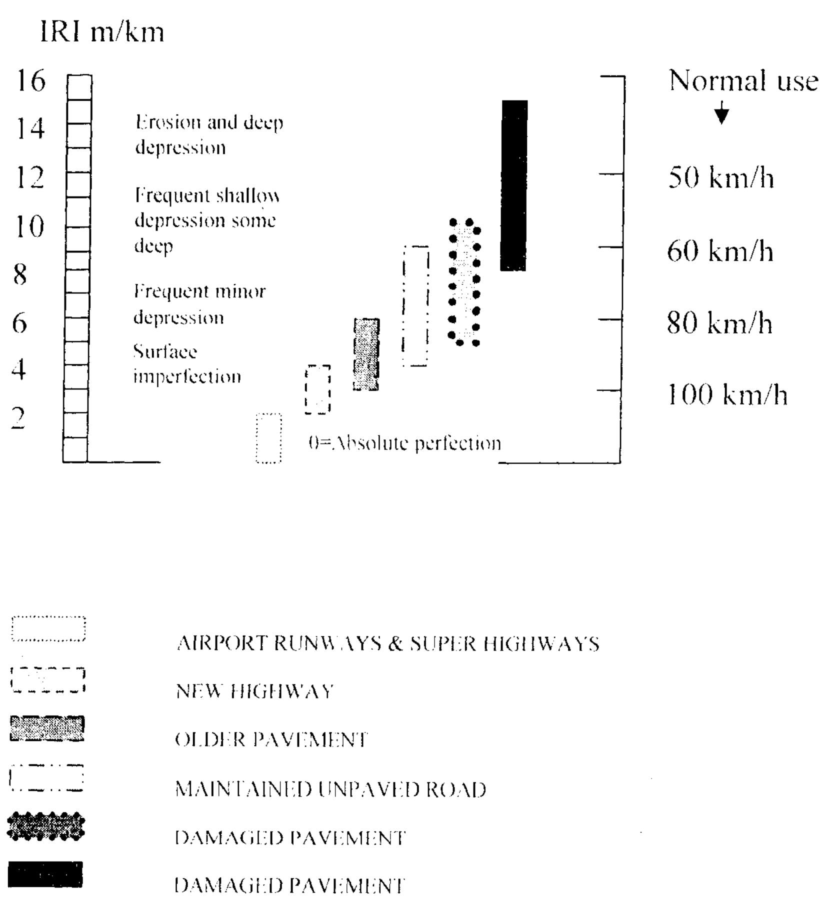

Figure 5.1 Scale for IRI (TAC 1997)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

2. Equitable Allocation of Resources: Adoption of IRI by large highway agencies encourages local transportation agencies to use IRI as well. A general use of IRI leads to more equitable allocation of pavement preservation funds since the pavement serviceability could be directly compared across the jurisdictional boundaries.
3. Cost Effectiveness: There are numerous companies that can measure IRI. Highway agencies can contract out roughness measurements through competitive bidding process.

5.1.2 Common Roughness Measurement Methods

Following are the commonly used devices to measure the profile and then IRI (TAC 1997). With the help of transfer functions, the IRI can be converted to Riding Comfort Rating (RCR).

Class 1 Precision Profiles (Most Accurate)

Digital Increment Profiler (Dipstick)

Rod and Level

Transport Research Laboratory (TRL) Profilometer

Class 2 Profilometric Methods

Automatic Road Analyzer (ARAN)

Profilograph

Dynatest Model 5051 RSP Laser Test System

K.J Law Inertial Profilometer

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Longitudinal Profile Analyzer (France)

Road Surface Tester (Laser RST) Sweden

Road Tester 3000

South Dakota Road Profiler

Class 3 Response Type Devices

K.J Law Model 8300 Roughness Surveyor

Mays Ride Meter (also a trailer version)

Portable Universal Roughness Devices (PURD)

Walker Roughness Device

Class 4 Subjective Rating (Least Accurate)

Riding Comfort Rating (from panel rating)

5.2 Methodology to Switch to IRI from PURD

It is explained here, how to switch to International Roughness Index (IRI) from Portable Universal Roughness Device (PURD) without losing MTO's historical data taken by the PURD (Hajek et al. 1998). A study was performed that addressed the following specific concerns (Hajek et al 1998):

1. Consequences of measuring IRI by using different equipments.
2. The ability of IRI to predict user's perceptions of the pavement roughness in terms of Ride Comfort Rating (RCR) for both car and truck occupants.
3. The development of a transfer function between IRI and RCR which would replace the transfer function between PURD measurements with RCR.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

5.2.1 Calibration Circuit Measurements for Methodology

The pavement sections in calibration circuit were selected to represent a variety of pavement types and pavement conditions (in terms of surface distress and roughness) typical for MTO highway network. The calibration circuit consisted of ten typical pavement sections that were used to compare the following subjective and objective methods:

a) Subjective Roughness Measurement

Two types of subjective measurements were used by Hajek et al. (1998).

1. Car based Ride Comfort Rating (RCR) by a panel of 16 raters. All the raters were MTO employees. The raters traveled in a passenger car, two per car.
2. Truck based Ride Comfort Rating (RCRT) done by a panel of two raters travelling in a three axle truck with semi trailer loaded up to 50% of its allowable load. It should be viewed as an indicator of truck Ride Comfort Rating .The variation in truck configuration is much greater than the car.

b) Objective Roughness Measurements

1. Profile based International Roughness Index (IRI) measurements by three different inertial profilers were used by three different companies, class II and class III, as described in specifications by American Society for Material and Testing (ASTM E950-94). The basic parameters of profilers are summarized in Table 5.1 (Hajek et al. 1998) and are denoted A, B and C in this report.
2. Portable Universal Roughness Device (PURD) was used to measure the roughness.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

5.2.2 Operation

The three companies conducting International Roughness Index (IRI) measurements operated under the following instructions.

1. The measurements were conducted in the fall, preferably in October or November.
2. Three consecutive measurements were taken on each section. The pavement sections used in this study were not surveyed using contact profiling devices of class I (ASTM E950-94).

5.2.3 Consequences of Measuring IRI Using Difference Devices

One objective of the study conducted by Hajek et al. (1998) was to assess the consequences of using different International Roughness Index (IRI) equipments. It should be noted that the objective was not to assess, compare or to improve the accuracy of the existing IRI equipment. The difference in the IRI measurements obtained by the three systems is illustrated in Fig. 5.2. This figure compared the average IRI measurement (average of the two wheel paths for the three runs) obtained for all ten sections of the calibration circuit by the three IRI measuring system. The average difference between the systems seldom exceeds 0.4 m/km.

It is also apparent, that the different systems systematically provide lower or higher values. The overall mean values obtained from all sections (and runs) by three IRI measuring systems were 1.57m/km, 1.84m/km and 1.90 m/km. On the other hand, the R^2 correlations between the three IRI measuring systems were in a very high range of 0.95 to 0.98. Similar results were reported by Asnani et al. (1993) who compared the differences

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

in the IRI measurements obtained by different versions of the South Dakota road profilers. The following observations are based on data presented in Fig. 5.2 (Hajek et al. 1998):

1. All the three IRI measuring systems evaluated in this study appear to be equally capable of providing reliable roughness measurements for network-level monitoring purposes and the systems correlate very well with each other.
2. IRI measurements obtained with any of the three IRI systems were repeatable.
3. There was significant difference between the IRI systems, which can negatively affect monitoring of pavement performance trends, on a network-level and a project (section level). The system cannot be used interchangeably and must be calibrated to match the existing historical roughness measurement scale RCR.
4. To maintain the historical validity of roughness data, it is important that a switch from the existing roughness measurement procedure to IRI measurements should be based on transfer function obtained by extensive comparative analysis.
5. The ability of IRI (Hajek et al. 1998) to predict the RCR is better than Portable Universal Roughness Device (PURD) with Root Mean Square Vertical Acceleration (RMSVA). R^2 for IRI was 0.72 to 0.87 (Figs. 5.3, 5.4, and 5.5), and R^2 for PURD was 0.67 (Fig. 5.6) (Hajek et al. 1998).
6. The ability of IRI to predict the Ride Comfort Rating for Trucks (RCRT) was similar to its ability to predict RCR for cars (Fig. 7).
7. There is little difference in transfer function for Southwestern and Northwestern regions (Fig. 5.8) (Hajek et al. 1998)
8. The transfer function between IRI and RCR for Ontario is shown in Fig. 5.9 and Eq. 5.1 (Hajek et al. 1998).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 5.1 Selected Parameters for Inertial Profilers (Hajek et al. 1998)

Parameter	IRI Measuring System		
	A	B	C
ASTM E 950-94 Class	II	II	III
Sensor Type	Inertial Accelerometer and Transducer Light Sensors	Inertial Accelerometer and Laser	Inertial Accelerometer and Acoustic Ultrasound
Wheel Path	Both	Both	Both
Distance Between Wheel Path	1.650 m	N/A[1]	1.650 m
Longitudinal Sampling	< 150mm	< 150mm	<300mm
Test Speed	80 km/h	80 km/h	80 km/h

N/A[1] Not Available

Table 5.2 Transfer Functions for IRI and PURD (Hajek et al. 1998)

Pavement Type	Roughness Statistics	Number of Observations	Transfer Function	R^2	Equation No
Asphaltic Concrete Pavement	IRI	787	$RCI=RCR=8.52-7.49*Log_{10}(IRI)$	0.652	(5.1)
	PURD	787	$RCR=27.6-7.51*Log_{10}(PURD)$	0.572	(5.2)
Composite Pavement	IRI	135	$RCR=8.48-3.81*Log_{10}(IRI)$	0.201	(5.3)
	PURD	135	$RCR=9.83-0.0035*Log_{10}(PURD)$	0.301	(5.4)
Exposed Concrete Pavement	IRI	30	$RCR=9.27-6.22*Log_{10}(IRI)$	0.509	(55)
	PURD	30	$RCR=119*(PURD)^{-0.421}$	0.478	(5.6)
Surface Treated Pavement	IRI	233	$RCR=15.7e^{-0.307}$	0.062	(5.7)
	PURD	233	$RCR=7.57e^{-0.0000221(PURD)}$	0.032	(5.8)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

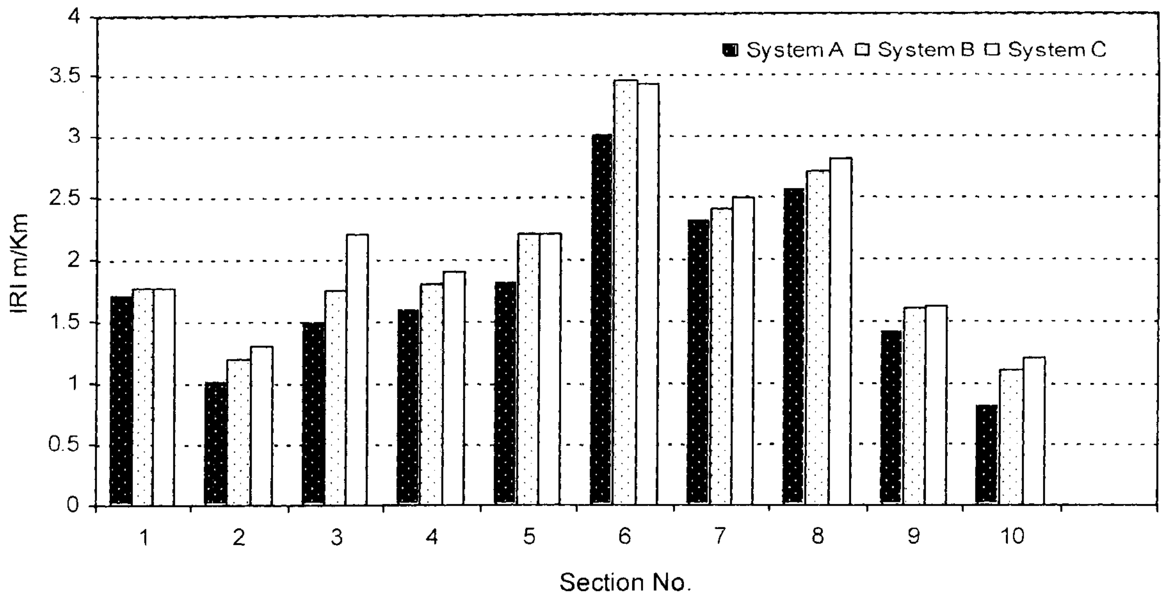

Figure 5.2 Difference Between IRI Systems (Hajek et al. 1998)

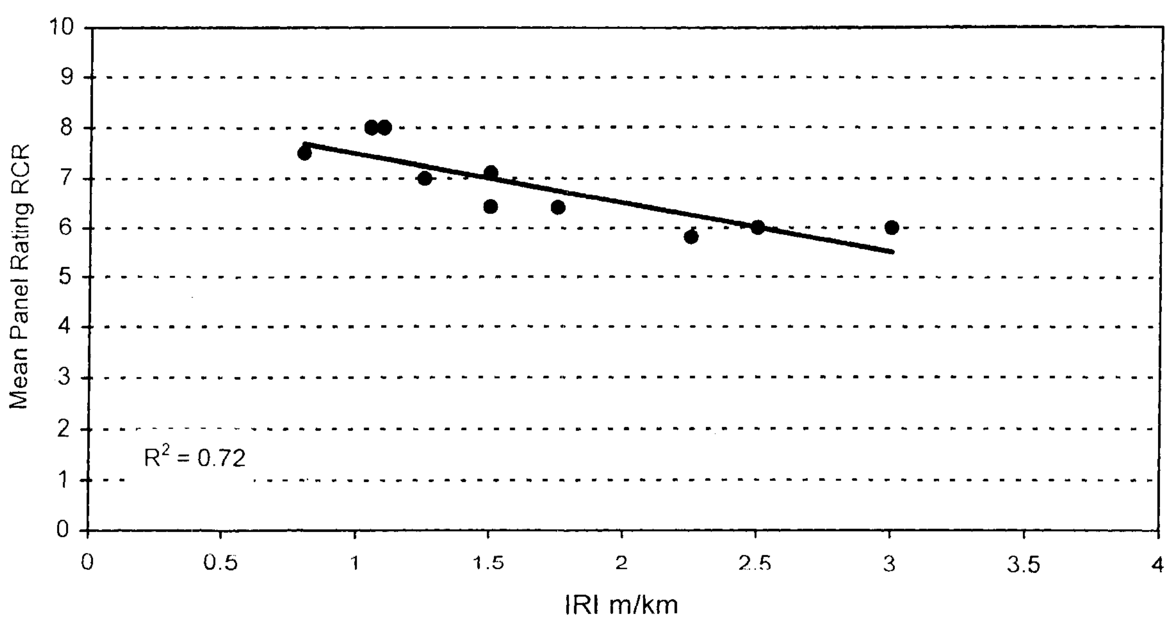

Figure 5.3 IRI System A vs. RCR (Hajek et al. 1998)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

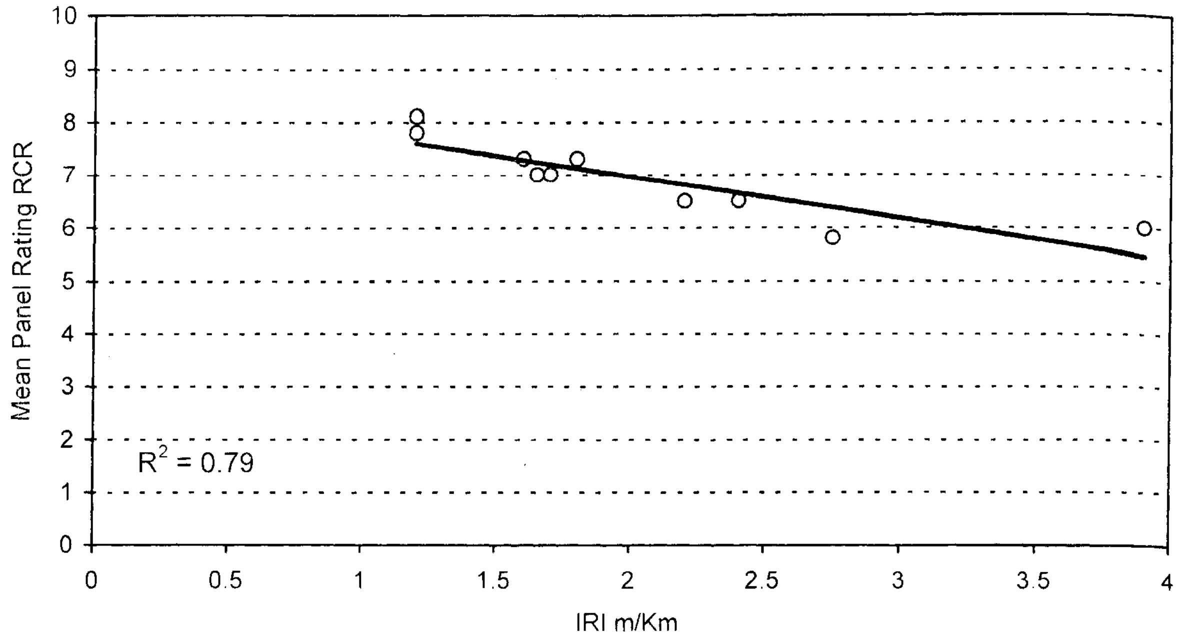

Figure 5.4 IRI System B vs. RCR (Hajek et al. 1998)

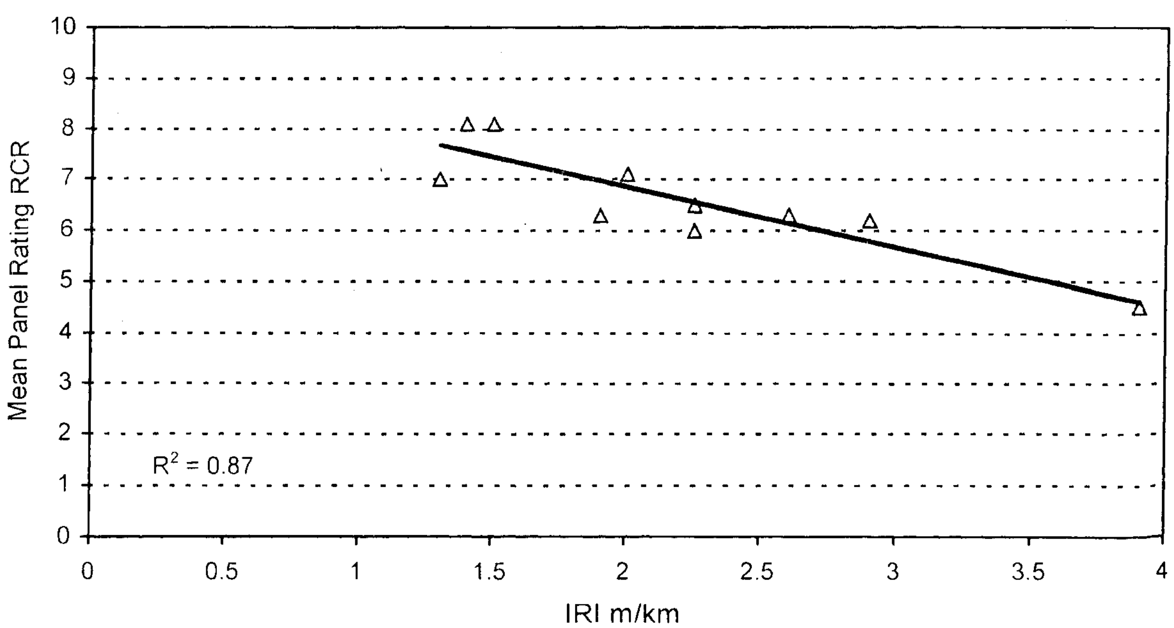

Figure 5.5 IRI System C vs. RCR (Hajek et al. 1998)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

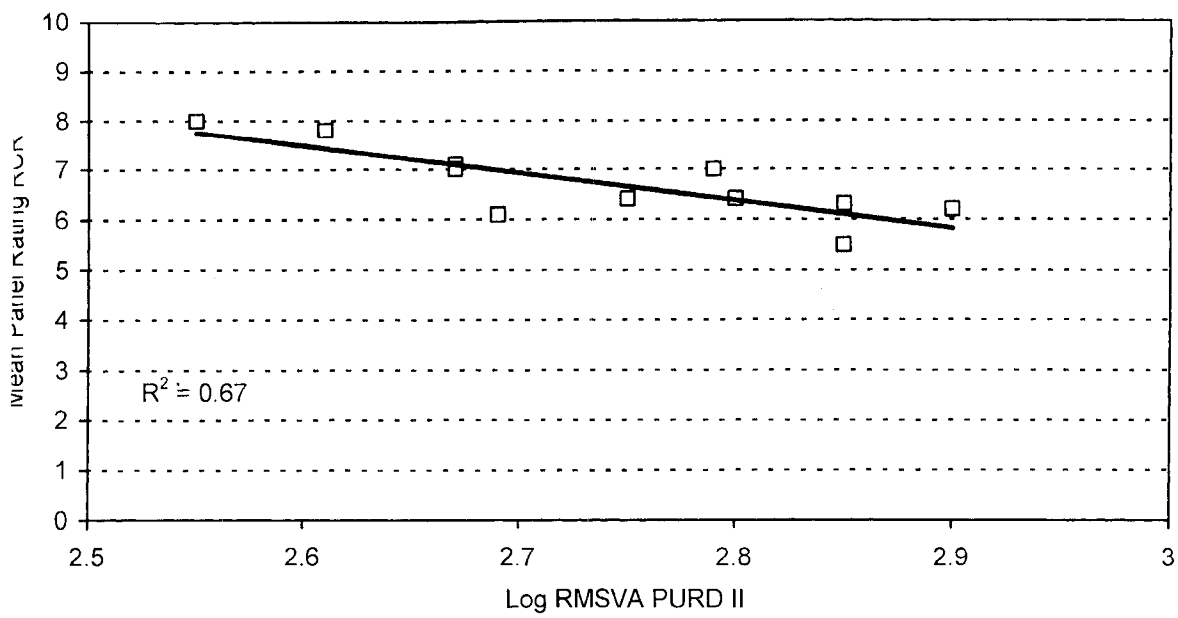

Figure 5.6 PURD vs. RCR (Hajek et al. 1998)

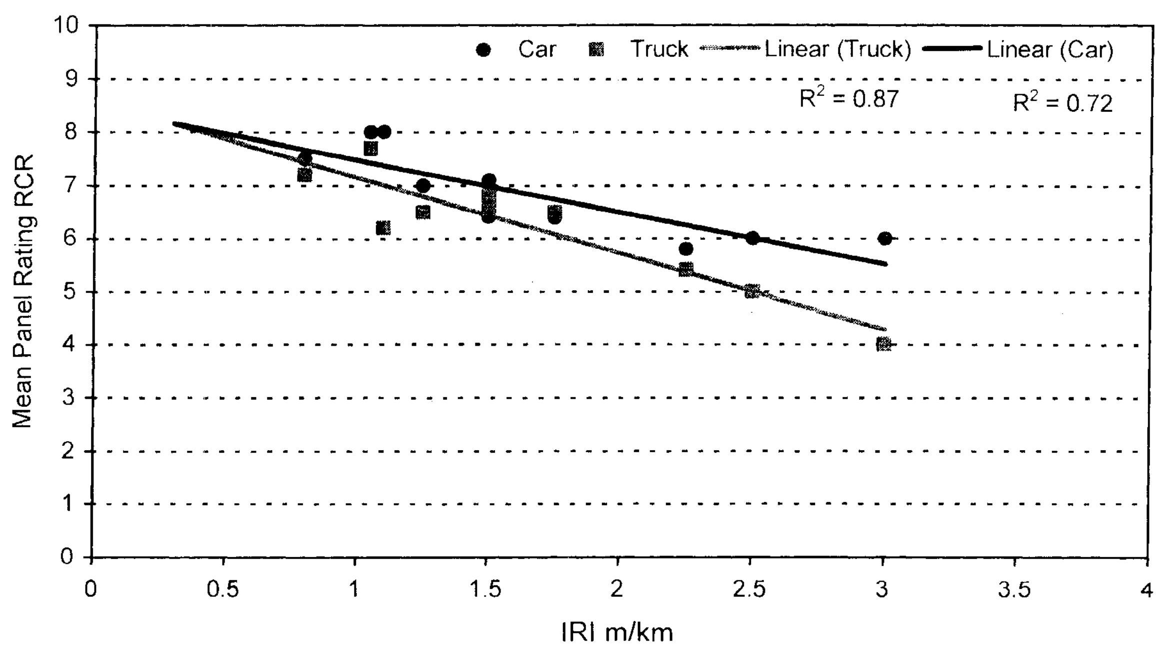

Figure 5.7 Comparison of RCR (Car) and RCRT (Truck) for IRI System A (Hajek et al. 1998)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

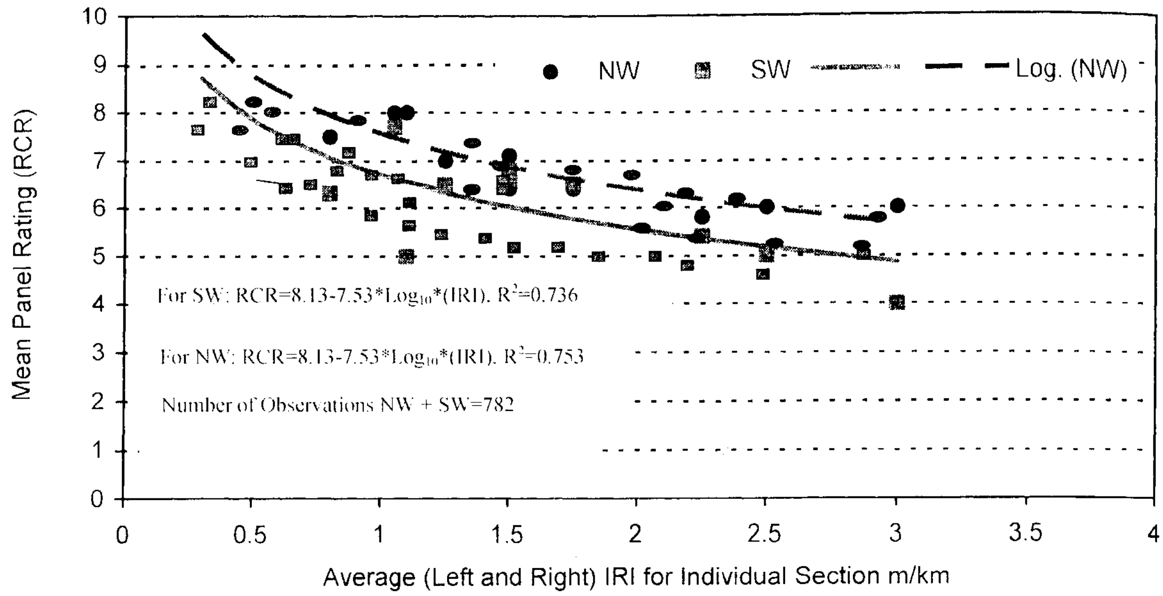

Figure 5.8 Comparison of Transfer Functions for Southwestern and Northwestern Regions (Hajek et al. 1998)

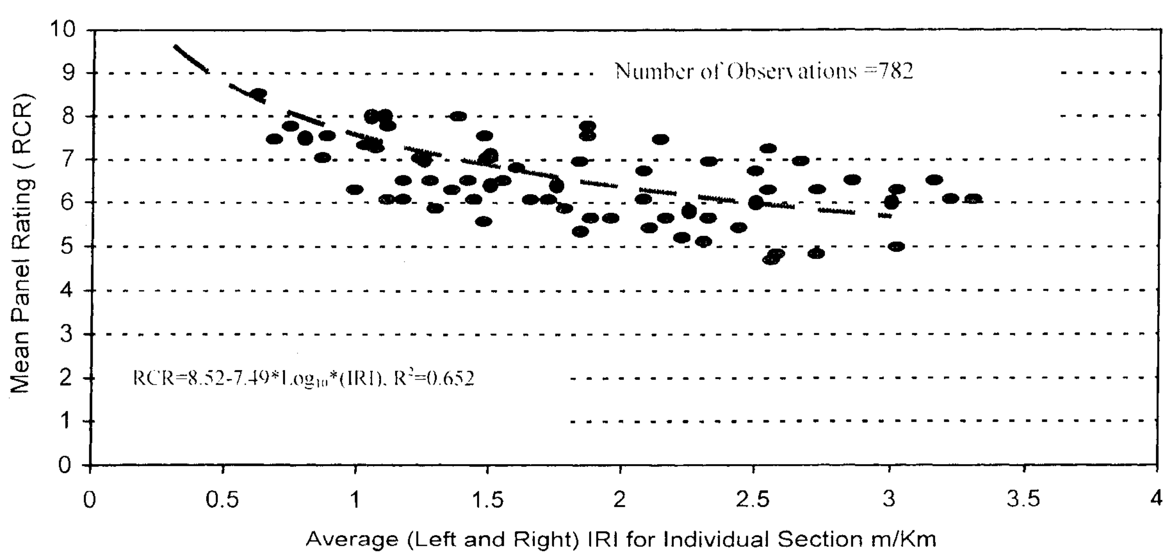

Figure 5.9 IRI Transfer Function for Asphalt Concrete (Hajek et al. 1998)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

5.2.4 Influence of Wheel Path, Lane Selection and Cracking on IRI Measurements

Influence of wheel path, lane selection, and cracking on International Roughness Index (IRI) measurements is described in Hajek et al. (1998). The IRI is defined as a property of a single wheel path profile. There are no strict guidelines regarding where the profiles should be located and how many of them should be used. The general recommendation is that the profiles should be measured in the two wheel paths with the IRI values for each being averaged to obtain a summary IRI for the traffic lane (Sayers 1995). IRI measured by profilers equipped with laser sensors may be influenced by the presence of cracks, particularly transverse cracks, even if the pavement on both sides of the crack is level (Sayers 1995). This can occur because the crack opening is detected by the profiler and appears as a negative spike in the profile.

5.2.5 Quality Assurance of IRI Network Measurements

Since 1997, MTO has established a pavement testing circuit for calibrating pavement roughness measurements to take into account variations and errors that may be caused by various factors (Kazmierowski et al. 2001). As of May 2000, a total of 12 pavement sections were selected for calibration measurement purposes, including eight asphalt concrete sections, two jointed Portland cement concrete sections and two surface treated sections.

The length of individual pavement sections selected for IRI measurement calibration ranges from 1.0 km to 2.5 km with approximately uniform roughness over the length. Care was taken to select sites with similar roughness levels on both wheel paths. The goal was to identify road sections with minimum variability in IRI over their lengths.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The calibration sites were located on road sections that were not planned for immediate rehabilitation. It was required that contractors specify in the bidding document the type of roughness profile measuring device to be used and the accuracy level of the device when calibrated to a Class I survey device such as a Dipstick (TAC 1997). In addition, the following five individual calibration measurements are required as a part of quality assurance process (Kazmierowski et al. 2001):

1. Pre-contract Qualification Calibration
2. Initial Calibration
3. Mid-survey Calibration
4. Post-survey Calibration
5. Final Calibration

5.2.5.1 Pre-contract Qualification Calibration

To ensure that contractor meets the basic qualification requirements, pre-contract calibration measurement is required as part of the bidding process for IRI measurements. It is imperative that pre-contract calibration be performed with the same equipment to be used for the rest of the survey work.

5.2.5.2 Initial Calibration

The selected contractor was required to conduct the initial calibration prior to the start of the production surveys. In the event the calibration data is found unacceptable, the contractor would be required to repeat the initial calibration at no extra cost to the Ministry. Actual survey should not proceed until such time as the Ministry finds the initial calibration results satisfactory.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

5.2.5.3 Mid-survey Calibration

Upon completing half of the network International Roughness Index (IRI) measurements, a mid-survey calibration is to be performed. Further survey work should not proceed until such time as the Ministry finds the mid-survey calibration results satisfactory. At any rate, the contract shall not carry out more than 60% of the entire survey before providing the Ministry with satisfactory mid-survey calibration results.

5.2.5.4 Post-survey Calibration

Upon completing the entire survey, the contractor should repeat the calibration procedure and submit the calibration results to the Ministry within three working days. If the calibration results fail to meet the criteria for the acceptance, it will be the contractor's responsibility to provide satisfactory results, which may include repeating some or all of the previous measurements. Remaining survey work shall not proceed until such time as the Ministry finds the post-survey calibration results satisfactory.

5.2.5.5 Final Calibration

The final calibration was required to ensure year-to-year consistency of the survey data. The results of the final calibration shall be submitted within five working days. If the calibration results fail to meet the criteria for acceptance, it will be the contractor's responsibility to repeat the calibration survey at no extra cost to the Ministry until the calibration results meet the acceptability criteria.

5.2.5.5 Monitoring Site Surveys

The contractor's measurements of pavement roughness were monitored during the production surveys using about 30 monitoring sites that were randomly selected

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

throughout the network. The contractor was informed within one working day when the survey crew had passed over a monitoring section. It was required that the contractor submit to the Ministry the monitoring section's International Roughness Index (IRI) summary results (i.e., average IRI value for the monitoring section) within three working days following the notification by the Ministry. If there was a large unexplained discrepancy between the IRI values reported by the contractor and those obtained by the Ministry (e.g., a difference greater than 20%), then investigation and detailed analysis would be required.

5.2.6 Conclusions

1. The International Roughness Index (IRI) has become a well recognized standard for measurement of road roughness.
2. $RCR=8.52-7.49*Log_{10}(IRI)$ currently used by the MTO (Hajek et al. 1998).
3. The use of standardized IRI by a highway agency has several advantages. It can provide direct transferability and utilization of knowledge and direct comparison of pavement conditions across jurisdictional boundaries. The use of IRI also enables highway agencies to solicit IRI (Hajek et al. 1998) measurement services from different suppliers and to obtain actual pavement profiles for project level work.
4. The ability of the IRI (Hajek et al. 1998) to predict Ride Comfort Rating (RCR) was found to be better than that achieved by Portable Universal Roughness Device (PURD).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Chapter 6: PAVEMENT PERFORMANCE RATING

6.1 Introduction

Pavement performance is a combination of the surface distresses (as described in chapters two and three) and the ride quality (as described in chapters four and five). Traditionally, pavement performance has been defined as an indicator of how well the pavement serves the travelling public. The pavement performance evaluation can be measured subjectively and objectively. Subjectively, it is measured according to the guidelines as mentioned in Table 6.1. Objectively, it is/was measured by the MTO with the different indexes: Distress Index (DI) (1979-1986) developed by (Phang et al 1979), Pavement Condition Index (PCI_I) (1986-2001) developed by (Hajek et al 1986), and revised Pavement Condition Index (PCI) (2001-present) developed by Ningyuan et al 2001. This chapter presents the historical development of these pavement rating indexes along with their influence, and their usage to evaluate pavement performance.

6.2 Procedure for Subjective Pavement Evaluation

The guidelines for the estimation of Pavement Condition Rating (PCR) for flexible pavements are described in Table 6.1. For the flexible pavement, eight stages in the life of pavement have been identified by the word description of ride quality, distortion and the range of rating numbers appropriate to each stage has been assigned. The raters compare their evaluation of RCR, distortion and distresses with the standard description of the stages (Table 6.1) and then decide which stage most closely fits the pavement being rated and whether the pavement is closer to the top or the bottom of the range for the stage (Chong et al. 1975).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 6.1 A Guide for the Estimation of Pavement Condition Rating (PCR) (Chong et al. 1975)

Reconstruct within 2 years	0-20	Pavement is in poor to very poor condition with extensive severe cracking, alligatoring and dishing. Rideability is poor and the surface is very rough and uneven.
Reconstruct in 2 - 3 years	20 - 30	Pavement is in poor condition with moderate alligatoring and extensive severe cracking and dishing. Rideability is poor and the surface is very rough and uneven.
Reconstruct in 3 - 4 years	30-40	Pavement is in poor to fair condition with frequent moderate alligatoring and extensive moderate cracking and dishing. Rideability is poor to fair and surface is moderately rough and uneven.
Reconstruct in 4 - 5 years or resurface within 2 years with extensive padding	40- 50	Pavement is in poor to fair condition with frequent moderate cracking and dishing and intermittent moderate alligatoring. Rideability is poor to fair and surface is moderately rough and uneven.
Resurface within 3 years	50-65	Pavement is in fair condition with intermittent moderate and frequent slight cracking and with intermittent slight or moderate alligatoring and dishing. Rideability is fair and surface is slightly rough and uneven.
Resurface in 3- 5 years	65- 75	Pavement is in fairly good condition with frequent slight cracking, slight or very slight dishing and a few areas of slight alligatoring. Rideability is fairly good with intermittent rough and uneven sections.
Normal maintenance only	75- 90	Pavement is in good condition with frequent very slight or slight cracking. Rideability is good with a few slightly rough and uneven sections.
No maintenance required	90 - 1 00	Pavement is in excellent condition with few cracks. Rideability is excellent with few areas of slight distortion.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The rater next assigns the PCR value to the rated pavement as described in Table 6.1. Because the rater also does the pavement design work, this rating is influenced by his or her perception of the need for maintenance and rehabilitation. The rater also has to consider at the time of inspection, what and when rehabilitation may be needed (Column 1 Table 6.1). He is thus alerted, at the time of inspection, to the need for closer examination where necessary in order to make recommendation for remedial measures.

The PCR assessment is made by one, two or more persons as available for the task. The PCR is the average value from these raters. The assessments are made in each five regions of the province by the engineering staff of the geotechnical department. Assessment is generally made in the late spring and early summer. Training circuits are established in the regions to maintain the standard assessment methods through the periodic calibration of the staff members. The circuit is also used for the training of new and inexperienced staff members (Chong et al. 1982).

6.3 Distress Index (DI)

Distress Index (DI) was developed by Phang et al. (1979). It was a measurement of pavement performance. It was used by the MTO from 1979 to1986. The DI was comprised of subjective RCR and Distress Manifestation (DM). The DI was calculated by using the following model.

$$\text{Distress Index (DI)} = 100 * [(RCR/10)]^{0.5} \frac{[320 - DM]}{320} \tag{6.1}$$

The DI was rated on a scale from 0 to 100 where 100 meaning excellent and 0 for very poor pavement condition. The RCR (Phang et al. 1979) was calculated subjectively (chapter four). The DM is calculated by using from Eq. 3.1 (Phang et al. 1979). The DI

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

calculated by using Eq. 6.1 was then compared with the Pavement Condition Rating (PCR) (Chong et al. 1975) assigned by the raters. The effect of DM on DI was investigated by Chong et al. (1982).The results indicated that on a province-wide basis, DM values were generally less than 100 and the effect on DI was not exceed 30% (Table 6.2).

6.4 Pavement Condition Index (PCI_I)

Pavement Condition Index (PCI_I) was developed by Hajek et al. (1986). It was a measurement of pavement performance. It was used by the Ministry from 1986 to 2001. The PCI_I was calculated by using the following model (Hajek et al. 1986).

$$\text{Pavement Condition Index } (PCI_I) = 100(0.1*RCR)^{0.5}\frac{[205-DMI_I]}{205}*c+s \qquad R^2=0.72 \quad (6.2)$$

The PCI_I was rated on a scale from 0 to 100 where 100 meaning excellent and 0 for very poor pavement condition. Riding Comfort Rating (RCR) was calculated using Eq. 4.5 (Hajek et al. 1986) i.e., it was based on Portable Universal Roughness Device (PURD) (TAC 1990) measurements. If the PURD (TAC 1990) derived RCR (Hajek et al. 1986) was not available, subjectively assigned RCR (Chong et al. 1975) may be substituted, to approximate PCI_I. Distress Manifestation Index (DMI_I) was calculated by using Eq. (3.2) (Hajek et al. 1986). Probable maximum value of DMI_I was 205. If RCR calculated by Eq. 4.5, then the constants were c = 1.077 and s = 0. If RCR established subjectively to approximate PCI_I then constants were c =0.924 and s = 8.856.

The structure of Eq. 6.2 was same as proposed for Distress Index (DI) by Phang et al. (1979). The variables c and 205 were designed in such a way to ensure that, on average, the PCI_I was equal to the PCR and slope of linear model relating PCI_I and PCR

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

was equal to 1 and an intercept was equal to 0. In other words, on average, the PCI_l by Hajek et al. (1986) was numerically equal to the PCR by Chong et al. (1975).

The R^2 of the linear model relating PCI_l to PCR, based on the 298 highway sections used in the roughness study, for which, all pertinent data were available, was 0.72 (Hajek et al. 1986). PCI_l was designed by Hajek et al. (1986) to supersede the previously used PCR and DI. However, because the PCI_l was derived more objectively and was a more consistent measurement of pavement performance, there may be substantial differences between the two measurements on an individual pavement section (Hajek et al. 1986).

6.5 Revised Pavement Condition Index (PCI)

Since 2001, MTO is using the following revised model for PCI (Ningyuan et al. 2001).

Revised Pavement Condition Index (PCI) = $10(0.1*RCI)^{0.5}*DMI*C_i$ (6.3)

The PCI is rated on a scale from 0 to 100 where 100 represents excellent and 0 for very poor pavement condition. The PCI inherits the concept of the PCI_l (Hajek et al. 1986) with some important modifications.

1. RCI=RCR component is based on International Roughness Index (IRI) (Hajek et al. 1998) using modern laser technology (Eq. 5.1) rather than on the mechanical measurements (Hajek et al. 1986).
2. DMI Eq. 3.3 based on a scale of 0 to 10.

C_i is a coefficient calibrated for each pavement type based on regression analysis between the objectively calculated PCI and subjective PCR which is usually observed and ranked by raters. For that section with missing RCI data, a subjective RCR is used for the regression analysis on Hot Mix Asphalt (HMA) pavements. For instance, Fig. 6.1

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

shows the statistics relationship between revised PCI and PCR based on the data collected in 1997 by the Ministry.

6.6 Assessment of Current Needs

The Ministry currently uses the PCI (Ningyuan et al. 2001) as a performance measurement within its business plan for network pavement maintenance and rehabilitation programming as documented in Pavement Design and Rehabilitation Manual (MTO 1990). A common method used to identify sections that needed work now is calculated by comparing the condition of each section for each year within the analysis period (Table 6.4).

The trigger values are normally based on pavement surface type, functional classification and traffic loadings. The trigger level at which a pavement reaches the minimum acceptable condition and requires rehabilitation or major maintenance is specified in the M&R analysis program of the PMS2. Levels for different functional classes of highways are listed in Table 6.4. In order to determine the corresponding RCI and DMI triggers for each functional class, major historic maintenance and rehabilitation construction activities and their performance data (1986 to 1999) were reviewed in comparison to the specified PCI ranges. The RCI and DMI values shown in Table 6.4 are the 75th percentiles of field observations and engineering judgments.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

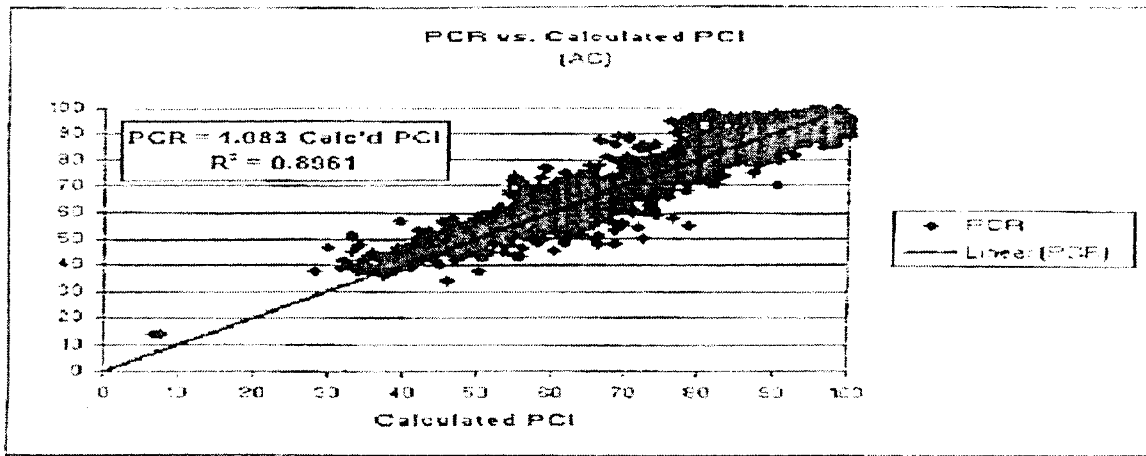

Figure 6.1 Regression Analysis Between PCI and PCR (Ningyuan et al. 2002)

Table 6.2 The Effect of DM on DI (Chong et al. 1982)

DM	DI (%)
20	6
40	12
60	19
80	25
100	32

Table 6.3 Coefficients Calibrated for PCI (Ningyuan et al. 2001)

Pavement Type	Model Coefficient C_i	R^2
Flexible HMA	1.088	0.86
Rigid (PCC)	0.998	0.63
Composite (COM)	1.03	0.52
Surface Treated	0.962	0.51

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 6.4 Trigger Values for Maintenance and Rehabilitation (M&R) Activities (Ningyuan et al. 2002)

Functional Class	PCI	RCI=RCR	DMI
Freeway	65	6.0	6.9
Arterial	60	6.0	6.9
Collector	55	6.2	6.3
Local	50	5.6	6.1

Table 6.5 Hot Mix Asphalt (HMA) Pavement Performance Prediction Models (Ningyuan et al. 2002)

Index	Model Form	Individual Performance Prediction Model	R^2	Eq. No.
RCI (Freeways)	Sigmoidal	$Y = Y_0 - \text{Exp}\,(6.2 \times 0.9^t - 4.955)$	0.9640	6.4
	Exponential	$Y = 7.83e^{-0.0142x}$	0.8668	6.5
RCI (Arterials)	Sigmoidal	$Y = Y_0 - \text{Exp}\,(10.2*0.9^t - 12.4)$	0.9600	6.6
	Exponential	$Y = 7.84e^{-0.0139x}$	0.9945	6.7
PCI	Sigmoidal	$Y = Y_0 - \text{Exp}\,(1.1\ 14*\ 0.6^t\ 0.62)$	0.9670	6.8
	Polynomial	$Y = 0.001\ 12x^4 - 0.257x^3 + 1.8449x^2 - 6.1035x + 86.242$	0.9710	6.9
DMI	Sigmoidal	$Y = Y_0 + \text{Exp}\,(1.17*0.6^t - 0.45)$	0.9860	6.10
	Exponential	$Y = 23.41e^{0.0689x}$	0.9136	6.11

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

6.6.1 Performance Prediction Models

Different types of prediction models are used for the prediction of RCI (Hajek et al. 1998) PCI and DMI in PMS2 (Ningyuan et al. 2001).

$$Y = Y_0 - 2e^{(a-b*c^t)} \tag{6.12}$$

$$Y = a\,(\exp)^{(bx)} \tag{6.13}$$

$$Y = \frac{1}{(a+bx)} \tag{6.14}$$

$$Y = a + \sum b_i x_i \, (i = 1, 2 ...) \tag{6.15}$$

Y = performance index like RCI, DMI, PCI, etc. Y_0 = Y value corresponding to age 0 or rehabilitation year of a pavement section. x = independent variable, either pavement age or cumulative equivalent single axle loads (ESALs). t=loge(1/Age). a, b, and c=model parameters to be calibrated. The procedure used by PMS2 in the development of individual or combined performance prediction index for a specified pavement category is described below:

1. All historic data used for performance modeling should reflect a specified category of pavement type and highway class. In PMS2, pavement sections are classified in terms of traffic, structural thickness, environment and subgrade type.
2. Prediction of individual performance prediction indexes using each of the above modeling forms (Eqs. 6.13 to 6.15) in comparison with the sigmoidal model (Eq. 6.12).
3. Provided in Table 6.5 are some coefficients a, b and c in the default models used to predict RCI DMI and PCI on the basis of the classified performance for each

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

pavement type. A common practice is to develop initial default models using the available information and expected engineering judgment (Ningyuan et al. 2001).

4. Using the sigmoidal curves to model pavement deterioration through regression analysis. these default performance models can be then modified by updating the coefficients used for individual pavement sections if site specific data/performance is available.

Table 6.5 is a summary of the individual performance index prediction models based on the sample data. but sigmoidal models are used as default performance prediction models in the PMS2. Presented in Figs. 6.2 and 6.3 are examples showing regression analyses of pavement performance data taken of flexible pavements from Ontario freeways

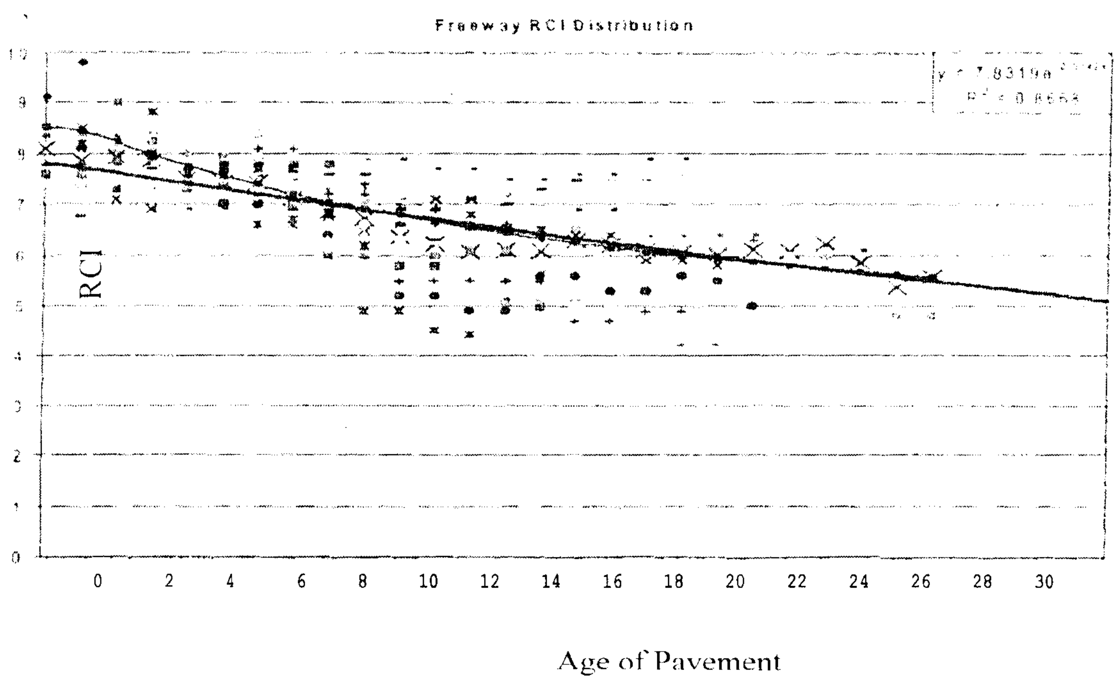

Figure 6.2 Modeling of Freeway Pavement Roughness in Terms of RCI=RCR and Age of Pavement (Ningyuan et al. 2002)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

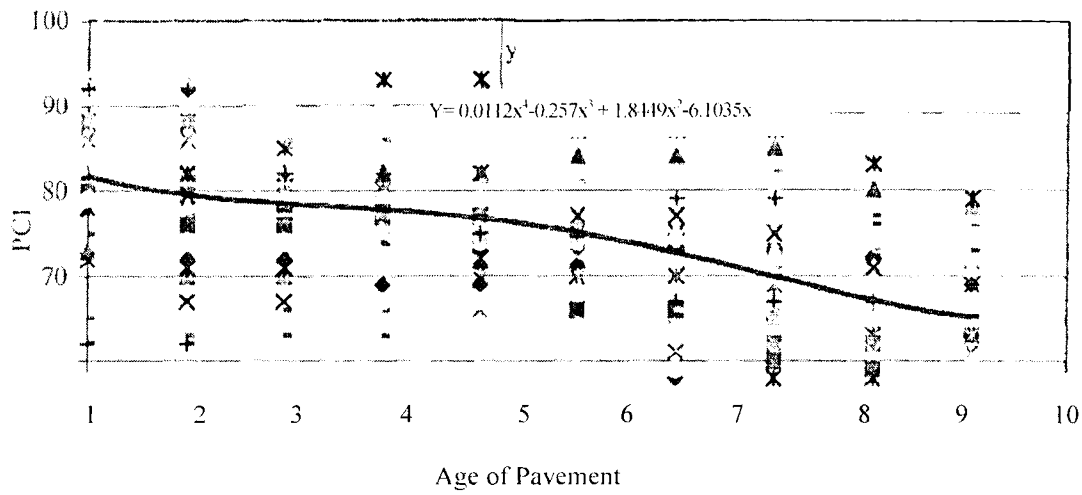

Figure 6.3 Modeling of Freeway Flexible Pavement Condition Trends in Terms of PCI and Age of Pavement (Ningyuan et al. 2002)

and arterial highways. Fig. 6.2 displays the modeling of pavement ride quality deterioration by using exponential curves for flexible pavements on freeways. Fig. 6.3 illustrates how the average overall pavement condition history is fitted by a polynomial curve for freeway flexible pavements.

6.7 Second Generation Pavement Management System Software (PMS2)

The existing pavement management system used by the MTO was developed in 1985 (Kazmierowski et al. 2001) and is currently being updated with regards to its data management and network analysis capabilities. The major components were a main frame based database maintained by the pavement management section at the headquarters. In 1998 the Ministry decided to develop second generation Pavement Management System software (PMS2) in order to facilitate data management. Stantec Consulting Ltd. was awarded the contract for the project development (Kazmierowski et al. 2001). The pavement management database maintains the historical pavement condition data from the mid-1980s

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

to the current year. Fig 6.4 is an example of default prediction models for RCI and DMI. Fig. 6.5 is the example of the decision tree to select the maintenance and rehabilitation treatments based on the criteria for DMI and RCI. (Kazmierowski et al. 2001).

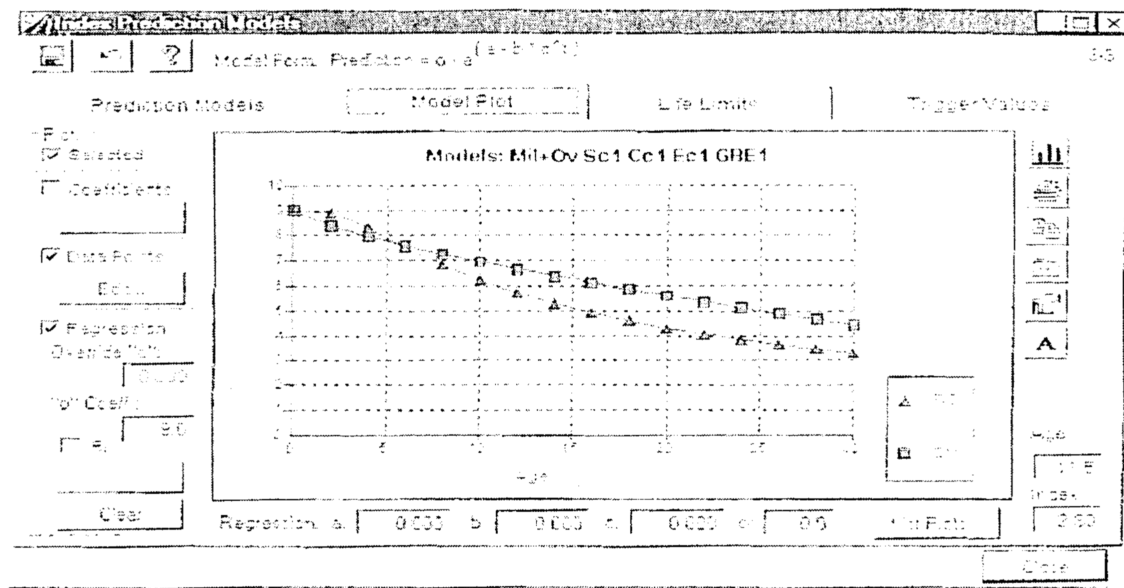

Figure 6.4 Example of Default RCI=RCR and DMI Prediction Models in PMS2 (Kazmierowski et al. 2001)

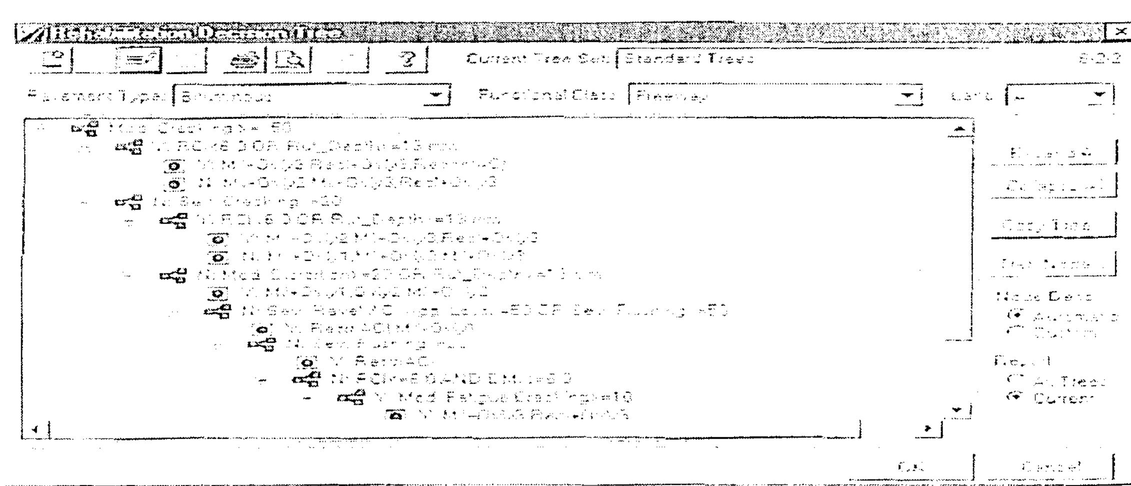

Figure 6.5 Example of Decision Tree Used for the Treatment Selection in PMS2 (Kazmierowski et al. 2001)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

6.8 Example for Pavement Performance Evaluation

This example explains how the data is collected and manipulated for the evaluation of the pavement performance.

6.8.1 Data Collection

The rater found that the pavement segment has moderate flushing on 30 % area and severe wheel-track rutting on 12% area of pavement section. After collecting these visual observations the rater has marked the checks in the appropriate places as shown on the 'Data for Pavement Performance Evaluation Example' (Table 6.6). The ride quality or roughness in terms of the International Roughness Index (IRI) is 1.9 m/km.

6.8.2 Data Analysis

Pavement performance is evaluated by a single parameter called PCI. It consists of two interrelated components DMI and RCI. From Eq. 3.3, DMI is calculated as follows:

$$DMI=10*\frac{208-(0.5*(2+2)+3*(3+1))}{208}=10*\frac{208-14}{208}=9.32$$

From Eq. 5.1, RCI=RCR is calculated as follows:

$RCI=RCR=8.52-7.49*\log(1.9)=6.4$.

From Eq. 6.2, PCI is calculated as follows:

$PCI=10*(0.1*6.43)^{0.5}*9.32*1.088=81.31$.

6.8.3 Assessment of Current Needs

The trigger values at which a pavement reaches its minimum acceptable condition are defined in Pavement Design and Rehabilitation Manual (MTO 1990). For Freeway, these

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 6.6 Data for Pavement Performance Evaluation Example

RIDING COMFORT RATING (AT 80 km/h)	EXCELLENT	GOOD	FAIR	POOR	VERY POOR
	10	8	6	4	2

				SEVERITY OF PAVEMENT DISTRESS					DENSITY OF PAVEMENT DISTRESS					
				VERY SLIGHT	SLIGHT	MODERATE	SEVERE	VERY SEVERE	FEW <10%	INTERMITTENT 10-20 %	FREQUENT 20-50%	EXTENSIVE 50-80%	THROUGHOUT 80-100%	
PAVEMENT DISTRESSES			NO \ Weight	05	1	2	3	4	0.5	1	2	3	4	W_i
SURFACE DEFECTS	RAVELLING AND COARSE AGG. LOSS		1											3.0
SURFACE DEFECTS	FLUSHING		2			√					√			0.5
SURFACE DEFORMATION	RIPPLING AND SHOVING		3											1.0
SURFACE DEFORMATION	WHEEL-TRACK RUTTING		4				√			√				3.0
SURFACE DEFORMATION	DISTORTION		5											3.0
CRACKING	LONGITUDINAL WHEEL-TRACK	S & M	6											1.0
CRACKING	LONGITUDINAL WHEEL-TRACK	ALLIGATOR	7											3.0
CRACKING	CENTRE LINE	S & M	8											0.5
CRACKING	CENTRE LINE	ALLIGATOR	9											2.0
CRACKING	PAVEMENT EDGE	S & M	10											0.5
CRACKING	PAVEMENT EDGE	ALLIGATOR	11											1.5
CRACKING	TRANSVERSE	H, F & M	12											1.0
CRACKING	TRANSVERSE	ALLIGATOR	13											3.0
CRACKING	LONGITUDINAL MEANDER AND MID-LANE		14											1.0
CRACKING	RANDOM		15											0.5

S & M — Single and Multiple
H, F and M — Half, Full and Multiple

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

are DMI =6.9. RCI =RCR=6.0 and PCI = 65 as shown in Table 6.4. In this example all calculated parameters are higher than the corresponding trigger values as. DMI =9.32>6.9. RCI =RCR= 6.43>6.0. and PCI =81.31>65. Therefore. the segment does not require any rehabilitation or major maintenance at the current time. From the above results it can be concluded that the ride quality or roughness is almost reaching its trigger value. but the PCI and DMI are not so low. The overall segment condition is good.

6.8.4 Performance Prediction Model

As mentioned above the segment roughness or the ride quality is almost reaching its trigger value. From here it can concluded that in the near future. the segment will be on the list for maintenance or rehabilitation. The Riding Comfort Index (RCI) of the section is 6.43 and 'x' is the age of the segment in service after the construction or major rehabilitation can be calculated from Eq. 6.5. x = (ln (6.43/7.84))/ (-0.0142) =13.96 years. In 2008. the Riding Comfort Index (RCI) value will be 5.98. As it is less than the trigger value. the segment should be considered for maintenance and rehabilitation. The Fig. 6.6 explains the results of the example.

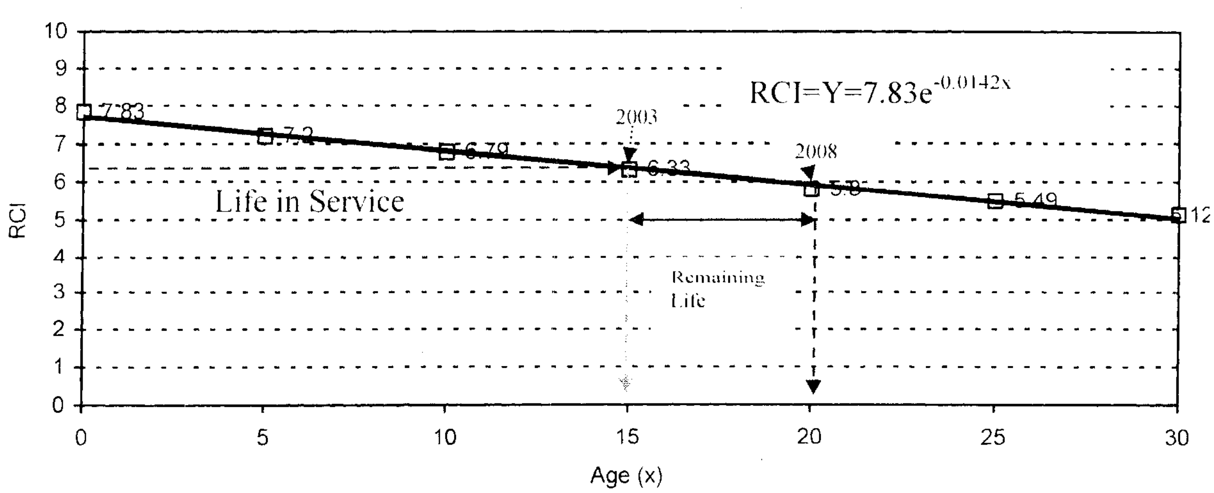

Figure 6.6 RCI=RCR Prediction Model for Pavement Evaluation Example

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 7: OPTIMIZATION OF FUNDS ALLOCATION FOR HIGHWAYS MAINTENANCE

7.1 Introduction

The revised Pavement Condition Index (PCI) is used as a decision variable in the optimization modeling of the maintenance and rehabilitation. Further details can be found in Fig. 1.4 and chapter six. Selection of the investment alternatives is not easy with the mathematical programming because: (a) there is usually multiple investment objectives for each of the many individual pavement sections involved in the network and (b) considerable uncertainty may exist for the future funding and deterioration prediction for each individual pavement section. Each prioritization method has certain specific features in terms of model development, design parameter and the economic analysis (Hajek and Phang 1989).

Based on the example as described in this chapter, the most cost-effective maintenance and rehabilitation program for the preservation of a pavement network can be achieved through the dynamic process of pavement performance prediction and optimization programming. Determination of the optimal maintenance and rehabilitation program for preserving a road network above a certain serviceability level with a limited budget is critically dependent on the pavement performance prediction models. The whole process including analysis of the sensitivities to various budget levels and projected network pavement conditions corresponding to various budget levels is automated in PMS2. Selection and the application of the optimal maintenance and rehabilitation strategy integrated with time-related pavement performance prediction models is being used in the Ministry's PMS2 software.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

7.2 Optimization Model of Funds Allocation

The optimization model proposed for use in PMS2 is cost-effective and based on multi-year priority programming as shown in Eqs. 7.1 to 7.5. The objective function is given with the budget limitations and the other constraints, to maximize the total value of cost effectiveness (i.e. the total benefit cost ratios) for given alternate pavement treatments of a pavement network with total S sections on a yearly basis (Ningyuan et al. 2001).

$$\sum_{s=1}^{N}\left[\sum_{m=1}^{M} X_{stm} * \left\{\frac{(PCS_{stm}-A_{st})*L_{st}*AADT_{st}*D_{st}}{L_{st}*W_{st}*C_{stm}*(1*R)^{-t}}\right\}\right],\ \forall t \tag{7.1}$$

Subject to,

$$\sum_{m=1}^{M} X_{stm}=1\ ,\quad \forall s,t \tag{7.2}$$

$$X_{stm}=\begin{cases}1 \text{ if maintenanace alternate m is selectd for section s in year t}\\ 0 \text{ otherwise}\end{cases} \tag{7.3}$$

$$\sum_{s=1}^{S}\sum_{m=1}^{M} X_{stm}\times(L_{st}\times W_{st}\times C_{stm})\ \leq B_{t}\quad \text{for } t=1,2,3,\ldots T \tag{7.4}$$

$$PCS_{S(t+1)}=PCS_{st}+(X_{stm}\Delta PCS_{m})\ \leq PCS_{max}\quad \forall s,t,m \tag{7.5}$$

PCS = Generalized Pavement Condition State (such as PCI) for section s (of total S sections) at year t (of total T years of the analysis period).

A_{st} = The minimum acceptable level of PCI (Table 6.4) required for a pavement section s at year t, and (PCS_{st} – A_{st}) can be either positive or negative value.

L_{st} = Length (km) of pavement section in year t.

$AADT_{st}$ = Annual average daily traffic carried on pavement section s in year t.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

D_{st} = Number of service days for traffic flows by pavement section s in year t if treatment alternative strategy m is selected.

W_{st} = Width (m) of pavement section s in year t.

C_{stm} = Unit cost ($/per square meter, Fig 7.1) of a standardized M&R treatment alternative strategy m, applied to pavement section s in year t.

R= Discount rate for calculating present value of future cost.

B_t= Budget limit for all M&R actions in the network in programming year t.

ΔPCS_m = Treatment effect of a standardized M&R action, which is defined as an amount of PCI that can be recovered, from the existing Pavement Condition State (PCS), by the maintenance & rehabilitation alternative m.

$PCS_{max.}$ = A maximum value of pavement condition state defined for a pavement. For example, if PCS is defined by PCI, which is measured on a scale of 0 to 100, with 100 being perfect, then the highest level of the PCS is 100, i.e. $PCS_{max.}$ is 100.

A brief description of each above mentioned equation is stated as: Eq. 7.1 is the objective function of the optimization model, which maximizes the value of the total cost- effectiveness over the entire programming period. It is used to find the optimal maintenance and rehabilitation action program for the network in each programming year, as compared to all other alternative maintenance and rehabilitation action programs. Eqs. 7.2 and 7.3 state that the total number of available standardized maintenance and rehabilitation treatment strategy options designed for the network is M. In each programming year one and only one of these maintenance and rehabilitation options for the pavement section s must be chosen, which produces the highest cost effectiveness

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

from the network system point of review.

Eq. 7.4 controls the maximum investment or annual budget available for the network maintenance and rehabilitation projects of each year. Within the period of multi-year M&R program, available budget of each programming year can be different from each other. Eq. 7.5 indicates that a pavement serviceability level (PCI) cannot be higher than its maximum level at any time. Actually, this constraint plays a role of penalty function, which avoids the optimization model from selecting the projects for those pavements that have a high PCI but generate low economic benefit or effectiveness.

7.3 Example for Optimization of Funds Allocation for Highways Maintenance

A small road network consisting of two pavement sections is used to demonstrate, how the optimization model is applied to develop annual pavement maintenance and rehabilitation programme for the network. Following are the data used in this example,

PCS_{st} = At year t_0 (2004) the PCI is 55 and 60 for sections 1 and 2.

A_{st} = The minimum acceptable level of PCI for sections 1 and 2 is 50 in analysis period (2004, 2005, and 2006).

L_{st} = Length (km) of pavement sections 1 and 2 is 1200m in year $t_{0,1,2}$.

$AADT_{st}$ = Annual average daily traffic carried on pavement sections 1 and 2 is 1000 in year $t_{0,1,2}$.

D_{st} = It is assumed constant as 1.

W_{st} = Width (m) of pavement sections 1 and 2 is 7 m in year $t_{0,1}$.

C_{stm} = Unit cost $1.5 and $7/per square meter for the major maintenance and minor rehabilitation (Fig 7.1).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

$R=$ Discount rate for calculating the present value of future cost is 10%.

$B_{t}=$ Budget limits for all the M&R actions in the network in programming years $t_{0,1}$ are \$ 0,10000, 40000, 80000, 100000.

$\Delta PCS_{m}=$ Treatment effect of a standardized M&R actions, which is defined as an amount of PCI that can be recovered, from the existing PCI. 10 for major maintenance and 30 for minor rehabilitation (Fig. 7.1)

$PCS_{max.}=$ The highest level of the PCI is 100, i.e. $PCI_{max.}$ is 100.

The minimum PCI for each pavement in the network is 50. The two standardized pavement treatment costs in this example are 1.5 and 7.0 dollars per square meter for major maintenance and minor rehabilitation (Fig. 7.1). In addition, the effect of each treatment on existing pavement is specified, for instance, if the maintenance and rehabilitation alternative strategy 1 (major maintenance Fig. 7.1) is selected for year t, then a rise of 10 units of PCI can be obtained in that year. Alternatively, if a minor rehabilitation treatment, i.e., strategy 2 is selected in year t, then an amount of 30 units of PCI is recovered in that year. Following the PCI jump point, where a treatment action is applied, a new deterioration model (Table 6.5), which reflects the improved pavement structure by the treatment should be established to predict the pavement deterioration in year t+1. The procedure is repeated in each consecutive year until the entire analysis period is completed for the integrated performance prediction.

Fig. 7.2 shows the maximum benefits (the maximum value of Eq. 7.1 with constraints) obtained by different budget levels. The Fig. 7.2 also explains that spending more than \$100,000 for maintenance is useless because the achieved benefits are not increasing. The optimization is done in Excel with the optimization add-in software called Solver. Fig. 7.3 explains that the optimum expenditure for maintenance is \$80,000

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

and spending more money even reduces the benefits cost ratio. Figs. 7.4 and 7.5 show how the PCI increases for section 1 and 2 as the budget increases from \$0 to \$100,000. Figs. 7.6 and 7.7 explain how the budget is utilized to optimize the benefits. When the budget was \$100,000 then \$12,600+ \$ 12,600 were spent on sections 1 and 2 in the year 2004. In 2005, the \$58,800 on section 1 and \$12,600 on section 2 are utilized.

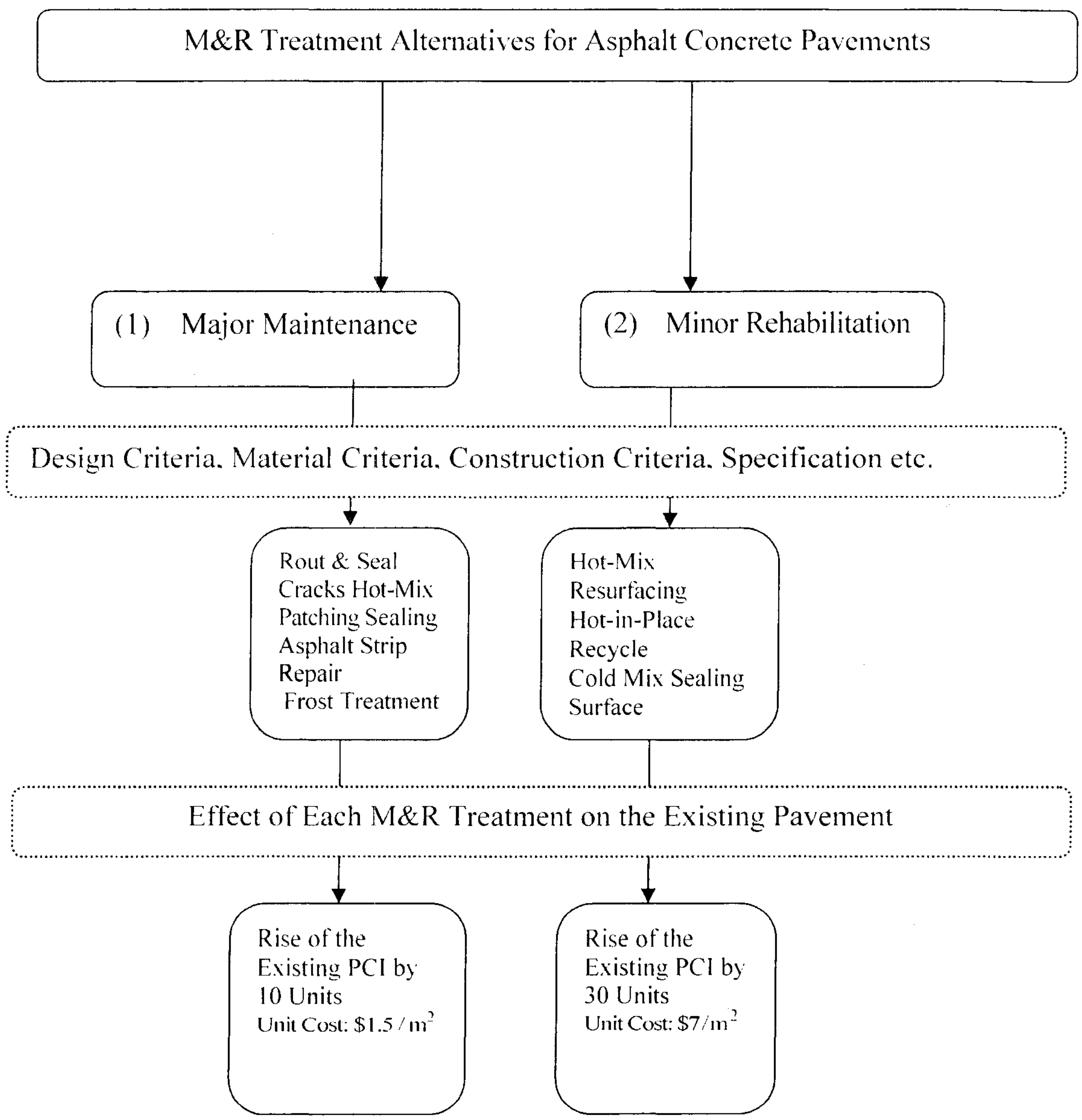

Figure 7.1 A Set of Maintenance and Rehabilitation (M& R) Treatment Activities.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

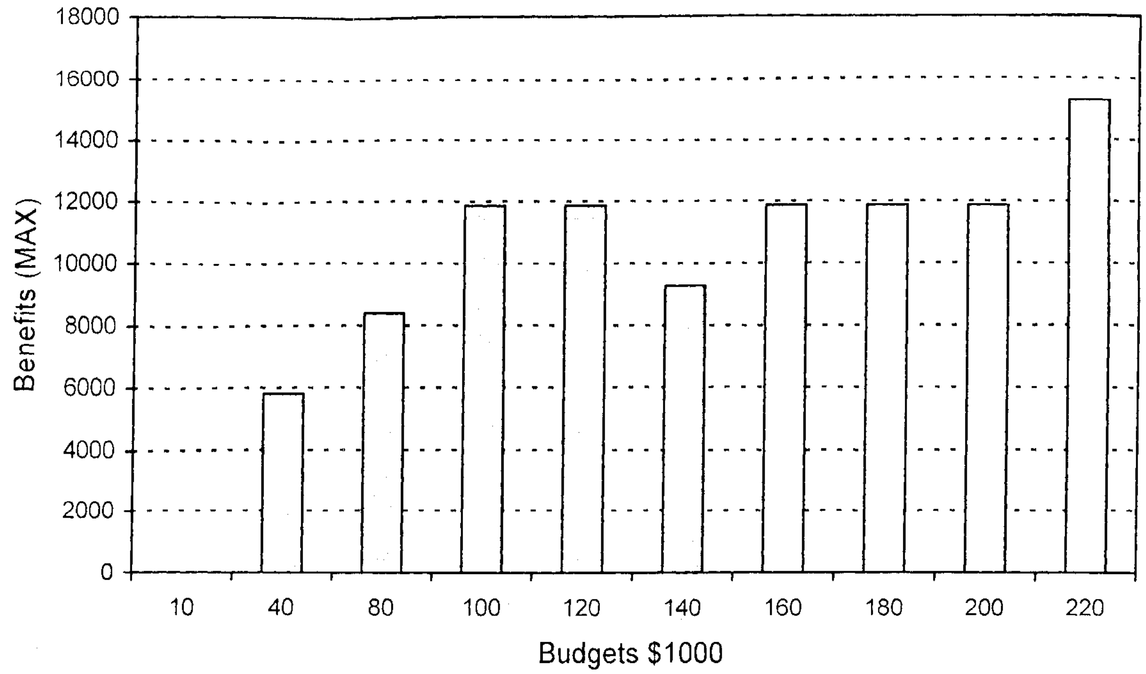

Figure 7.2 Influence of Budget Constraint on the Investment Benefits

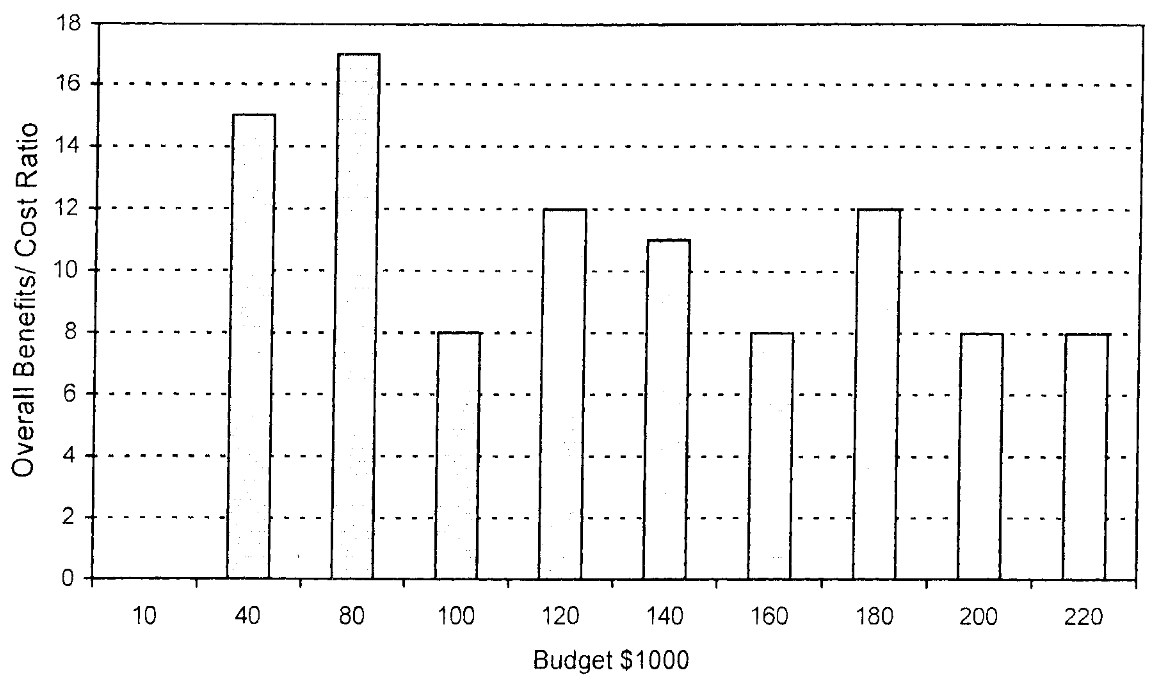

Figure 7.3 Influence of Budget Constraint on Overall Benefits/Cost Ratio

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

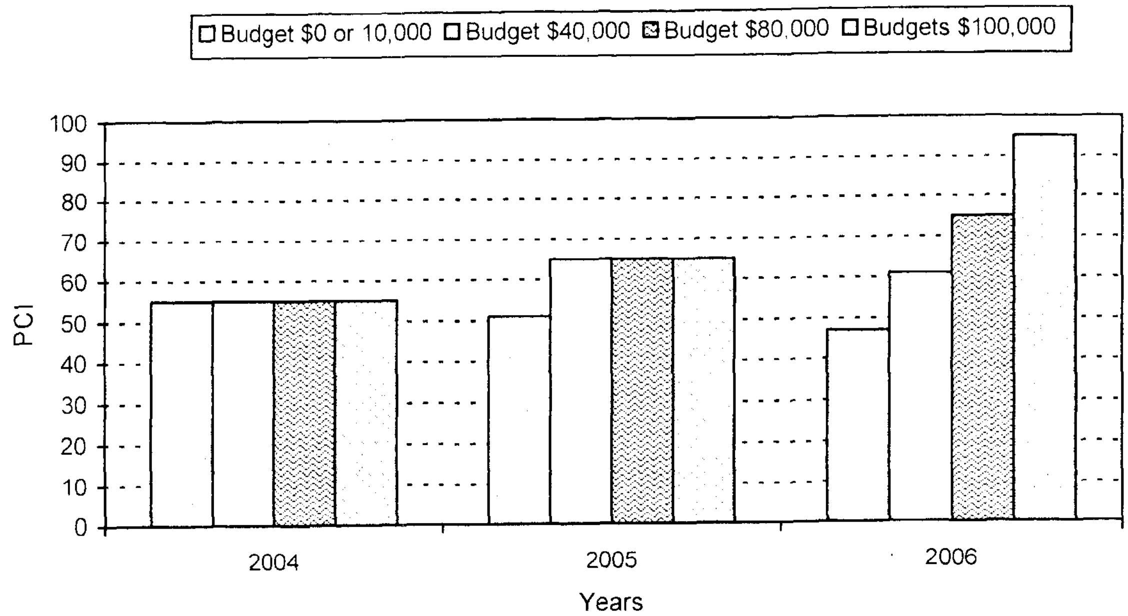

Figure 7.4 PCI for Section 1 for Different Budget Level

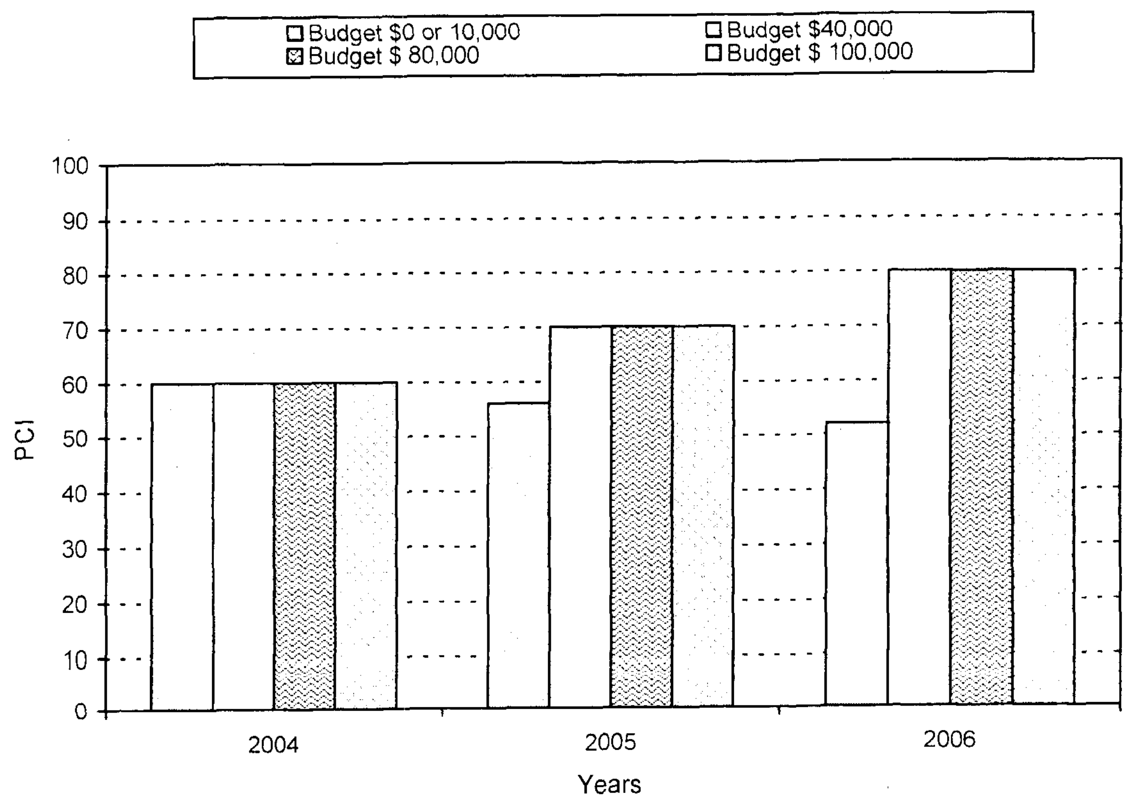

Figure 7.5 PCI for Section 2 for Different Budget Levels

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

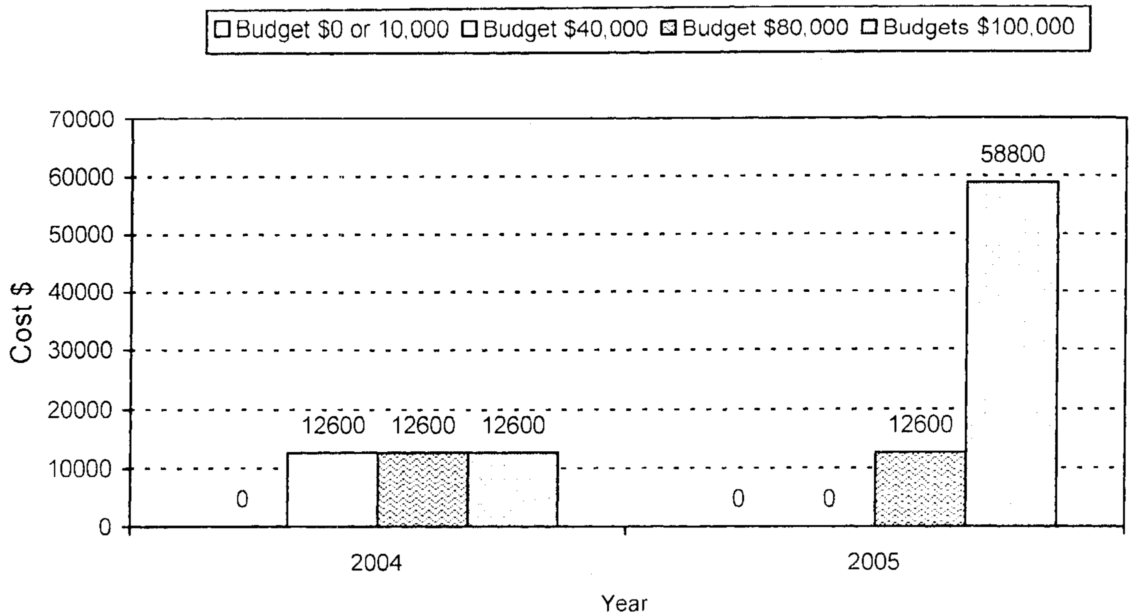

Figure 7.6 Division of Cost for Section 1 for Different Budget Levels

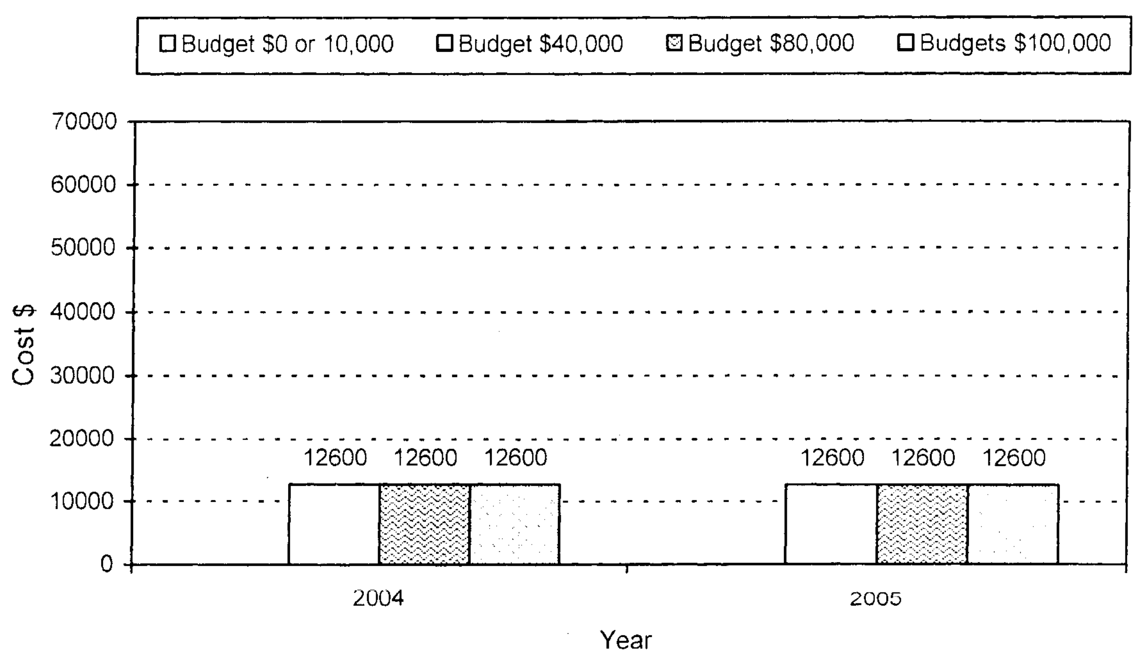

Figure 7.7 Division of Cost for Section 2 for Different Budget Levels

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 8: CONCLUSIONS, RECOMMENDATIONS AND SUMMARY

8.1 Summary

1. Currently, MTO is using the following parameters and models to evaluate the flexible pavement performance in its PMS2:

$$PCI = 10(0.1*RCI)^{0.5} * DMI*C_i \tag{6.3}$$

$$DMI = 10*\frac{208 - \sum_{i=1}^{15} W_i(S_i + D_i)}{208} \tag{3.3}$$

$$RCI=RCR=8.52-7.49*Log_{10}(IRI) \tag{5.1}$$

PCR= It is rated according to the guidelines described in Table 6.1.

2. Currently, MTO is using PCI as decision variable in its PMS2 to optimize the funds allocation for highway maintenance.

$$\sum_{s=1}^{N}\left[\sum_{m=1}^{M} X_{stm} * \left\{\frac{(PCI_{stm} - A_{st})*L_{st}*AADT_{st}*D_{st}}{L_{st}*W_{st}*C_{stm}*(1*R)^{-1}}\right\}\right], \ \forall t \tag{7.1}$$

Subject to,

$$\sum_{m=1}^{M} X_{stm} = 1 \ , \quad \forall s,t \tag{7.2}$$

$$X_{stm} = \begin{cases} 1 \text{ if maintenanace alternate m is selectd for section s in year t} \\ 0 \text{ otherwise} \end{cases} \tag{7.3}$$

$$\sum_{s=1}^{S}\sum_{m=1}^{M} X_{stm}\times(L_{st}\times W_{st}\times C_{stm}) \le B_t \quad \text{for t=1,2,3,...T} \tag{7.4}$$

$$PCI_{S(t+1)} = PCI_{st} + (X_{stm}\Delta PCI_m) \le PCI_{max.} \quad \forall s,t,m \tag{7.5}$$

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

3. Currently, MTO is using the following models for the prediction of flexible pavement performance in term of RCI, DMI and PCI in its PMS2 (Table 6.5).

Index	Model Form	Individual Performance Prediction Model	R^2	Eq. No.
RCI (Freeways)	Sigmoidal	$Y = Y_0 - Exp\,(6.2 \times 0.9^t - 4.955)$	0.9640	6.4
	Exponential	$Y = 7.83e^{-0.0142x}$	0.8668	6.5
RCI (Arterials)	Sigmoidal	$Y = Y_0 - Exp\,(10.2 * 0.9^t - 12.4)$	0.9600	6.6
	Exponential	$Y = 7.84e^{-0.0139x}$	0.9945	6.7
PCI	Sigmoidal	$Y = Y_0 - Exp\,(1.1\ 14 * 0.6^t\ 0.62)$	0.9670	6.8
	Polynomial	$Y = 0.001\ 12x^4 - 0.257x^3 + 1.8449x^2 - 6.1035x + 86.242$	0.9710	6.9
DMI	Sigmoidal	$Y = Y_0 + Exp\,(1.17 * 0.6^t - 0.45)$	0.9860	6.10
	Exponential	$Y = 23.41e^{0.0689x}$	0.9136	6.11

4. Currently, MTO is using the following trigger values in terms of RCI, DMI and PCI for the maintenance and rehabilitation of highways in its PMS2 (Table 6.4).

Functional Class	PCI	RCI=RCR	DMI
Freeway	65	6.0	6.9
Arterial	60	6.0	6.9
Collector	55	6.2	6.3
Local	50	5.6	6.1

5. MTO has used the PCI_I, DMI_I and RCR to evaluate the performance of flexible pavements from 1986 to 2001.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

$$PCI_1 = 100(0.1*RCR)^{0.5}\frac{[205-DMI_1]}{205}*c+s \quad (6.2)$$

$$DMI_1 = \sum_{i=1}^{15} W_i(S_i + D_i) \quad (3.2)$$

$$RCR = 27.6 - 7.51*Log_{10}(RMSVA), \quad RMSVA = PURD \quad (5.2)$$

6. MTO has used the DI, DM, subjective RCR and Mays Ride Meter to evaluate the performance of flexible pavements from 1979 to 1986.

$$DI = 100*[(RCR/10)]^{0.5}\frac{[320 - DM]}{320} \quad (6.1)$$

$$DM = \sum_{i=1}^{27} W_i(S_i + D_i) \quad (3.1)$$

RCR = 9.38 - 0.0177(MAYs), or can be measured subjectively. (3.2)

7. Prior to 1979, MTO has used PCR and subjective RCR to evaluate flexible pavement performance.

8.2 Conclusions

1. This report has demonstrated the process and technical methods used by the MTO in the pavement performance evaluation over the last 30 years, including data collection, data management/reporting, performance evaluation, prediction models, need analysis.
2. Several key issues related to quality control and quality assurance are discussed with reference to the roughness measurements and verification techniques used by the Ministry. Particularly, this report discussed the techniques used for the evaluation of pavement performance in terms of IRI and its application.
3. The sigmoidal models are used for the prediction of pavement performance

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

deterioration in terms of roughness, surface distress and overall pavement condition indexes.

9. The IRI has time-stability, transferability and ready measurability by almost all existing roughness devices. As the IRI is a geographically transferable, repeatable and time-stable measure, therefore, it has attractiveness as a suitable measurement for the quality control of new pavement construction projects or rehabilitation. Thus, given the IRI parameter and the relative information, a highway agency can be able to assess objectively how the condition of its pavement network responds to the pavement investment.

8.3 Recommendations

1. The DMI values measured by different raters for different segments could be different. This can be resolved by measuring the network by the same raters so that the error could be reduced in average value. But still this is impractical to measure the province network so there is a need for the development and use of new technologies to measure the distresses objectively.
2. The existing manual should be updated to eliminate any ambiguity in the identification and assess distresses like distortion, random cracking, half, full single, and multiple cracks etc.
3. The regional training of raters must be conducted regularly to improve the overall province-wide consistency.
4. Still, there are no fixed standards for the calculation of International Roughness Index (IRI) from laser-based devices at the province and the municipality level. Therefore, the standards or guidelines should be developed for different types of

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

sensors, number of sensors, sensor spacing, profile sampling, recording interval, base length for moving average filter, survey direction, data collection environment condition, seasonal variations, minimum data collection speed and the minimum start up length to reduce error in IRI measurements.

5. The approach should be mechanistic empirical for the prediction models of RCI and DMI. There is need to develop prediction models for each distress to address pavement structure, material properties (elastic modulus, poison's ratio), and the traffic loading.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

REFERENCES:

American Association of State Highway and Transportation Official, 2001. "Pavement Management Guide", AASHTO, Washington, D.C.

American Association of State Highway and Transportation Official, 1962. "The AASHTO Road Test Report 5, Pavement Research", AASHTO, Highway Research Board, USA.

American Society for Testing and Material, 1994. "Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference", ASTM E950-94, Vol. 04.03, pp 702-706.

American Society for Testing and Material, 1996. "Terminology Relating to Traveled Surface Characteristics", ASTM E 867-96, Vol. 04.03.

American Society of Testing Material, 1996. "Standard Guide for Prioritization of Data Needs for Pavement Management", ASTM E1777- 96, Vol. 04.03.

Asnani S., Ksaibati K., and Al-Suleiman I., 1993. "Consistency of Roughness and Rut Depth Measurement Collected with 11 South Dakota Road Profilers", Transportation Research Record 1410, pp 41-51, ISBN: 0-30905-5571.

Chong G., Phang W., and Wrong G., 1982. "Ontario Flexible Pavement Distress Assessment for Use in Pavement Management", Ontario Ministry of Transportation and Communications, Transportation Research Record 893, pp 51-59.

Chong G., Phang W., and Wrong, G.A., 1975. "Manual for Condition Rating of Flexible Pavement-Distress Manifestation". Ontario Ministry of Transportation and Communications, Downsview Ontario.

Chong G., Phang W., and Wrong G., 1982. "Manual for Condition Rating of Flexible

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Pavement", SP- 004, Ontario Ministry of Transportation and Communications, Downsview, Ontario.

Chong G., Phang W., and Wrong G., 1989. "Manual for Condition Rating of Flexible Pavement–Distress Manifestation", Report SP-024, Ontario Ministry of Transportation and Communications, ISBN: 0-7729-831-9.

Hajek J., and Phang W., 1986. "Moving from Subjective to Objective Evaluation of Pavement Performance", Ontario Ministry of Transportation, Downsview, Ontario, Canada.

Hajek J., and Phang W., 1989. "Prioritization and Optimization of Pavement Preservation Treatments", Transportation Research Record 1261, pp 58-68.

Hajek J., Kazmierowski T., and Musgrove G., 1998. "A Switch to the International Roughness Index", Transportation Research Board 1643, pp 116-124, ISBN: 0-30906-515-1.

Hajek J., Phang W., Wrong G., Prakash A., and Stott G., 1986. "Pavement Condition Index (PCI) for Flexible Pavement", Ontario Ministry of Transportation, Downsview, Ontario.

Hass R., and Hudson W., 1978. "Pavement Management System", McGraw-Hill.

Joseph P., Khan T., Phang W., and Haas R., 1984. "Universal Standard for Correlation of Road Roughness Measurements", Transportation Forum, Vol. 1-3, pp 61-69.

Kazmierowski T., Zhiwie H., and Brian K., 2001. "A Second Generation PMS for the Ontario Ministry of Transportation", Fifth International Conference on Managing Pavements, Seattle, Washington USA.

Kazmierowski T., Li N., and Sharma B., 2000. "Measuring Performance of Asphalt Pavements Using the International Roughness Index", Proceedings, 45th Canadian

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Technical Asphalt Association, pp 299-317.

Kazmierowski T., Ningyuan L., and Sharma B., 2001. "Verification of Network-level Pavement Roughness Measurements", Transportation Research Record 1764, pp 128-138, ISBN: 0-3090-722-55.

Loughnan J., Evers R., 1980. "The Mays Ride Meter", Ontario Ministry of Transportation, Downsview, Ontario, Report No. EM-35.

Lytton R., 1987. "Concepts of Pavement Performance Prediction and Modeling", Proceeding of Second North American Conference on Managing Pavements, pp 2.3-2.19.

McKenzie D., and Srinarawa M., 1978. "Root Mean Square Vertical Acceleration (RMSVA) as Basis for Mays Meter Calibration", Brazil Project Tech. Memo, BR-23, Centre for Transportation Research, The University of Texas at Austin.

Ontario Ministry of Transportation, 1990. "Pavement Design and Rehabilitation Manual", MTO, Downsview, Ontario, ISBN: 0-7729-6379-7.

Novak E., and DeFrain L., 1992. "Seasonal Changes in the Longitudinal Profile of Pavements Subject to Frost Action", Transportation Research Record 1362, pp 95-100, Washington, D.C., ISBN: 0-3090-540-28.

Ningyuan L., Kazmierowski T., Susan T., and Ralph H., 2001. "Integrating Dynamic Performance Prediction Models in to Pavement management System and Rehabilitation Programs", Fifth International Conference on Managing Pavement, Seattle Washington, Paper ID: 94.

Ningyuan L., Kazmierowski T., and Sharma B., 2002. "Development of Flexible Pavement Roughness Prediction Models for Use in Network-level Programming", Presented at Ryerson Polytechnic University Toronto, Ontario Ministry of Transportation,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Downsview, Ontario, Canada.

Ningyuan L., and Kazmierowski T., 2002a. "The Evolution of Pavement Management in Ontario", 47th Canadian Technical Asphalt Association, Calgary, Canada.

Ningyuan L., and Kazmierowski T., 2002b. "Modeling Flexible Pavement Performance Using Canadian Historical Data", International Society for Asphalt Pavements, St. Paul, USA..

Phang W., Shahin M., Darter M., and Kohn S., 1979. "Pavement Condition Rating and Rehabilitation Needs", Transportation Research Record 700, pp 11-19.

Ponniah J., 2001. "A Critical Review of an Existing Pavement Condition Rating System", Fifth International Conference on Managing Pavements, Seattle, Washington USA.

Ponniah J., 2001. "MTO Pavement Design Evaluation: Procedures and Design", Presented at Ryerson Polytechnic University Toronto, Ontario Ministry of Transportation, Downsview, Ontario, Canada.

Prakash A., Sharma B., and Kazmierowski T., 1994. "Investigation in to Observational Variations in Pavement Condition Survey", Third International Conference on Managing Pavements, Texas, USA.

Queiroz C., 1981. "A Procedure for Obtaining a Stable Roughness Scale from Rod and Level Profiles", Working Document 22, GEIPOT. SAN Q.38.A.

Roads and Transportation Association of Canada, 1977. "Pavement Management Guide", RTAC, Ottawa, Canada.

Sayers M., 1995. "On the Calculation of IRI from Longitudinal Road Profile", Transportation Research Board 1501, pp 1-15, ISBN: 0-3090-616-95.

Sayers M., Gillespie, T., and Paterson, W., 1986. "Guidelines for the Conduct and Calibration

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

of Road Roughness Measurements", World Bank Technical Paper No. 46, The World Bank, Washington. D.C.

Transportation Association of Canada, 1997. "Pavement Design and Management Guide", TAC, Ottawa, Canada.

Transportation Association of Canada, 2001. "Standardization of IRI Data Collection and Reporting in Canada", TAC, ISBN: 1-55187-149-1.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

APPENDIX: GLOSSARY OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Material and Testing
ARAN	Automatic Road Analyzer
D_i	Density of Distress occurrence
DMI_I	Distress Manifestation Index
DMI	Revised Distress Manifestation Index
FHWA	Federal Highway Authority
GS	Gravel Surfaced Pavements
HMA	Hot Mix Asphalt
IRI	International Roughness Index
LCCA	Life Cycle Cost Analysis
M& R	Maintenance and Rehabilitation
MRM	Mays Ride Meter
MTO	Ontario Ministry of Transportation
PCI_I	Pavement Condition Index
PCI	Revised Pavement Condition Index
PCS	Pavement Condition State
PCR	Pavement Condition Rating
PMS	Pavement Management System
PMS2	Second Generation Pavement Management System Software
PURD	Portable Universal Roughness Device
PCC	Portland Cement Concrete
QA	Quality Assurance

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

RAM	Relative Axle Movement
RCR	Riding Comfort Rating (Car based)
RCRT	Ride Comfort Rating (Truck based)
RMSVA	Root Mean Square Vertical Acceleration
RTRRMS	Response Type Road Roughness Measurement System
RTAC	Road and Transportation Association of Canada
S_i	Severity of Distress
S V	Slope Variance
TAC	Transportation Association of Canada

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

APPENDIX: GLOSSARY OF ACRONYMS

These definitions are taken from TAC 2001, 1997, and ASTM E950-94.

Accuracy: Closeness of agreement between the result of a measurement and a true value of the measurement.

Alligator Cracking: Cracks which occur in asphalt pavements, in areas subjected to repeated traffic loadings which develop into a series of interconnected cracks, with many sided, sharp angled pieces, characteristically with an alligator pattern.

Asphalt Concrete: A high quality mixture of asphalt cement, carefully graded coarse and fine aggregates.

Asphalt Pavement: Pavement consisting of asphalt concrete layers on supporting courses such as concrete base (composite pavement), asphalt treated base, cement treated base, granular base and/or granular subbase placed over the subgrade.

Base Length: The length over which the individual profile samples are averaged or filtered and needs to be selected based on the intended use of the resultant data.

Blind Verification Site: A reference site where the vehicle operator has no knowledge of its location when conducting the survey.

Calibration: A method to standardize a measurement by determining the deviation from a standard so as to ascertain proper correction factors.

Class I Profiler: Longitudinal sampling is less than or equal to 150mm. Vertical measurement resolution is less than or equal to 0.1mm.

Class II Profiler: Longitudinal sampling is greater than 25mm to 150mm. Vertical measurement resolution is greater than 0.1mm to 0.2mm.

Class III Profiler: Longitudinal sampling is greater than 150mm to 300mm. Vertical measurement resolution is greater than 0.2mm to 0.5mm.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Class IV Profiler: Longitudinal sampling is greater than 300mm. Vertical measurement resolutions is greater than 0.5mm.

Closure Verification Site: Same as a known verification site but tested at the completion of all data collection activities.

Composite Pavement: A pavement structure which combines both flexible and rigid pavement components.

Corrective Maintenance: Maintenance treatments, such as pot hole patching to correct localized failures or minor problems, carried out as routine practice.

Cost Effectiveness: An economic measure defined as the effectiveness of an action or treatment divided by the present worth of life cycle costs.

Dipstick: An ASTM Class I profiler.

Equivalent Single Axle Load: A concept which equates the damage to a pavement structure caused by the passage of a non standard axle load to a standard 80 KN axle load, in terms of calculated or measured stress, strain or deflection at some point in the pavement structure, or in terms of equal conditions of distress or loss of serviceability.

End Result Specification (ERS): The specification of an end result to be achieved in construction, such as a minimum density, as compared to a method type of specification.

Flexible Pavement: A pavement structure usually composed of one or more asphalt concrete layers over an unbound aggregate or stabilized base.

Geographic Information System: A computerized database which defines the specific locations of various attributes features or data items on a coordinate basis.

Global Positioning System: A technology for identifying the x, y, z coordinates location

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

of object based on satellite signals.

Golden Car: A set of model vehicle parameters specifying tires/axle/suspension components which best correlated with field tests from available devices but differed from true suspension performance because it incorporated larger suspension dampening coefficients. The gold car model parameters subsequently became the single wheel and suspension simulation basis for determining the IRI.

Inertial Profilers: A vehicle equipped with a distance measuring device, vertical height sensors and accelerometers used to determine the profile of a roadway based on the concept of a vertical acceleration, inertial reference plane.

International Roughness Index (IRI): An index computed from a longitudinal profile measurement using a quarter car simulations at a simulation speed of 80 km/h. or A summary of statistic which characterizes road surface longitudinal roughness based on simulation of a standardized quarter car moving over the longitudinal profile of the road.

Known Verification Site: A reference site where the vehicle operator has knowledge of its location prior to conducting the survey.

Laser Height Sensor: Height measurement based on the transmission and detection of laser light (light amplification through the stimulated emission of radiation).

MIRI: Mean International Roughness Index (IRI) defined as the average of the outer wheel path and inner wheel path IRI.

Maintenance: Well timed and executed activities to ensure or extend pavement life until deterioration of the pavement layer materials.

Method Based Specification: A specification involving the methodology or technique to be applied to a construction item, such as number of passes of a certain weight of

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

roller.

Pavement Management System: A wide spectrum of activities including the planning or programming of investments, design, construction, maintenance, and the periodic evaluation of performance used to provide an effective and efficient road network.

Precision: Precision in the measurement of pavement profile elevation is related to the closeness of agreement between the repeated measurements of the same pavement profile.

Pre-Qualification: A process specified that requires all potential service providers to demonstrate that performance requirements can be met before being allowed to respond to a request for services.

Preventive Maintenance: Major maintenance treatments to retard deterioration of a pavement, such as chip seal, rout and crack seal, etc.

Profiler Bias: Bias error indicates whether the profiler is systematically high or low compared to the truth.

Quality Assurance: A system of activities whose purpose is to provide assurance that the overall quality control job is in fact being done effectively. It involves a continuing evaluation of the effectiveness of the overall quality control program with a view to having corrective measures initiated where necessary. For a specific product or service, this involves verifications, audits and the evaluation of the quality factors that affect the specification, production, inspection and use of the product or service.

Quality Control: The overall system of activities whose purpose is to provides a quality of product or service that meets the needs of users. The aim of quality control is to

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

provide quality that is satisfactory, adequate, dependable and economic. The overall system involves integrating the quality aspects of several related steps including: (a) the proper specification of what is wanted (b) production to meet the full intent of the specifications (c) inspection to determine whether the resulting product or service is in accord with the specifications and review of usage to provide for revision of specification.

Quarter Car IRI: Calculation of the IRI from a single wheel path profile using the golden car simulation parameters.

Recording Interval: The effective distance between recorded roadway profile height measurements taken by the data acquisition system as the profile moves down the roadway.

Rehabilitation: A term in pavement management involving the restoration of pavement serviceability through such actions as overlays.

Riding Comfort Index (RCI): A measure to characterize the ride quality of a pavement on a scale of 0 to 10.

Riding Comfort Rating (RCR): A measure to characterize the ride quality of a pavement similar to RCI.

Repeatability: Closeness of the agreement between the results of successive measurements of the same measure and carried out under the same conditions of measurements.

Sample Interval: The smallest distance between successive physical measurements of the roadway profile by the data acquisition system as the profiler moves down the roadway.

Scarification: Ripping (usually with grader teeth), reshaping and recompacting a

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

pavement surface and/or base and/or sub base layer.

Serviceability: The ability of a pavement to serve the traffic which uses it.

Specification: A specification involving minimum or maximum levels of performance items at certain ages, such as roughness, surface distress, surface friction or structural adequacy.

Strategic Highway Research Program: A comprehensive, multi million dollar research program in the USA and other countries involving research in Long Term Pavement Performance (LTTP), asphalt, concrete structures and highway operations. The Canadian counterpart is known as C-SHRP.

Transportation Association of Canada (TAC): Formerly, Roads and Transportation Association of Canada (RTAC) and before that the Canadian Good Roads Association (CGRA).

Ultrasonic Height Sensor: Height sensor measurement based on the transmission and detection of acoustic pulses.

Verification: A process to establish the truth, accuracy or reliability of a measurement.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.