This is to certify that the
thesis entitled

THE USE OF RELIABILITY ANALYSIS FOR DETERMINING
THE LIFE EXPECTANCY OF PREVENTIVE MAINTENANCE
FIXES IN APSHALT SURFACED PAVEMENTS

presented by

JASON PAUL BAUSANO

has been accepted towards fulfillment
of the requirements for the

M.S. degree in CIVIL ENGINEERING

Major Professor's Signature

July 2, 2003

Date

THE USE OF RELIABILITY ANALYSIS FOR DETERMINING THE LIFE EXPECTANCY OF PREVENTIVE MAINTENANCE FIXES IN ASPHALT SURFACED PAVEMENTS

By

Jason Paul Bausano

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Civil and Environmental Engineering

2003

ABSTRACT

THE USE OF RELIABILITY ANALYSIS FOR DETERMINING THE LIFE EXPECTANCY OF PREVETNIVE MAINTENANCE FIXES IN APSHALT SURFACED PAVEMENTS

By

Jason Paul Bausano

The research in this thesis used a large data set of pavement performance parameters in the form of Distress Index (DI) and Ride Quality Index (RQI) to conduct a reliability-based analysis for the purpose of determining the life expectancy and evaluating the guidelines for preventive maintenance (PM) fixes.

The model developed in this research is a probabilistic model that uses pavement performance parameters, (DI and RQI). Probability distributions were developed for the following fixes over time: Non-structural bituminous overlay, surface milling with a non-structural bituminous overlay, single chip seal, multiple course micro-surfacing, and bituminous crack seal.

Reliability tables were then developed expressing the probability that a given PM treatment will not reach the performance threshold after n years. These tables provide the pavement life expectancy for a given PM treatment at various reliability levels. A highway agency can then use these tables to select PM strategies based on the expected life of the fix. In addition, the PM guidelines (in terms of DI and RQI) were evaluated using a series of two-sample t-tests as well as using the reliability approach.

ACKNOWLEDGEMENTS

First, I would like to extend my thanks and gratitude to Robert and Ellen Thompson for providing the fellowship at Michigan State University (MSU) so I could further my education and improve the research in the field of asphalt pavements.

A special thanks goes to my advisor, Dr. Chatti, for his guidance and help during my research project at MSU and Michigan Technological University (MTU). I would also like to thank him for allowing me to attend MTU during the fall semester of 2002.

I would also like to thank Dr. Baladi and Dr. Wolff for sitting on my master's committee and providing me with support and guidance throughout my education.

A special thanks also goes to Dr. Williams for taking on "one" more graduate student while I was at MTU, providing me with additional insight, and guidance for my research project, and sitting on my masters thesis committee.

Finally, I extend a sincere thanks to my parents, family, and friends for their never ending support and encouragement throughout all my years of study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 - INTRODUCTION

1.1 Problem Statement

The highway system in the United States represents the single largest engineering investment ever made in this nation. Maintaining the highway system is necessary in order for this nation's economy to continue to thrive and advance. Without efficient and modern transportation systems, farm products would spoil in fields and industrial goods would remain in the factories [57].

Unfortunately, highway systems are not built to last forever. They deteriorate and disintegrate at an accelerating rate unless they are properly and continually maintained, rehabilitated, redesigned, and reconstructed. The focus of road construction has shifted from constructing new pavements to maintaining and rehabilitating the existing pavement system since the highway system is basically complete [57].

The Michigan Department of Transportation (MDOT) has implemented a successful preventive maintenance program that is aimed at maintaining the pavement network by slowing the rate of deterioration and correcting minor pavement deficiencies. This is accomplished by using treatments that correct pavement surface defects caused by the environment and the paving materials [13]. Applying preventive maintenance treatments to a pavement at the appropriate time can extend its service life for a number of years at a relatively low cost as compared with the cost of rehabilitation.

The MDOT has existing guidelines for the various preventive maintenance fixes in the form of limiting values of the Distress Index (DI), Ride Quality Index (RQI), and Rut Depth beyond which, preventive maintenance fixes should not be applied. The guidelines also include the expected life extension for the different preventive maintenance fixes. The expected life extension values are based on the past experience and engineering judgment of the MDOT. The research conducted in this study will add engineering analysis to confirm the life expectancy values and guidelines for the various preventive maintenances fixes.

1.2 Maintenance

Maintenance activities are generally divided into three categories: (1) Preventive, (2) corrective, and (3) routine. Preventive maintenance includes those activities that protect the pavement structure, hinder the rate of pavement deterioration, and provide a smooth ride while not increasing the structural capacity of the pavement [11]. Corrective maintenance are those activities performed to correct a specific pavement failure or areas of distress [11].

1.2.1 Preventive Maintenance

Preventive maintenance includes such fixes as thin overlays, surface seals, and crack sealing. Thin non-structural overlays and surface seals are those activities that consist of asphalt and aggregate or asphalt alone applied to the pavement surface. "They (1) rejuvenate or retard the oxidation of the asphalt surface; (2) restore skid resistance; (3) seal fine cracks which have appeared at the surface; (4) prevent the intrusion of water into the pavement structure through cracks; and (5) retard raveling [4]." The most common types of overlays are non-structural bituminous overlays, surface milling with non-structural bituminous overlay, and micro-surfacing. The most common type of surface seals are chip seals and micro-surfacing. The most common type of crack sealing is crack treatment and overband crack sealing. Each preventive maintenance activity will be discussed further in Chapter 2.

1.2.2 Corrective Maintenance

Corrective maintenance mainly consists of patching, chip seals, and thin bituminous overlays [4]. Only patching will be discussed in the following section, since the latter treatments have been discussed above.

Patching is one of the most common methods of repairing localized areas of intense cracking whether the cracking is load associated (fatigue), non-load associated (environmental-transverse or construction-longitudinal) [4]. If the cracks have deteriorated to the point of spalling then the spalled material must be removed and replaced. Patching usually consists of full-depth patches.

Partial depth patches involve removing the surface layer and replacing it with Hot Mix Asphalt (HMA). They are used to fix slippage cracking due to poor bond between the HMA surface and the underlying layer or for shoving and corrugations [4]. Full-depth patches involve replacing the entire asphalt concrete layer. They are used to fix fatigue cracking and potholes.

1.2.3 Routine Maintenance

AASHTO defines routine maintenance as "the day-to-day maintenance activities that are scheduled or whose timing is within the control of maintenance personnel [54]." Some examples of routine maintenance include filling cracks on the pavement surface, painting pavement markings or cleaning ditches.

1.3 Research Objective and Organization

1.3.1 Research Objective

The research objective is to use the wealth of Pavement Management System (PMS) performance data gathered on two hundred forty (240) preventive maintenance (PM) projects since 1992 to perform a reliability-based analysis for the purpose of determining the life expectancy and the evaluation of the limiting values for the different PM fixes. The pavement performance parameters that MDOT gathers are distress index (DI), ride quality index (RQI), and rut depth. These performance parameters will be discussed further in Chapter 3.

1.3.2 The Proposed Model

Reliability analysis is a statistical tool stemming from the fact that there is some uncertainty and variability in modeling the behavior of a system. The objective of the analysis is to insure some level of reliability in predicting performance. There are numerous levels of uncertainties in the prediction of pavement deterioration. Reliability analysis addresses three basic questions about the reliability of a system:

- What are the possible outcomes?
- What is the likelihood of each outcome?
- What are the consequences of decisions based on the knowledge of the probability of each outcome [55]?

The reliability-based model which uses the distress index as the main performance measure allows for estimating the life expectancy for the following MDOT fixes: Non-structural bituminous overlay, surface milling with a non-structural bituminous overlay, single chip seal, multiple course micro-surface, and bituminous crack seal. Once the life expectancy values are determined they can be compared to the life extension values that the MDOT uses.

The next goal is to evaluate the effectiveness of the guideline values for the preventive maintenance fixes. This is accomplished by knowing the pre-existing condition of the pavement before the preventive maintenance fix was applied. The evaluation of the DI guidelines was tested by looking at the mean distress indices of two populations:

- Population one: DI values less than or equal to the DI guideline value at the time of the preventive maintenance.
- Population two: DI values greater than the guideline value at the time of the preventive maintenance.

1.3.3 Organization

This thesis is organized in seven chapters as follows:

Chapter 1 gives some background information on the research undertaken and provides the problem statement and objectives of the research study.

Chapter 2 presents a literature review of existing preventive maintenance models for selecting the appropriate fix, the timing of the fix, the life extension of the fix, and the cost benefits from preventive maintenance.

Chapter 3 gives a brief overview of the MDOT Pavement Management System (PMS) focusing on the type of data collected and the indexes used, while Chapter 4 describes the data extraction process and the development of the database used in this research.

Chapter 5 describes the use of reliability analysis and hypothesis testing to develop estimates of pavement life expectancy and evaluate the guideline values for the preventive maintenance fixes.

Chapter 6 presents the results of this research and includes a comparison with MDOT's life expectancies and an evaluation of their PM guidelines.

Chapter 7 presents the summary of findings and provides recommendations for future research.

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction

The objective of a preventive maintenance program is to protect the pavement structure, reduce the rate of pavement deterioration and/or correct pavement surface deficiencies [13].

Pavement maintenance can be organized into three activity groups: preventive, corrective, and routine maintenance. According to AASHTO, "preventive maintenance is a planned strategy of cost-effective treatments to an existing roadway system and its appurtenances that preserves the system, retards future deterioration and maintains or improves the functional condition of the system without (significantly) increasing structural capacity [22]." Corrective maintenance are activities that must be done in response to events beyond the control of the highway agency. Some events require immediate response for safety concerns and hence, they cannot be scheduled [22]. Some examples of corrective maintenance activities include pothole patching, removing and patching pavement blowups, or unplugging drainage facilities. AASHTO defines routine maintenance as "the day-to-day maintenance activities that are scheduled or whose timing is within the control of maintenance personnel [54]." Some examples of routine maintenance include filling cracks, painting pavement markings or cleaning ditches. If delays in preventive maintenance occur, pavement defects and their severity level increase so that when corrected the cost is much greater. As a result, the life-cycle costs of the pavements will be considerably increased.

2.2 Facts about Preventive Maintenance

Below are some facts about preventive maintenance that have been extracted from the literature:

- Pavement Management Systems (PMS) have been around since the early 1970's in the United States and internationally [11].
- The policy of preventive maintenance did not catch on in the U.S. until the early 1990's [11].
- France in 1969 began reconditioning its 28,000 km of roads after adopting a preventive maintenance policy [2].
- In 1991, the U.S. Congress amended Section 119 of Title 23, of the United States Code with the Intermodal Surface Transportation Equity Act. This act provided for federal-aid fund eligibility for preventive maintenance type projects [13].
- In Michigan there is approximately 9,580 lane-miles of highway constructed of flexible, rigid and composite pavements [13].
- Between 1992 and 1998, approximately 2,650 miles of trunk line pavement have been treated with preventive maintenance [13].
- Rehabilitation and Reconstruction costs 14 times more per lane-mile than preventive maintenance projects [13].
- Since 1997 the annual budget for the capital preventive maintenance program has grown from $3,000,000 to $60,000,000.

- An estimated savings of more than $700 million has been realized since Michigan's preventive maintenance program was implemented in 1992 as opposed to rehabilitating the pavements[13].
- Highway agencies are now in a maintenance/rehabilitation mode of operation since no new highways/interstates are being constructed.

2.3 Asphalt Pavement Distresses

Some of the most common types of distresses in flexible pavements are listed below:

- Transverse Cracking,
- Longitudinal Cracking,
- Longitudinal Joint Deterioration,
- Alligator Cracking,
- Block Cracking,
- Rutting,
- Raveling & Weathering/Segregation,
- Patching, and
- Roughness.

The causes of these distresses will not be discussed here, but they can be found in several publications from various sources including the National Center for Asphalt Technology [4].

2.4 Preventive Maintenance Treatments

The MDOT uses a mix of fixes to benefit the highway network. The guidelines for each preventive maintenance fix were obtained from the MDOT's Capital Preventive Maintenance Program Guide [22]. The following lists the MDOT's preventive maintenance fixes:

- Non-Structural Bituminous Overlay,
- Surface Milling with Non-Structural Bituminous Overlay,
- Chip Seal,
- Micro-Surfacing,
- Crack Treatment,
- Overband Crack Filling,
- Bituminous Shoulder Ribbons, and
- Ultra-Thin Bituminous Overlay.

Non-Structural Bituminous Overlay

Description: A dense-graded bituminous mixture limited to 90-kg/m^2-application rate.

Purpose: A non-structural bituminous overlay is the highest type of surface treatment fix available in the Capital Preventive Maintenance Program (CPMP). It will provide some protection to the pavement structure, slow the rate of pavement deterioration, correct many pavement surface deficiencies, improve the ride quality, and add some strength to the existing pavement structure.

Existing Pavement Condition: The existing pavement condition should exhibit a good base condition and a uniform cross section. The visible surface distress may include moderate raveling, longitudinal and transverse cracks and small amounts of block cracking. Low associated distress may be present. The pavement should only have some minor base failures and depressions. Table 2.1 gives performance criteria for distress index, ride quality index, and rut depth as to when the non-structural bituminous overlay should be applied.

Table 2.1 – MDOT Performance Threshold Values for Non-Structural Bituminous Overlay (MDOT, 1998)

Pavement Type	**Minimum RSL (years)**	**D.I.**	**R.Q.I.**	**Rut Depth**
Flexible	3	<40	<70	<12mm
Composite	3	<25	<70	<12mm

Performance: This treatment performs best on flexible pavement structures, but is also applicable to composite pavements depending on the extent of the reflective cracking. Table 2.2 gives the estimated life extension for the non-structural bituminous overlay for flexible and composite pavements.

Table 2.2 - Estimated Life Extension for Non-Structural Bituminous Overlay (MDOT, 1998)

Pavement Type	**Years***
Flexible	5 to 10
Composite	4 to 9

*The time range is the expected life extending benefit given to the pavement, not the anticipated longevity of the treatment.

Surface Milling with Non-Structural Bituminous Overlay

Description: The removal of an existing bituminous surface by the cold milling method and the placement of a dense-graded bituminous mixture limited to 90-kg/m^2 application rate.

Purpose: In the CPMP, the cold milling operation has been used to: (1) correct specific existing surface deficiencies, (2) correct the shape of the existing cross section, and (3) produce a more economical project as compared to a non-structural bituminous overlay project. The non-structural bituminous overlay replaces the bituminous material that is removed.

Existing Pavement Condition: The existing pavement should exhibit a good base condition. The visible surface distress may include: severe surface raveling, multiple longitudinal and transverse cracking with slight raveling, a small amount of block cracking, patching in fair condition, debonding surface and slight to moderate rutting. The cold milling operation is used to correct rutting in the existing bituminous surface layer where the rutting is not caused by a weak base and when the condition of the existing pavement has deteriorated to a point where it is not practical to correct the rutting problem by a more economical treatment. The cold milling operation is also used to remove an existing bituminous course that is debonding. Table 2.3 gives performance criteria for distress index, ride quality index, and rut depth as to when the surface milling with a non-structural bituminous overlay should be applied.

Table 2.3 – MDOT Performance Thresholds for Surface Milling with a Non-Structural Bituminous Overlay (MDOT, 1998)

Pavement Type	Minimum RSL (years)	D.I.	R.Q.I.	Rut Depth
Flexible	3	<40	<80	<25mm
Composite	3	<30	<80	<25mm

Performance: This type of type of treatment will protect the remaining pavement structure, slow the rate of deterioration and improve the ride quality. Table 2.4 gives the estimated life extension for surface milling with a non-structural bituminous overlay for flexible and composite pavements.

Table 2.4 - Estimated Life Extension for Surface Milling with a Non-Structural Bituminous Overlay (MDOT, 1998)

Pavement Type	**Years***
Flexible	5 to 10
Composite	4 to 9

*The time range is the expected life extending benefit given to the pavement, not the anticipated longevity of the treatment.

Chip Seal

Description: A chip seal is the application of a polymer modified asphalt emulsion with a cover aggregate. A single or a double chip seal can be used in the CPMP.

Purpose: A chip seal will seal and/or retard the oxidation of an existing pavement surface, improve skid resistance of the pavement surface, seal fine surface cracks in the pavement thus reducing the intrusion of water into the pavement structure, and will retard the raveling of aggregate from a weathered pavement surface.

Existing Pavement Condition: The existing pavement condition should exhibit a good cross section and a good base. The visible surface distress may include slight raveling and surface wear, longitudinal and transverse cracks with a minor amount of secondary cracking and slight raveling along the crack face, first signs of block cracking, slight to moderate flushing or polishing and/or occasional patch in good condition. Table 2.5 gives performance criteria for distress index, ride quality index, and rut depth as to when single and double chip seal should be applied.

Table 2.5 – MDOT Performance Thresholds for Chip Sealing (MDOT, 1998)

Pavement Type	**Minimum RSL (years)**	**D.I.**	**R.Q.I.**	**Rut Depth**
Flexible	5 (double) 6 (single)	<30 (double) <25 (single)	<54	<3mm
Composite	5 (double)	<15 (double)	<54	<3 mm

Performance: Since chip seals are used to seal the cracks and construction joints in the pavement in lieu of only extensive overband crack fill, the life expectancy may vary based on reflective cracking. Table 2.6 gives the estimated life extension for single and double chip seals for flexible and composite pavements.

Table 2.6 - Estimated Life Extension for Chip Seals (MDOT, 1998)

Pavement Type	Years*
Flexible:	
Single Seal	3 to 6
Double Seal	4 to 7
Composite:	
Double Seal	3 to 6

*The time range is the expected life extending benefit given to the pavement, not the anticipated longevity of the treatment.

Micro-Surfacing

Description: Micro-Surfacing is a mixture of polymer modified asphalt emulsion, mineral aggregate, mineral filler, water, and other additives, properly proportioned, mixed, and placed on a paved surface.

Purpose: A single course of micro-surfacing will retard oxidation and improve skid resistance in the pavement surface. Multiple courses of micro-surfacing is used to correct certain pavement surface deficiencies including severe rutting, minor surface profile irregularities, polished aggregate or low skid resistance and light to moderate raveling. Micro-surfacing is typically used on flexible or composite pavements and can perform satisfactory under all traffic volumes.

Existing Pavement Condition: The existing pavement condition should exhibit a uniform cross section and a good base. The visible surface distress may include slight raveling, rutting, minor surface irregularities, flushed or polished surface and/or moderate raveling. Table 2.7 gives performance criteria for distress index, ride quality index, and rut depth as to when single and multiple micro-surfacing should be applied.

Table 2.7 – MDOT Performance Thresholds for Micro-Surfacing (MDOT, 1998)

Pavement Type	Minimum RSL (years)	D.I.	R.Q.I.	Rut Depth
Flexible	5 (multiple) 10 (single)	<30 (multiple) <15 (single)	<54	<25mm
Composite	5 (multiple)	<15	<54	<25mm

Performance: This treatment corrects rutting, flushing and low friction. A Micro-Surface performs well on high volume roadways to correct the pavement surface conditions described above. Table 2.8 gives the estimated life extension for single and multiple micro-surfacing courses for flexible and composite pavements.

Table 2.8 - Estimated Life Extension for Micro-Surfacing (MDOT, 1998)

Pavement Type	Years*
Flexible: Single Course Double Course	 3 to 5 4 to 6
Composite: MDOT acknowledges that micro-surfacing will provide a life extension to a composite pavement; however data is not available to quantify the life extension.	

*The time range is the expected life extending benefit given to the pavement, not the anticipated longevity of the treatment.

Crack Treatment

Description: Crack treatment consists of both crack sealing and crack filling. Crack sealing is attained by the Cut and Seal Method. Crack filling is attained by the Overband Crack Fill Method. The Cut and Seal Method consists of cutting the desired reservoir shape at the working crack in the existing bituminous surface, cleaning the cut surfaces and placing the specified materials into the cavity to prevent the intrusion of water and incompressible into the crack. The Overband Crack Fill Method consists of cleaning the non-working crack into the bituminous pavement surface and placing the specified materials into and above the crack to substantially reduce the infiltration of water and to reinforce the adjacent pavement.

Purpose: The purpose of sealing and filling cracks and construction joints in the flexible pavement surface is to prevent water and incompressible materials from entering the pavement structure.

Existing Pavement Condition: The existing bituminous surface should be a relatively newly placed surface on a good base and with a good cross section. On a flexible base, the bituminous surface should be two to four years old and on a composite pavement, one to two years old. The visible surface distress may include: fairly straight open longitudinal and transverse cracks with slight secondary cracking and slight raveling at the crack face, and no patching or very few patches in excellent condition. Table 2.9 gives performance criteria for distress index, ride quality index, and rut depth as to when a bituminous crack treatment should be applied.

Table 2.9 – MDOT Performance Thresholds for Bituminous Crack Treatment (MDOT, 1998)

Pavement Type	Minimum RSL (years)	D.I.	R.Q.I.	Rut Depth
Flexible	10	<15	<54	<3mm
Composite	10	<5	<54	<3mm

Performance: The effectiveness of the seal will greatly depend upon the width of the crack being sealed and the movement of the pavement structure at the crack. Table 2.10 gives the estimated life extension for bituminous crack treatment for flexible and composite pavements.

Table 2.10 - Estimated Life Extension for Bituminous Crack Treatment (MDOT, 1998)

Pavement Type	Years*
Flexible	Up to 3
Composite	Up to 3

*The time range is the expected life extending benefit given to the pavement, not the anticipated longevity of the treatment.

Overband Crack Filling

Description: Overband Crack Filling consists of cleaning the crack in the bituminous pavement surface and placing the specified materials into and above the crack to substantially reduce infiltration of water and to reinforce the adjacent pavement.

Purpose: The purpose of overband filling the cracks in the surface of the bituminous pavement is to prevent water and incompressible materials from entering the pavement structure. This treatment is commonly used as a surface preparation for the Micro-Surface and Chip Seal treatments. Use as a stand-alone preventive maintenance treatment, due to excess wear or failure shall be limited to older pavements where the cut and seal method is suitable.

Existing Pavement Condition: The condition of the existing bituminous surface depends upon the other preventive maintenance treatment that Overband Crack Filling treatment will be used as a surface preparation. Overband Crack Filling should be used to fill all non-working cracks. Table 2.11 gives performance criteria for distress index, ride quality index, and rut depth as to when overband crack filling should be applied.

Table 2.11 – MDOT Performance Thresholds for Overband Crack Filling (MDOT, 1998)

Pavement Type	Minimum RSL (years)	D.I.	R.Q.I.	Rut Depth
Flexible	7	<20	<54	<3mm
Composite	7	<10	<54	<3mm

Performance: This treatment will help extend the service life of the surface treatment it is being used with as a pretreatment. Stand-alone overband crack filling will also extend the life of the pavement structure. Table 2.12 gives the estimated life extension for overband crack filling for flexible and composite pavements.

Table 2.12 - Estimated Life Extension for Overband Crack Filling (MDOT, 1998)

Pavement Type	Years*
Flexible	Up to 2
Composite	Up to 2

*The time range is the expected life extending benefit given to the pavement, not the anticipated longevity of the treatment.

Bituminous Shoulder Ribbons

Description: This work includes the construction of a new bituminous shoulder ribbon where gravel shoulders exist or the removal and replacement of a deteriorated bituminous shoulder ribbon.

Purpose: The purpose of a bituminous shoulder ribbon is: (1) to accommodate an increasing encroachment of traffic, (2) to expedite runoff water from the traveled lane pavement, (3) to provide other usage such as bicycle paths, (4) to reduce edge stresses and edge and corner deflections by increased lateral support, and (5) to reduce the development of pavement edge drop-offs.

Existing Pavement Condition: In order for this treatment to be used in the CPMP, the condition of the adjacent pavement structure must meet the CPMP's pavement condition criteria. The design life of the shoulder ribbons should be equal to or less than the Remaining Service Life (RSL) of the main line pavement.

Performance: Most shoulder deterioration is attributable to truck encroachment, water intrusion in the longitudinal joint, use of lower quality materials, and inadequate structural thickness. Field observations have shown that shoulder distress is primarily concentrated within 0.6 m from the traveled lane. The extension of pavement life will be up to 3 years.

Ultra-Thin Bituminous Overlay

Description: A dense-graded bituminous mixture limited to 49-kg/m^2 application rate and a maximum average thickness of 20 mm.

Existing Pavement Condition: The existing pavement condition should exhibit a good base condition and a uniform cross section. The visible surface distress may include slight raveling, minor surface irregularities, and slight polished surface. The cross sections should be free of ruts or distortions. Table 2.13 gives performance criteria for distress index, ride quality index, and rut depth as to when an ultra-thin bituminous overlay should be applied.

Table 2.13 – MDOT Performance Thresholds for Ultra-Thin Bituminous Overlay (MDOT, 1998)

Pavement Type	**Minimum RSL (years)**	**D.I.**	**R.Q.I.**	**Rut Depth**
Flexible	7	<20	<54	<3mm
Composite	7	<10	<54	<3mm

Performance: This treatment performs best on surfaces that are distortion free and exhibit very little crack sealing material that may bleed through the mat. Table 2.14 gives the estimated life extension for the ultra-thin bituminous overlay for flexible and composite pavements.

Table 2.14 - Estimated Life Extension for Ultra-Thin Bituminous Overlay (MDOT, 1998)

Pavement Type	Years*
Flexible	3 to 5**
Composite	3 to 5**
**It is acknowledged that an ultra-thin bituminous overlay will provide a life extension to a pavement; however data is not available to quantify the life extension.	

*The time range is the expected life extending benefit given to the pavement, not the anticipated longevity of the treatment.

2.5 Selecting Appropriate Treatment and Timing

Three factors affect the future performance of a highway; they are the applicability of the treatment, application time, and quality of the maintenance it receives [10]. It is understood that inexpensive preventive maintenance activities are more economical than high cost rehabilitation/reconstruction treatments; engineers must recognize the causes of pavement deterioration and apply appropriate treatments at the right time during the pavement life.

The first factor that should be looked at is the applicability of the treatment. Each preventive maintenance fix serves a certain purpose. If the appropriate fix is not applied, the life extension of the preventive maintenance fix will be drastically shortened. Hicks, Dunn, and Moulthrop have developed decision trees to determine the appropriate fix for various distresses [11]. These distresses include roughness, rutting, cracking, structural condition, and bleeding. The decision trees take into account several factors that cause a pavement to deteriorate over time. Some of these variables are traffic, stability of the pavement structure, types of cracking, and material related distresses. Thus a decision maker can identify the distresses in the asphalt pavement and from that select an appropriate maintenance strategy. Hicks, Moulthrop, and Daleiden developed a table for selecting the appropriate treatment based on distress type, as can be seen in Table 2.15

[10]. From this table an engineer can identify the distress in the field and then select the appropriate fix for the distress.

Table 2.15 - Appropriate Maintenance Strategies for Various Distress Types (Hicks, et.al, 1998)

	Preventive Maintenance Treatments							
Pavement Distress	Crack Sealing	Fog Seal	Micro-Surfacing	Slurry Seal	Cape Seal	Chip Seal	Thin Overlay	Mill or Grind[a]
Roughness - Nonstability Related			X		X		X	X
Roughness - Stability Related							X	
Rutting			X	X	X		X	
Fatigue Cracking								
Longitudinal & Transverse Cracking	X	X	X	X	X	X	X	
Bleeding			X			X		X
Raveling		X	X	X	X	X		

Key: X=appropriate strategy

[a]This is a corrective maintenance technique.

Hicks, Moulthrop, and Daleiden also developed a decision matrix to include the effects of several variables in the selection process of the appropriate fix [10]. These rating variables are determined based on the level of significance and then multiplied by a scoring factor based on level of importance to give a total score for that variable. The total scores are then summed together for each variable, and the same procedure is repeated for different fix types. The fix type with the highest score will be the one to use for that specific project.

Selection of the appropriate fix/treatment is a difficult task as numerous factors affect the selection of the appropriate maintenance according to Table 2.16 [24].

Table 2.16 - Factors Affecting Preventive Mainenance Treatments

Type and extent of distress	Traffic loading
Climate	Existing pavement type
Cost of treatment	Expected life
Availability of qualified contractors	Availability of quality materials
Time of year of placement	Pavement noise
Facility downtime	Surface friction

Once one understands the above factors and how they influence each potential treatment, then the selection of the most cost effective treatment can be done.

The next critical element in a preventive maintenance program is the determination of the application time of a given fix. This is illustrated in Figure 2.1 and Figure 2.2 according to the MDOT [13]. A distress value of fifty (50) points or less indicates a pavement in "satisfactory" condition, while a distress value of more than fifty (50) indicates a pavement in "unsatisfactory" condition. Figure 2.1 shows the pavement life extension when a preventive maintenance treatment is applied at the appropriate time to a pavement in "satisfactory" condition. Figure 2.2 shows the result when a preventive maintenance treatment is applied to a pavement in "unsatisfactory" condition. From these figures certain conclusions can be drawn. Treatments applied to severely distressed pavements receive little benefit. However, if treatments applied to pavements with light to moderate distress, the same treatment provides substantial benefit by significantly extending the life of the pavement. Note that while the curves for Figure 2.1 and 2.2 are linear, this may not be the case for most pavements. The figures are therefore just for illustration purposes.

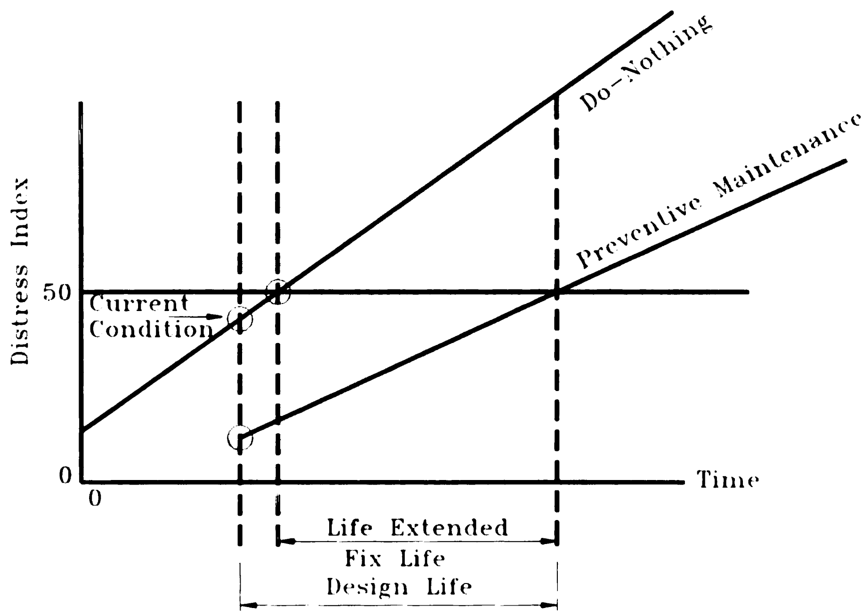

Figure 2.1 - Properly Applied Preventive Maintenance (Galehouse, 1998)

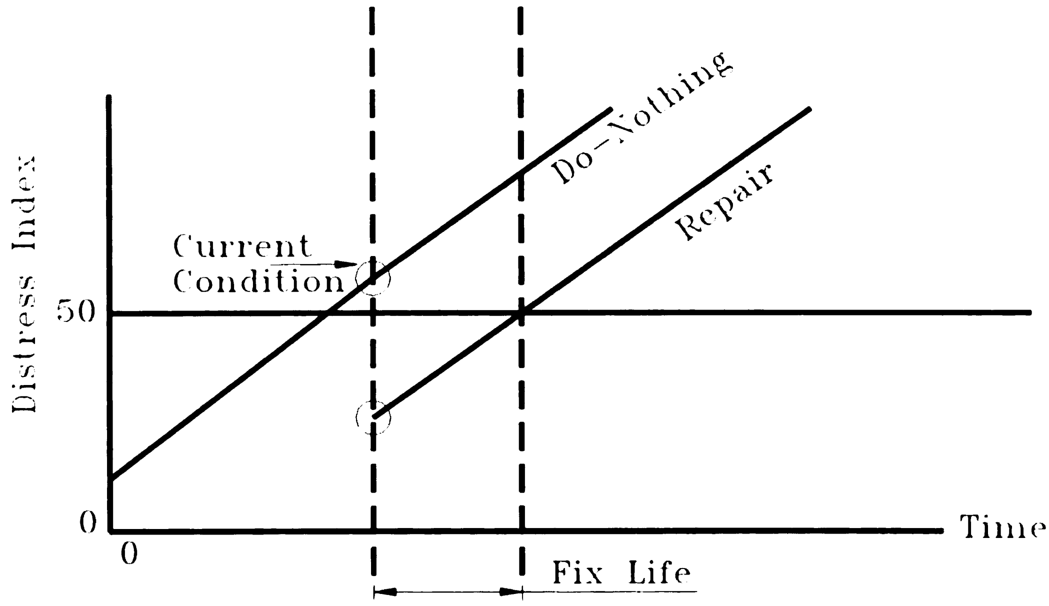

Figure 2.2 - Delayed Preventive Maintenance (Galehouse, 1998)

Figure 2.3 is an example of a decision making process that can be used in order to determine the timing of a treatment for a specific project. Using the data from a pavement condition survey on a scale of one to one hundred, threshold limits can be determined to define when a treatment type should be optimally applied.

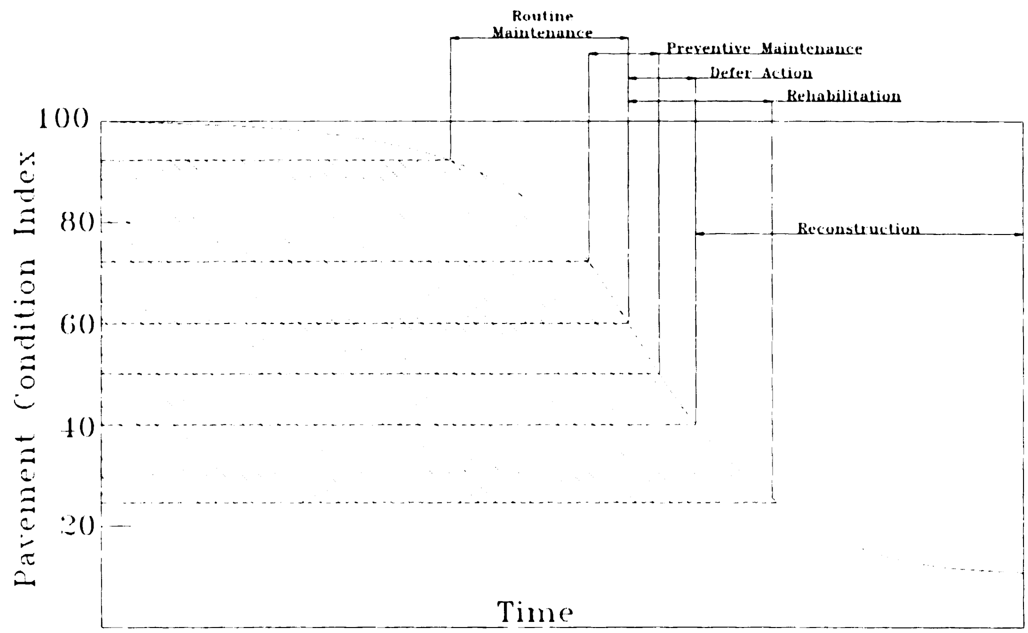

Figure 2.3 - Conceptual Relationship for Timing of Various Maintenance and Rehabilitation Treatments (Hicks et. al., 1998)

In summary, factors affecting the performance of a pavement that is subjected to preventive maintenance include the timing of the preventive maintenance activity, selection of the appropriate maintenance fix, and the construction problems and quality of materials. If all these factors are taken into account, then the appropriate fix will provide a smooth, high-quality facility that the public expects.

2.6 Performance Findings from Previous Studies

Various studies have been done to determine the life extension and optimal timing of preventive maintenance fixes. The models used to determine the life extension and optimal timing include: survival modeling, probabilistic modeling, regression and other statistical analyses, and field reviews.

2.6.1 Survival Modeling

A survival analysis of SPS-3 sites in the southern Long Term Pavement Performance (LTPP) region was conducted in 1999 [9]. The objectives of the study were to determine the following:

- The fix treatment life expectancy of the treatment (i.e. median survival time),
- The timing of the treatment application (i.e. was the pre-existing condition of the pavement in poor, good, fair, or excellent condition), and
- The benefit of the treatment in terms of life extension as compared with the "do nothing" option.

The Kaplan-Meier method, which is a nonparametric survival analysis technique, was used in determining the life expectancy and life extension. The survival probability for each fix can be estimated by using the calculated survival time on those pavements in which a fix was applied and then allowed to deteriorate until a poor condition is assessed. The failure probability is calculated as 1-P[survival]. Therefore the failure probability is a function of age only. The six year failure probability and the median survival times for the different treatments are shown in Table 2.17. The added life is calculated by taking the difference between the median survival time for the treatment and the median survival time for the control curves corresponding to the same original condition.

Table 2.17 - Results of 1999 Southern Region SPS-3 Survival Analysis (Elthahan et. al.)

Treatment	Original Condition	6-Year Failure Probability (%)	Average Median Survival Time (Years)	Average Median Benefit Compared to no Treatment (Years)*	Median Survival Time with No Treatment (Control Sections)**
Thin Overlay	Good	25	7.5	2.2	5.5
	Fair	30	7.3	4.8	1.5
	Poor	100	2.2	2.5	0
Slurry Seal	Good	48	6.5	2	5.5
	Fair	57	5	3.5	1.5
	Poor	100	2.5	2.5	0
Crack Seal	Good	50	6.5	1	5.5
	Fair	41	7.2	5.7	1.5
	Poor	100	0.75	0.75	0
Chip Seal	Good	25	N/A	N/A	5.5
	Fair	25	N/A	N/A	1.5
	Poor	32	N/A	N/A	0

*Median survival time is the number of years until 50% of the sections to which the treatment was applied failed.

**Median benefit compared to no treatment is the number of years a treatment adds to the median survival time compared to no treatment.

Elthahan et. al showed that after six years of treatment, sections with a poor condition had a probability of failure of 83% whereas those with a fair or good original condition had a probability of failure of 38% and 37%, respectively. The median survival times (life extension) for thin overlays, slurry seals, and crack seals were 7.0, 5.5, and 5.0 years, respectively. The chip seal sections did not reach the 50 percent failure probability after eight years of experiment. Therefore chip seals were concluded to have outperformed thin overlays, slurry seals, and crack seal treatments.

2.6.2 Regression Modeling

Morian et. al. used SPS-3 performance data and applied regression analyses in a 1998 study [51]. The data analyzed included distress, deflection, roughness, rut depth, and friction data. Prediction models using multiple regression were developed for cracking, rutting, roughness, friction, and an index called the Pavement Rating Score (PRS). The purpose of this study was to:

- Determine the effective timing of the various treatments,
- Evaluate the effectiveness of the different treatments, and
- Share information and experience among the profession.

Results of this study are summarized below:

- The structural adequacy was not found to have a significant effect on the performance of the SPS-3 treatments. Structural adequacy is "the actual structural number of the test section divided by structural number requirements to carry the section traffic volume." This means that "the pavements with inadequate structure performed as well, or as poorly, as those with adequate structure."

- There was an immediate reduction in rutting for the thin overlay treatment. Slurry seal sections rutted at a lower rate and chip seal sections at a slightly faster rate compared to the control section.
- Thin overlay achieved significant reductions in roughness; chip seals and slurry seals had a slight reduction, and crack seals did not reduce roughness.
- Composite regression curves (good, fair, and poor curves combined into one curve) were developed for each fix type and climatic region. This will allow for the determination of the life extension for each fix based on a threshold for the PRS.

Rajagopal et. al. looked at how timing and level of maintenance affect the deterioration rate and pavement life-cycle for three maintenance treatments [15]. They developed nonlinear regression models using pavement age, cumulative equivalent single-axle loads, composite structural number, life-cycle before overlay and thickness of the proposed treatment to determine the pavement condition rating (PCR) at some time (t). A relationship that included the preexisting condition of the pavement was also developed. From the regression equation, if one enters the PCR before the preventive maintenance action then one can estimate the PCR after the preventive maintenance action. Performance curves can then be developed showing the PCR versus age, and from these one can make a decision as to when the preventive maintenance should be applied.

Sebaaly et. al. developed a model that relates the present serviceability index (PSI) to age, material properties, traffic loading, and climate [18]. These performance models were for the flexible pavement maintenance treatments commonly used by the Nevada Department of Transportation (NDOT). For each NDOT district and fix type the actual PSI was compared with the PSI calculated by the developed model for validation since the model is only applicable to the range of values it was developed from. The majority of the models had R^2 values greater than 70% which indicates a good fit between the model and the data. Once the model is validated it can be used as a preventive maintenance tool to plan ahead for future activities.

Kuo et. al. looked at the projected rate of deterioration of pavement segments in Florida due to traffic, speed limit, rainfall, temperature, work-mix, historical condition ratings, distress types, pavement thickness, age, and most recent year-to-year rating decline [56]. An analysis was made to determine the appropriate response variable and predictor variables in the prediction model with statistical tests conducted to finalize the predictor variables for the model. The validity of the prediction model was compared with the predicted condition ratings. The model solves for the number of years until failure based on cracking given the amount of cracking at the current year. Once the model is validated it can be used as a preventive maintenance tool to plan ahead for future activities.

2.6.3 Statistical Modeling

Hall et. al. used Dunnet's method of Multiple Comparison with Control (MCC) to analyze LTPP data from the SPS-3 experiment. The following objectives were sought [47]:

- The initial effects, if any, of the fix type on the pavement condition,

- The long term effects, if any, of fix type on the performance of the pavement,
- The influence, if any, of the pre-existing condition of the pavement, and
- The relative effectiveness of the different preventive maintenance fixes.

The pavement condition measures were roughness (IRI), rutting, and fatigue cracking. The Dunnet's MCC method is a statistical test that defines a confidence interval for the difference between the observed values in the treated section versus the observed value in the control section. If zero is in the confidence interval then there is a significant effect of the treatment on the change in the pavement condition. This analysis was used for each fix type and for analyzing each objective using the pavement condition measures outlined above. The treatments used in this experiment were thin overlay, chip seal, slurry seal, and crack seal.

This study resulted in the following conclusions. In terms of roughness, rutting, and fatigue cracking, the most effective maintenance treatment in the SPS-3 experiment was a thin overlay followed by the chip seal treatment and then the slurry seal treatment. The thin overlay treatment was the only fix type to produce a small reduction in roughness and the only one to have a significant effect on long-term roughness relative to the control sections. For very rough pavements, chip seal and slurry seal had a small effect on long-term roughness relative to the control sections. Crack seals did not have a significant effect on long -term rutting, roughness, or fatigue cracking.

2.6.4 Probabilistic Modeling-Markovian Chains

The Markov Model is a very powerful probabilistic method that can be used as a decision making tool for determining optimal maintenance and repair strategies. Butt et.

al developed a Markov model that related pavement condition index (PCI) to pavement age [39]. Li et. al. looked at the deterioration of a pavement (pavement condition state (PCS)) over time due to traffic and climate [17].

The general process of a Markov model is as follows: There is a certain number of pavement sections in different "states/conditions" over time. These sections deteriorate into different "states" each year. This results in a Transition Probability Matrix (TPM). Each matrix element is the probability of a pavement being in that "state" the ensuing year. The validity of the model can be accomplished by plotting the actual PCI curve compared with the predicted PCI curve. The Markov process can be used in determining optimal pavement strategies for all pavement sections in the network.

2.6.5 Engineering Field Review of SPS-3 Projects

In the summer and fall of 1995, four Expert Task Groups (ETG's), one in each LTTP Region, visited and performed site reviews on fifty-seven SPS-3 sites [38]. The ETG members rated the pavements based on overall pavement condition irrespective of fix type, the overall condition of the fix types, the overall effectiveness of the fix types (in terms of the amount of distresses present), and whether or not the fix was appropriate. After analyzing the data the ETG's concluded that after five years of field performance the treatments have reduced the presence of cracking. The best performing treatments were thin overlays and chip seals as compared to the slurry seal and crack seal.

2.6.6 Engineering Field Review of MDOT's CPM Program

In 1999, 2000, and 2001 B.T. Bellner and Associates conducted a field review and data base study on the MDOT's Capital Preventive Maintenance (CPM) Program

[50]. The purpose of this study was to assess the overall effectiveness of the CPM Program and to make any improvements, if necessary. The field review was conducted to see if the CPM work met the warranty criteria and to evaluate the overall condition of the pavement surface such that a comparison can be made with the DI calculated in the MDOT's PMS database.

The consulting firm reviewed and reported on the following flexible preventive maintenance treatments: Single chip seal, sealing cracks in bituminous pavements, non-structural bituminous overlay, surface milling with non-structural bituminous overlay, micro-surfacing, overband crack sealing, double chip seals, ultra-thin bituminous overlays, flexible designed micro-surfacing and hot in-place bituminous recycling. Each project for each fix type was reviewed; field data were collected independently, and a report was written. After assessing all the projects, conclusions were drawn for each fix type.

B.T. Bellner and Associates reported that, overall the CPM Program had been successful in extending the life of the pavements. The majority of the projects were constructed prior to the CPM Program Guidelines in 1998. The projects were found to be cost-effective by extending the life of pavements at lower costs. The report did not rate the different fixes relative to each other.

2.7 Conclusions

The objective of this research is to determine the life expectancy of the preventive maintenance fixes and to evaluate the PM guidelines based on PMS data from the MDOT. From this literature review it can be concluded that the majority of the pavement performance models predict some future performance of the pavement, which can then be used to determine whether or not a preventive maintenance action should be taken. Only the survival analysis model by Elthahan, et. al. determined the life extension for chip seal, crack seal, slurry seal, and thin overlay treatments. It has been determined that preventive maintenance is cost effective and extends the life of pavements. The majority of the authors in the bibliography agree that the optimal timing of preventive maintenance treatments is when the pavement is in good to fair condition. When the pavement is in poor condition, the increased risk of failure is two to four times higher according to Elthahan et. al.

Preventive maintenance is a tool that the highway agencies can use to improve the quality of the pavement network while reducing expenditures. This is based on the fact that preventive maintenance is more economical than the higher cost treatments of rehabilitation/reconstruction. If the do-nothing option is chosen the pavement will slowly deteriorate beyond the point where a maintenance treatment will be of any economical benefit. By applying the appropriate maintenance at the right time (pavement in relatively good condition) during the pavement life, it will increase the quality of the pavement network by improving its serviceability level.

CHAPTER 3 - THE MDOT PAVEMENT PERFORMANCE MEASURES

3.1 Introduction

In order for highway agencies to manage their pavements and to provide a smooth ride, anticipate future routine maintenance, and correct pavement deficiencies, they must collect pavement condition data of the entire pavement network.

The MDOT collects pavement surface distress data, longitudinal pavement profile data, and rut depth for every tenth-of-a-mile along the pavement network under its jurisdiction. Friction data are collected on a per need basis and are kept in the appropriate region. The data are collected on one-half of the network every year. Therefore data for the entire network are collected every two years. The data are described in the ensuing sections.

3.2 Surface Distress Data

The pavement distress survey in Michigan is accomplished by videotaping fifty percent of the network each year. The videotaping is carried out by a private contractor and administered by the MDOT central office. The videotapes are reviewed one frame (each frame contains ten feet of pavement) at a time in the central office. During the review, pavement distresses are documented for each frame. Hence, the MDOT distress data are detailed and can be used at both the network and project levels. The pavement distresses collected by the MDOT are listed in Table 3.1.

Table 3.1 - Pavement Distresses Collected by the MDOT

Pavement Type		
Flexible	Rigid	Composite
Transverse tears	Transverse joints	Transverse tears
Transverse cracks	Transverse Cracks	Transverse cracks
Longitudinal cracks	Intensive transverse cracks	Longitudinal cracks
Alligator cracks	Longitudinal cracks	Block cracks
Block cracks	Delamination	Patches
Patches	Reactive aggregates	Raveling
Raveling	High steel	Flushing
Flushing	Mudjacked areas	Intensive reflective cracks
Intensive miscellaneous cracks	Patches	Rut depth
Rut depth	Corner Breaks	Ride Quality
Ride Quality	Popouts	
	Scaling	
	Ride Quality	

The distress data are than grouped into 0.1-mile long unit sections. The pavement management system (PMS) databank contains detailed data for each type of pavement distress, severity, and extent for each 0.1-mile section.

The MDOT pavement management group has developed a rating system whereby each type of principal distress and its associated distress are ranked and assigned 'Distress Points' (DP) based on their impact on pavement performance and on experience. For any pavement section, the Distress Index (DI) can be calculated as the sum of the distress points along a section normalized to the section length as stated in equation 3.1.

$$DI = \frac{\Sigma DP}{L} \qquad (3.1)$$

where: DI = Distress index,

Σ DP = Sum of the distress points along the pavement section, and

L =Number of 0.1-mile pavement sections.

The DI scale starts at zero for a pavement in perfect condition and increases (without bound) as the pavement condition worsens. The MDOT categorizes DI into three levels as shown in Table 3.2.

Table 3.2 - Distress Index Categories

Category	DI Level
Low	< 20
Medium	20-40
High	>40

A pavement with a DI of fifty or higher is considered to be in unacceptable condition and has therefore exhausted its service life. This DI-threshold value is based on historical pavement performance.

3.3 Longitudinal Pavement Profile Data

The longitudinal pavement profile is collected by the MDOT using a rapid inertial profiler. The system, which is composed of laser sensors mounted on a utility vehicle, measures the longitudinal profile of the road and records the data in three-inch increments. An onboard computer analyzes the data for each 0.1-mile of pavement and calculates the International Roughness Index (IRI) and the Ride Quality Index (RQI). The former is calculated to satisfy the Federal Highway Administration requirements and the latter is for use by the MDOT. The RQI is a weighted sum of the variances in elevation from three wavelength bands (short, intermediate, and long waves). The RQI has been calibrated to relate with the human perception of ride. The RQI scale starts at zero for a perfectly smooth pavement and increases (without bound) as the pavement gets rougher. Higher RQI implies lower ride quality. The RQI scale is subdivided into various categories as shown in Table 3.3.

Table 3.3 - Ride Quality Categories

RQI	Ride Quality Categories
0 to 30	Excellent
31 to 54	Good
55 to 70	Fair
>70	Poor

3.4 Rut Depth

Pavement rutting is also collected by the MDOT. The average rut depth for each 0.1-mile section is calculated and stored in the data bank. Unfortunately rut depth will not be used in the analysis since the MDOT database has only two years of data for this performance measure (1998 and 1999).

3.5 Friction Data

Pavement friction data are collected as requested by the different regions. The friction data are then kept in that region. Friction data will not be used in the analysis.

3.6 MDOT's Definition of Life Extension

According to the MDOT, the life extension from a preventive maintenance treatment is defined as follows:

$$\text{Life Extension} = RSL_2 - RSL_1 \tag{3.2}$$

Where RSL_1 is the remaining service life of a pavement section at the time of the preventive maintenance fix and RSL_2 is the remaining service life of the pavement section after being treated by the preventive maintenance fix.

The remaining service life (RSL) of a pavement section at a given time is defined by the MDOT as the time duration for a pavement section to reach the threshold distress index value of fifty. This can be estimated by extrapolation using some performance model with time. The MDOT uses a logistic growth function as their DI performance curve.

CHAPTER 4 - EXTRACTION AND DEVELOPMENT OF DATABASE

4.1 Introduction

The distress index and ride quality index data were acquired from the MDOT PMS database. The data were given in 0.1-mile increments for each project. A list of preventive maintenance projects was compiled by the PMS group at the MDOT from 1992 to 2001. The projects chosen for this research received a PM action sometime between 1993 and 1996. These years were selected because it would be possible to get some insight as to how the pavement performed prior to the fix and how the pavement performed after the fix. The pavement performance several years after the fix would allow us to compare the life expectancies calculated by the reliability analysis with current MDOT's life extension estimates for different preventive maintenance fixes.

4.2 Extraction of Data

The different projects were grouped according to fix type: 1) Non-Structural Bituminous Overlay; 2) Surface Milling and Non-Structural Bituminous Overlay; 3) Single Chip Seal; 4) Multiple Course Micro-Surface; and 5) Bituminous Crack Seal. Pavements where the DI or RQI decreased with time were not used in the analysis. The projects where the DI or RQI decreased with time were excluded because pavements performance should decrease with time, therefore it was assumed that some sort of action was taken to improve the condition of the pavement surface. This analysis looks at pavements that have had only one PM action taken. Also, the DI for pavements that had a subsequent preventive maintenance fix after the initial PM fix were not used because this project looks at the effect of single PM treatments and not multiple fixes. There were not enough data available to look at the effect of applying a mix of PM treatments to pavement surfaces. Figure 4.1 and 4.2 illustrate pie charts with the number of projects used for each fix type for DI and RQI, respectively.

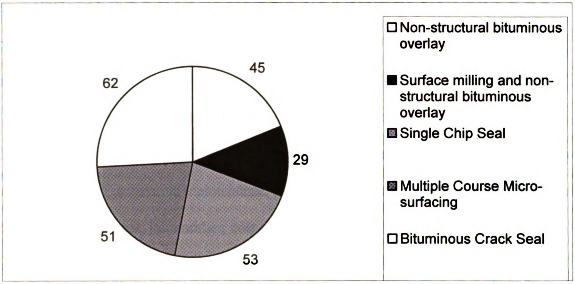

Figure 4.1 - Number of Preventive Maintenance Projects with Distress Index Data

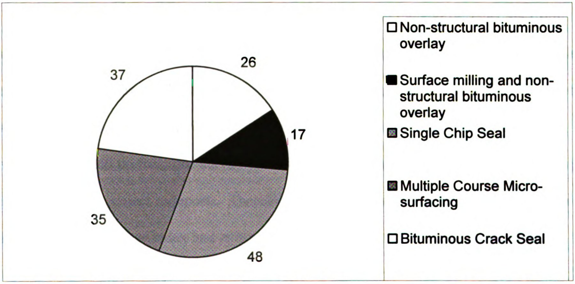

Figure 4.2 - Number of Preventive Maintenance Projects with Ride Quality Index Data

The automated PMS data collection at the MDOT originated in 1992. Therefore using projects from 1993 to 1996 would give the pre-existing condition of the pavement as well as the condition one to eight years after the preventive maintenance fix. Projects from 1997 and later would not provide additional insight into the life expectancy of the preventive maintenance fixes due to the lack of data available after the preventive maintenance action.

The first step in the research was to obtain a list of the preventive maintenance fixes that were done from 1992 to 2001. This database included all relevant information including year of preventive maintenance, route number, control section, beginning mile post, ending mile post, job number, cost of activity, and fix type. The data were filtered in order to obtain a set of projects from 1993 to 1996 that have had only one preventive maintenance treatment applied to them.

4.3 Development of Database

The next step was to develop a database by extracting the appropriate data from an individual project data file. This was done according to the beginning and ending mile posts. Distress Index and Ride Quality Index data are in separate data files; therefore two separate databases were compiled for each project. The surveyed distress index did not necessarily match up from one survey year to the next and also did not necessarily line up according to the project mileposts. Therefore the data had to be rearranged to correct for this, and a new distress index had to be calculated based upon the actual project limits.

This new distress index was formulated based on some assumptions. The first assumption is that the 0.1-mile distress index value is an average value over that 0.1-mile. The second assumption is that the variation of the distress index between measured points is piece-wise linear. This would allow us to use linear interpolation to calculate the distress index at a new point along the project length, as can be seen in the schematic diagram of Figure 4.3.

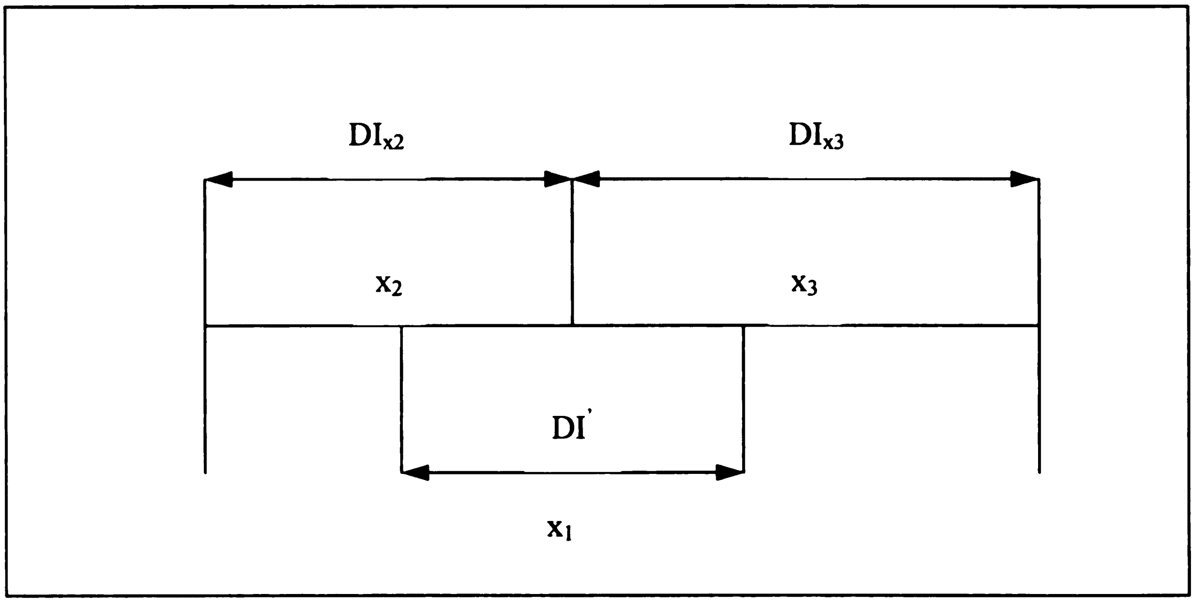

Figure 4.3 – Schematic drawing showing the above calculation

The equation used is as follows:

$$DI' = DI_{x2} - \frac{(x_2 - x_1)\times(DI_{x2} - DI_{x3})}{(x_2 - x_3)} \tag{4.1}$$

where:

DI'=New distress index calculated at a new milepost,

DI_{x2}=Distress Index at milepost 2,

DI_{x3}=Distress Index at milepost 3,

x_1= Section Length (at every 0.1 mile),

x_2=Survey length 2 (at every 0.1 mile), and

x_3=Survey length 3 (at every 0.1 mile).

This calculation was not needed for the ride quality index because the ride quality index was taken at the same point from year to year.

4.4 Compilation of the Data

The final step was to determine the DI and RQI values prior to the preventive maintenance fix at year one, year two, year three, year four, year five, year six, year seven, and year eight after the preventive maintenance fix. Determination of the condition of the pavement was calculated by taking the average DI or RQI over 0.1-mile sections within the project length for each survey year. This would allow us to determine if the DI or RQI increased or decreased from one survey year to the next. If the pre-existing condition was unknown for the year the preventive maintenance was done or decreased down to zero (i.e. the road was surveyed after the preventive maintenance) the DI from the previous year would be used as the pre-existing condition. The future performance of the preventive maintenance fix was calculated by using the DI or RQI at year one, year two, year three, year four, year five, year six, year seven, and year eight after the preventive maintenance fix. For example, if the preventive maintenance action occurred in 1994 and the pavement was surveyed in 1992, 1994, 1996, 1998, and 2000, then one would have the pre-existing condition along with the DI two years after the fix, four years after the fix, and six years after the fix.

CHAPTER 5 - RELIABILITY BASED MODEL AND ANALYSIS

5.1 Introduction

The word reliability infers dependability, trustworthiness, and steadiness. The mathematical definition of reliability is the probability that a system will not fail. Therefore, a system is considered reliable until it fails. The reliability value can be calculated as:

$$R=1-Pr(f) \qquad (5.1)$$

where Pr(f) is the probability of failure.

In the area of pavement performance, the American Association of State Highway and Transportation Officials (AASHTO) defines reliability as "the probability that the pavement system will perform its intended function over its design life and under the conditions (or environment) encountered during operation…the probability that any particular type of distress will remain below or within a permissible level…during the design life [54]."

The term failure in engineering reliability refers to any occurrence of an adverse event such as a column buckling during an earthquake or a pavement that is distressed beyond a threshold value set by a highway agency. In this research study, the limiting value for probability of failure is given in the MDOT capital preventive maintenance program guidelines, which were described in Chapter 2. The use of reliability analysis stems from the fact that there is uncertainty/variability in the distresses, climate, construction, structural capacity, etc.

5.2 Reliability-Based Model

According to Pendleton, reliability-based models contain three sources of variability [53]:

- Variability in the output variables,
- Variability in the input variables, and
- Uncertainty in the model.

Figure 5.1 is a schematic diagram showing a general reliability modeling process. The input side of the model may consist of known equations developed through mechanics or physical laws of nature. The input model may also include a hypothesized probability or model or it could be totally unknown in which nothing is known about the mathematical model or the input variables. Whatever model a researcher chooses to use, one must always realize that there is some error in the modeling process. The goal is to determine what kind of inputs will produce the lowest amount of error and thus give reliable outputs [53].

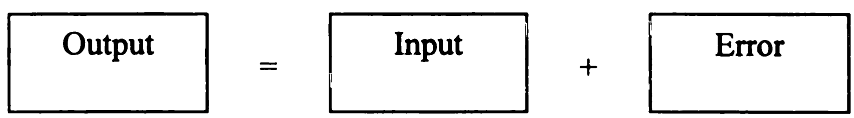

Figure 5.1 - Schematic Showing the Reliability Model (Pendleton, 1994)

In order to explain the developed model, pavements that have been treated with different preventive maintenance fixes will be used. Basically, an examination of how the various treatments perform based on the distress index (DI) and ride quality index (RQI) growth over time will be done. Some sources of variability include: traffic, environment, subgrade, pavement thickness, pre-existing condition, drainage, construction and material variability within fix types. For the most part, traffic (i.e. equivalent single axle loads, ESAL's) is less variable than the other variables since the preventive maintenance fixes are used mainly on low volume roads. One more source of variability is in calculating the DI since individual interpretation of the severity and extent of pavement distresses can vary. The goal is to have enough data where the variability will be minimized for those variables that may lead to an increase in the error.

The first step in doing a reliability-based model is the need for a large data set. The larger the data set is, the more defined the distribution becomes. In this research, the data used were obtained from the MDOT pavement management system (PMS). The MDOT uses four pavement performance parameters: Distress index, ride quality index, rut depth, and friction. This research project specifically looks at the distress index and ride quality index on pavements that have had a preventive maintenance activity done during the period from 1993 to 1996. The MDOT has distress index data from 1992 to 2001 and ride quality index data from 1992-1999. This will allow the examination of the pre-existing condition to see if it has a significant effect on future pavement condition. It will also provide up to eight years worth of performance data after the treatment.

Step two is to separate the projects into different preventive maintenance fix types so their effectiveness can be evaluated separately. The distress index and ride quality index for different years after the fix are used to monitor the performance of the fix. The distress index and ride quality index prior to the treatment are used to look at the effect of pavement condition prior to the fix on pavement performance after the fix.

Step three is to plot probability distributions of DI for each year after the treatment for each fix type. Frequency distributions of DI for each year after the treatment were plotted using the actual data. The reliability can then be calculated based on the MDOT's preventive maintenance guidelines. These distributions can be seen in Appendix A. Figure 5.2 is an example showing how the reliability is calculated graphically. The reliability based on a DI threshold of forty (40) is the area under the curve to the left of the limiting value.

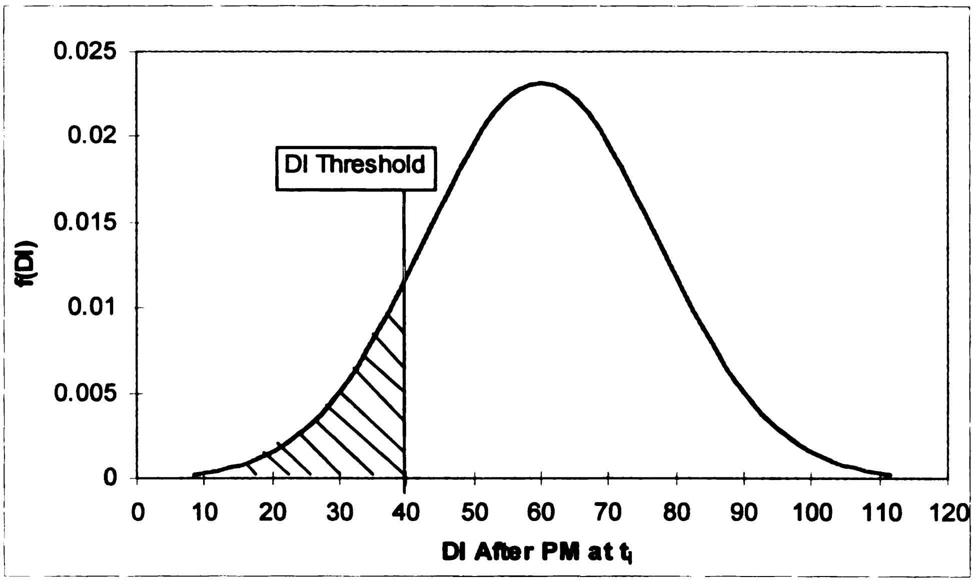

Figure 5.2 - Example Calculation for Reliability Analysis

The final step is to calculate the reliability for each year after the treatment. A table can then be produced showing the reliability values for each fix type at different years after the treatment. This will allow an engineer to estimate the life expectancy of a given fix using an acceptable reliability level. For example, the AASHTO recommends different reliability levels depending on the type of road and traffic volume, as shown in Table 5.1.

Table 5.1 - Suggested Levels of Reliability for Various Functional Classifications (AASHTO, 1986)

Functional classification	Recommended level of reliability (%)	
	Urban	Rural
Interstate and other freeways	85-99.9	80-99.9
Principal arterials	80-99	75-95
Collectors	80-95	75-95
Local	50-80	50-80

5.3 Reliability Analysis

The projects that were selected for the analysis were those preventive maintenance projects that were completed in 1993, 1994, 1995, and 1996. All the information (e.g. control section, project mileposts, and fix type) was given by MDOT so the appropriate project could be selected for the analysis. As described in Chapter 3, performance data in the form of DI and RQI values were available at 2-year intervals for 0.1-mile pavement sections. The preventive maintenance fixes that were looked at included: Non-structural bituminous overlay, surface milling and non-structural bituminous overlay, single chip seal, multiple micro-surfacing, and bituminous crack treatment.

A reliability analysis was performed on each fix type in order to determine the life expectancy for each treatment. Frequency distributions of DI at different years after the preventive maintenance activity were plotted for each fix type. Based on the actual distributions of DI values, the reliability was calculated as the number of the sections that have distress indices that are less than the DI guideline value divided by the total number of sections surveyed for that year. Table 5.2 shows the number of data points corresponding to 0.1-mile pavement sections for each fix type at different years after the preventive maintenance activity.

Table 5.2 - Number of Data Points for Each Fix Type

	Time After PM Fix							
Fix Type	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Bituminous Overlay	945	1261	879	862	439	344	159	105
Mill & Fill	210	566	169	407	88	17	9	0
Chip Seal	1775	1276	1312	823	1269	559	306	0
Micro-Surface	1015	1363	913	976	742	539	111	0
Crack Seal	1877	2596	1360	2472	1370	1094	628	83

5.4 Two-Sample t-test for Significance

Knowing when to apply the preventive maintenance activity is critical for a pavement management team. If the treatment is applied too early, its effect on pavement performance may not be as beneficial. On the other hand, if it is applied too late, the fix will not last as long, thus reducing the economic benefit. Therefore there is a need for evaluating the guideline limits at which a preventive maintenance fix should be applied. In order to accomplish this, a two sample t-test was used on two populations:

- Population One: Those pavements whose pavement performance parameter was less than the limiting value at the time of the preventive maintenance activity.
- Population Two: Those pavements whose pavement performance parameter was greater than the limiting value at the time of the preventive maintenance activity.

The goal of the two sample t-test is to compare the response in two groups assuming that the response in each group is independent of that in the other group. In order to use the t-test on sample sizes that are not equal, the data should be approximately normally distributed and meet the following criteria for sample size populations [27]:

- Sum of Sample Sizes is less than 15: Use t-test only when the data is normally distributed. If the data is clearly non-normal or outliers are present, do not use this statistical test.
- Sum of Sample Sizes is greater than 15 and less than 40: t-test can be used except when there are strong outliers or strong skewness.
- Sum of Sample Sizes greater than or equal to 40: t-test can be used even for distributions that are skewed.

5.4.1 Pavement Condition Using Distress Index (DI)

A two sample t-test was conducted in order to evaluate the DI guidelines that the MDOT imposes for the different preventive maintenance fixes. Under consideration will be the mean distress index for two populations:

- Population One: DI values less than or equal to the DI guideline values at the time of the preventive maintenance activity.
- Population Two: DI values greater than the guideline values at the time of the preventive maintenance activity.

For each treatment, mean distress indices at subsequent years were analyzed using this method. Below are the formulated null and alternative hypotheses:

- H_o: Mean DI at time (t_i) of population one equals mean DI at time (t_i) of population 2 or
- H_A: Mean DI at time (t_i) of population one does not equal mean DI at time (t_i) of population 2.

The next step is to select the appropriate level of significance (1-α). An alpha value (α) of five percent (5%) was chosen in this case, which corresponds to a 95% level of significance. This level of significance is the most common one used in statistics. This value is then compared with the computed p-value from the t-test. If the computed p-value is less than the level of significance we then state that the data is significant at that level (1-α). The smaller the p-value, the stronger evidence against the null hypothesis is provided by the data.

One can either accept or reject the null hypothesis based on comparing the computed estimate of the test statistic with the test statistic (from the p-value) estimated by the degrees of freedom and level of significance. If the computed value lies within the region of rejection defined by the alternative hypothesis (the critical value) then the null hypothesis is rejected. The distributions for each fix type and year after the preventive maintenance activity are given in Appendix B along with the population sample size.

5.4.2 Pavement Condition Using Ride Quality Index (RQI)

A two sample t-test was conducted in order to determine the relevance of the RQI guideline values that the MDOT imposes for the different preventive maintenance fixes. Under consideration will be the mean distress indices at subsequent years for two populations:

- Population One: RQI values less than or equal to the RQI guideline values at the time of the preventive maintenance activity.
- Population Two: RQI values greater than the guideline values at the time of the preventive maintenance activity.

For each treatment, mean distress indices at subsequent years were analyzed using this method. Below are the formulated null and alternative hypotheses:

- H_o: Mean DI at time (t_i) of population one equals mean DI at time (t_i) of population 2 or
- H_A: Mean DI at time (t_i) of population one does not equal mean DI at time (t_i) of population 2.

The distributions for each fix type and year after the preventive maintenance activity are given in Appendix C along with the population sample size.

CHAPTER 6 - RESULTS

6.1 Introduction

A reliability analysis was performed using distress index (DI) data in order to determine the life expectancy for the various preventive maintenance treatments. For each fix type, distributions of DI of 0.1-mile sections were generated for various years following the preventive maintenance. For a given year, the reliability was calculated as the number of sections with distress indices that are less than the guideline value divided by the total number of sections for that year. The same procedure was done for subsequent years (i.e. one year after the PM action, two years after the PM action, etc.)

6.2 Determination of Life Expectancy of the Various PM Fixes

The life expectancy of a given fix is the time (in years) it takes for a pavement section that was subjected to the fix to reach a limiting DI value. The life expectancy for each fix type was determined by plotting the distributions of DI values at subsequent years after the fix and calculating the area under the curve to the left of the DI guideline value. The reliability values were then plotted over time; a quadratic function was fitted to the data points; and the 95% confidence intervals over the mean values were then plotted. From these graphs, tables can be developed for each treatment showing the reliability, plus or minus some error n years after the initial treatment.

It should be noted that the life expectancy of a fix as defined above is different from the life extension provided by the fix as defined by the MDOT. The definition of MDOT's life extension is provided in Chapter 3.

In order to check the validity of reliability values, the average distress index for each fix type was plotted over time. Because the analyzed pavement sections had only one preventive maintenance treatment applied to them, the distress index is expected to grow over time. Figure 6.1shows that the distress index for crack seal, micro-surface, mill & fill, and bituminous overlay increase with time except for year six and year seven. The distress index for chip seal for the most part increases with time, but has some variability which could be due to a number of factors. Given that these values represent the average over multiple pavement sections, and that the general trend is upward, it can be inferred that the data are reasonable for further analysis.

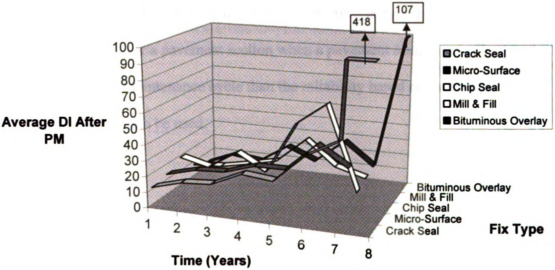

Figure 6.1 – Average DI after Preventive Maintenance versus Time

6.2.1 Non-Structural Bituminous Overlay

Figure 6.2 and Figure 6.3 show the reliability of the non-structural bituminous overlay versus time based on the PM guidelines and rehabilitation threshold, respectively. Figure 6.2 shows that the reliability is relatively constant up to year three and then starts to drop at a faster rate yet the reliability is still rather high at year six (78%). This agrees reasonably well with the MDOT's preventive maintenance guidelines, which state that the life extension for a non-structural bituminous overlay is five to ten years. Therefore one would not expect to see a very distressed pavement from year one to year five. Figure 6.3 shows that reliability based on the rehabilitation threshold over time is quite high up to year six (90%). Both of these figures show a small amount of variability around the mean value. Figure 6.2 will allow a highway agency to plan a preventive maintenance program for a pavement section when a pavement section gets close to the end of the preventive maintenance cycle than the reliability based on the rehabilitation threshold (Figure 6.3) can be used.

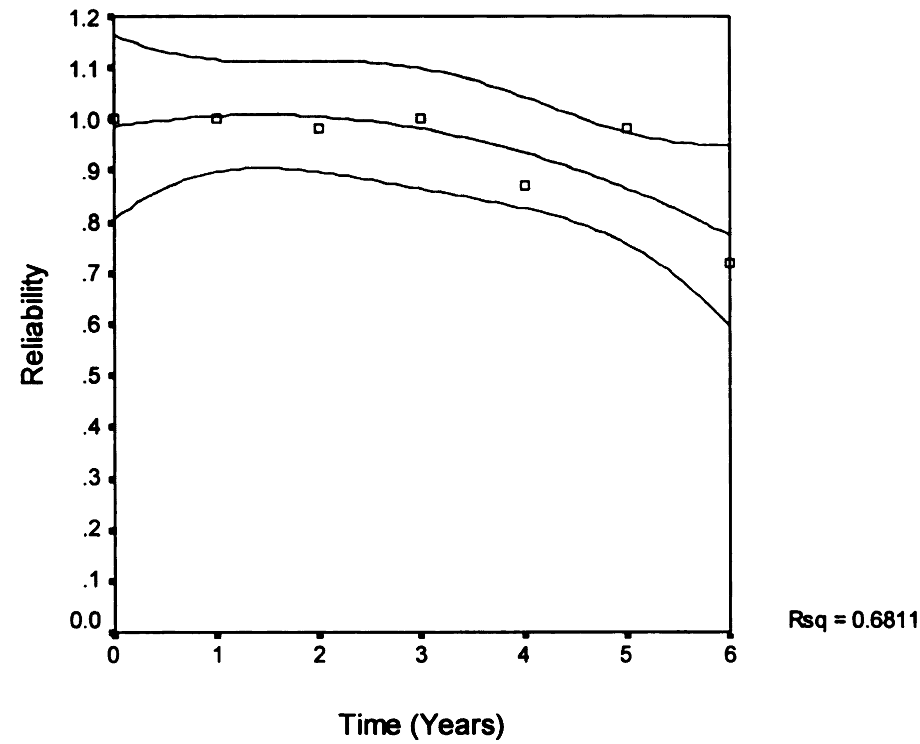

Figure 6.2 - Non-Structural Bituminous Overlay Reliability versus Time Based on the PM Guidelines (95% Confidence Interval)

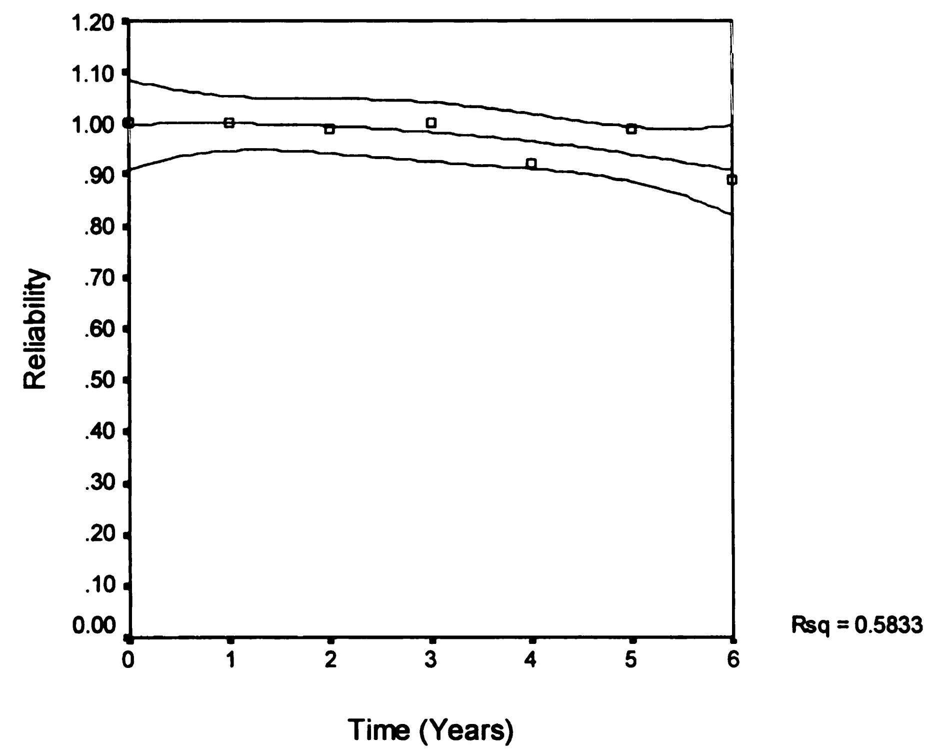

Figure 6.3 - Non-Structural Bituminous Overlay Reliability versus Time Based on the Rehabilitation Threshold (95% Confidence Interval)

6.2.2. Surface Milling with a Non-Structural Bituminous Overlay

Figure 6.4 and Figure 6.5 show the reliability of surface milling with a non-structural bituminous overlay treatment versus time based on the PM guidelines and rehabilitation threshold, respectively. The reliability is close to 100% for the first four years for both figures and the variability around the mean values is quite small. One would expect this since the MDOT life extension is from five to ten years. Therefore one would not expect to see a pavement that is very distressed from year one to year four since this treatment mills off the existing surface and a new bituminous overlay is placed to correct the existing distresses.

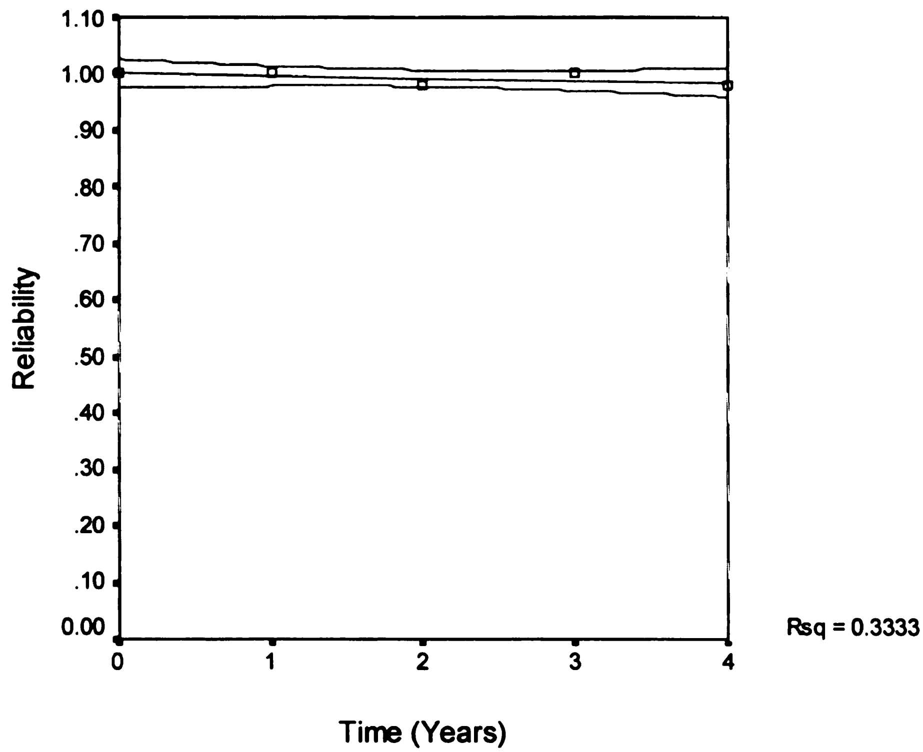

Figure 6.4 – Surface Milling with a Non-Structural Bituminous Overlay Reliability versus Time Based on the PM Guidelines (95% Confidence Interval)

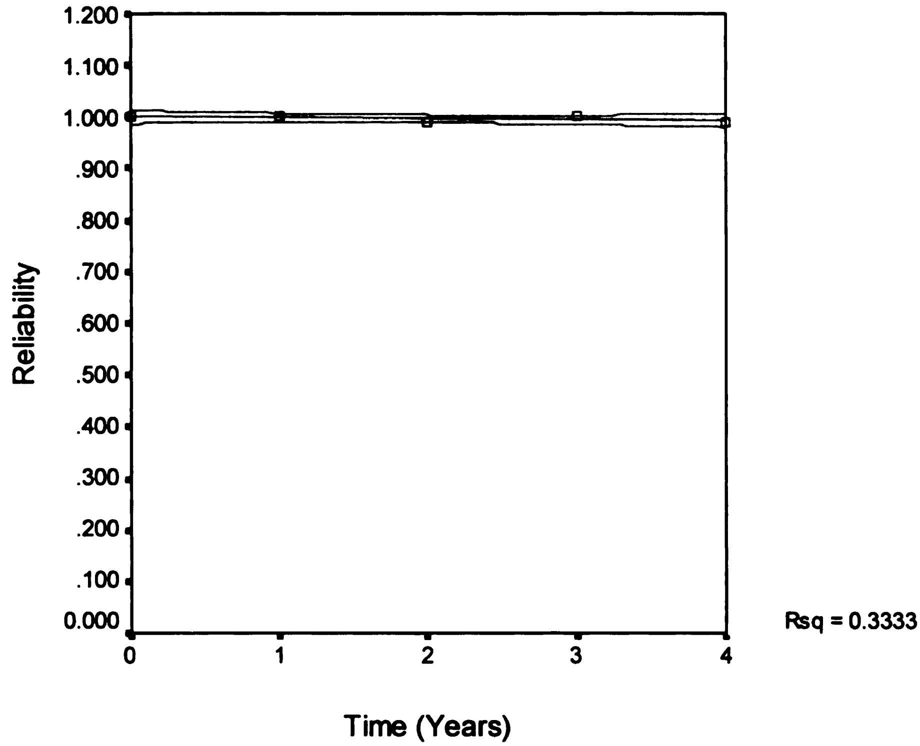

Figure 6.5 – Surface Milling with a Non-Structural Bituminous Overlay Reliability versus Time Based on the Rehabilitation Threshold (95% Confidence Interval)

6.2.3. Single Chip Seal

Figure 6.6 and Figure 6.7 show the reliability of the single chip seal treatment versus time based on the PM guidelines and rehabilitation threshold respectively. Figure 6.6 shows that there is quite a bit of variability around the mean reliability values. The overall trend for the mean values is to decrease with time with the rate of deterioration increasing after year three. Figure 6.7 shows the reliability over time based on the rehabilitation threshold. The variability around the mean value decreases with the overall trend showing that the reliability decreases with time. For a given year, the reliability value based on the rehabilitation threshold is higher than that from the preventive maintenance guideline, since the PM value is much more restrictive than the rehabilitation threshold. The results indicate that single chip seals have a reliability of about 80% after three years and about 60% after six years (±20%). The reliability values increase to about 90% after three years and about 70% after six years (±10%) when the rehabilitation threshold is used. This agrees reasonably well with the MDOT's preventive maintenance guidelines, which state that the expected life extension is three to six years.

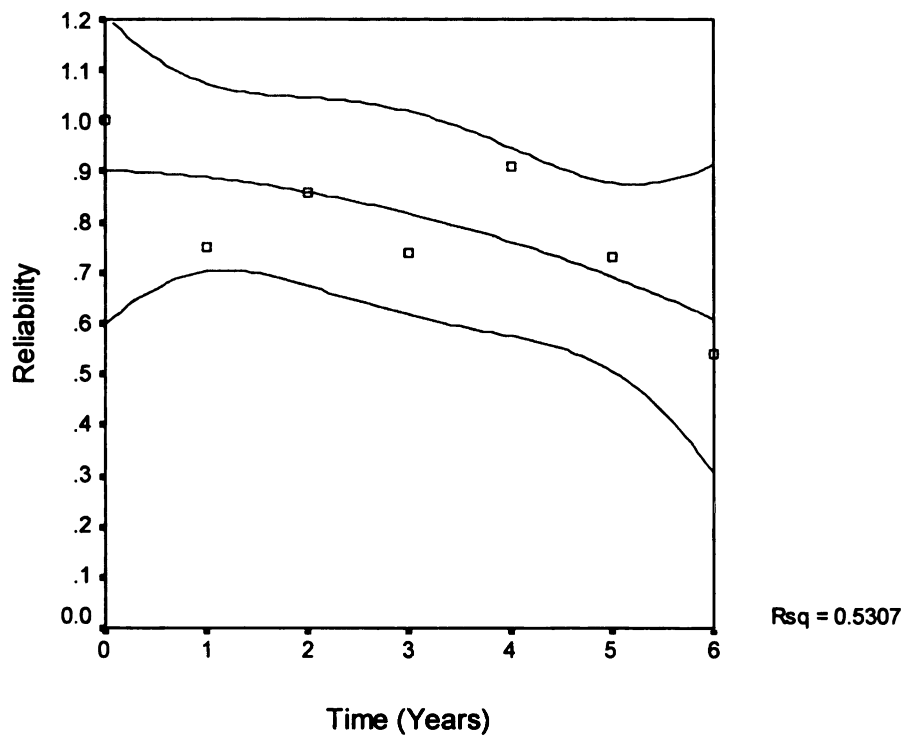

Figure 6.6 – Single Chip Seal Reliability versus Time Based on the PM Guidelines (95% Confidence Interval)

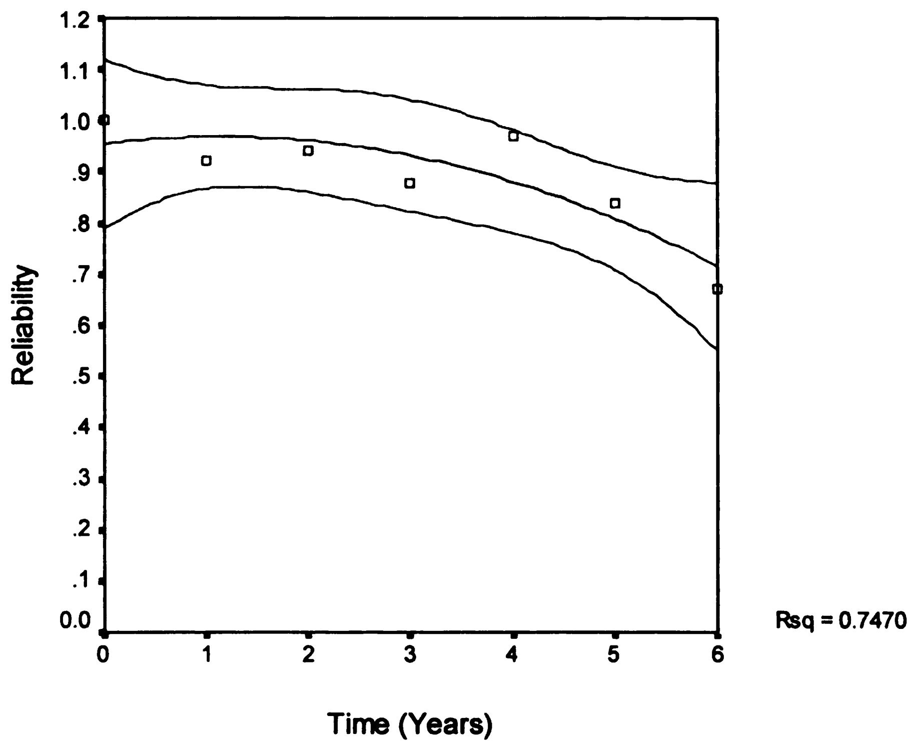

Figure 6.7 – Single Chip Seal Reliability versus Time Based on the Rehabilitation Threshold (95% Confidence Interval)

6.2.4. Multiple Course Micro-Surfacing

Figure 6.8 and Figure 6.9 show the reliability of the multiple course micro-surfacing treatment versus time based on the PM guidelines and rehabilitation threshold respectively. Both figures show the reliability over time decreasing at a slightly increasing rate with time. Also, the variability around the mean value is quite small. The results indicate that multiple course micro-surfacing have a reliability of about 80% after four years and about 65% after six years (±5%). The reliability values increase to about 85% after four years and about 75% after six years (±5%) when the rehabilitation threshold is used. This agrees reasonably well with the MDOT's preventive maintenance guidelines, which state that the expected life extension is four to six years.

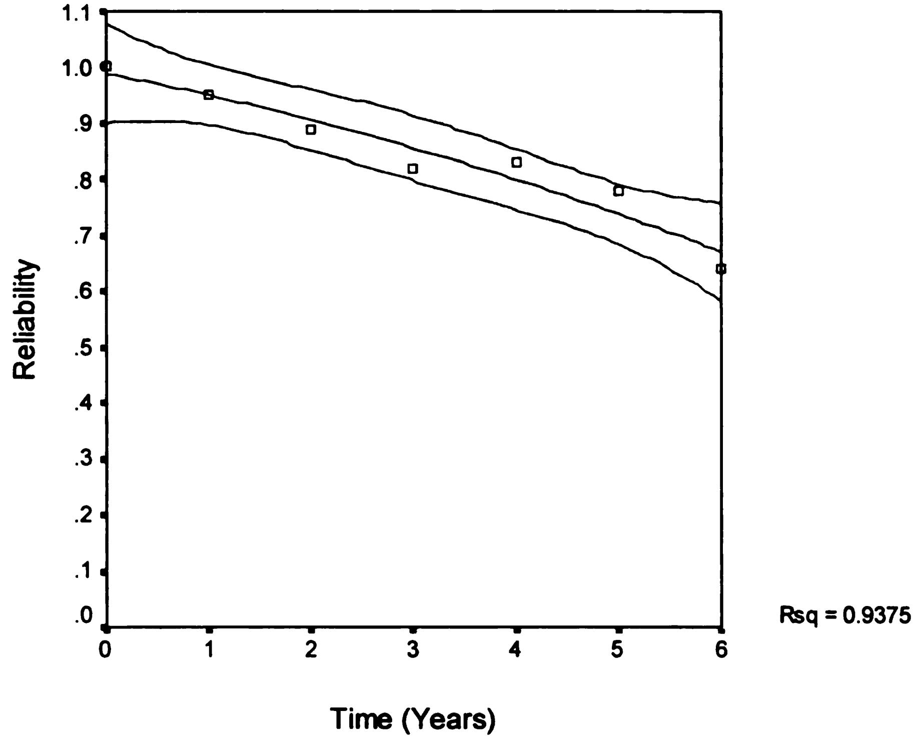

Figure 6.8 – Multiple Course Micro-Surfacing Reliability versus Time Based on the PM Guidelines (95% Confidence Interval)

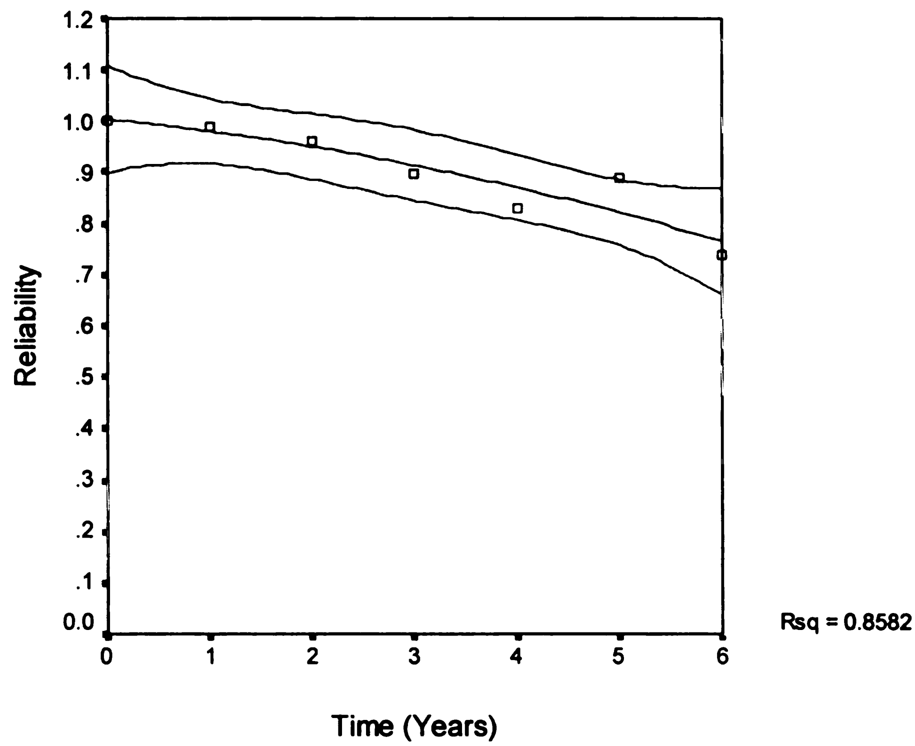

Figure 6.9 – Multiple Course Micro-Surfacing Reliability versus Time Based on the Rehabilitation Threshold (95% Confidence Interval)

6.2.5. Bituminous Crack Seal

Figure 6.10 and Figure 6.10 show the reliability of the bituminous crack treatment versus time based on the PM guidelines and rehabilitation threshold, respectively. Figure 6.10 shows that the reliability based on the preventive maintenance guideline decreases steadily with time, dropping to 80% after one year, 65% after two years, and 55% after three years (±5%). On the other hand, the reliability based on the rehabilitation threshold remains above 90% after four years, then starts dropping sharply after five years. The large discrepancy in the reliability values corresponding to the preventive maintenance and rehabilitation thresholds is mainly due to the fact that the distress points assigned to sealed cracks are about half of those for unsealed cracks. The limiting value based on preventive maintenance appears to be too restrictive. This agrees reasonably well with the MDOT's preventive maintenance guidelines, which state that the expected life extension of bituminous crack seals is up to three years.

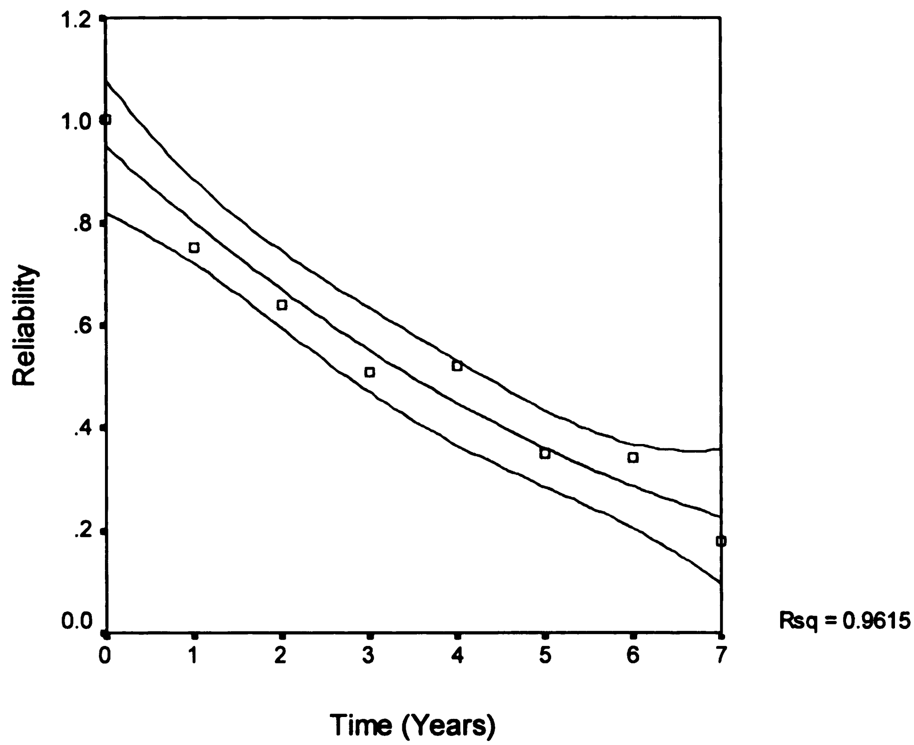

Figure 6.10 – Bituminous Crack Sealing Reliability versus Time Based on the PM Guidelines (95% Confidence Interval)

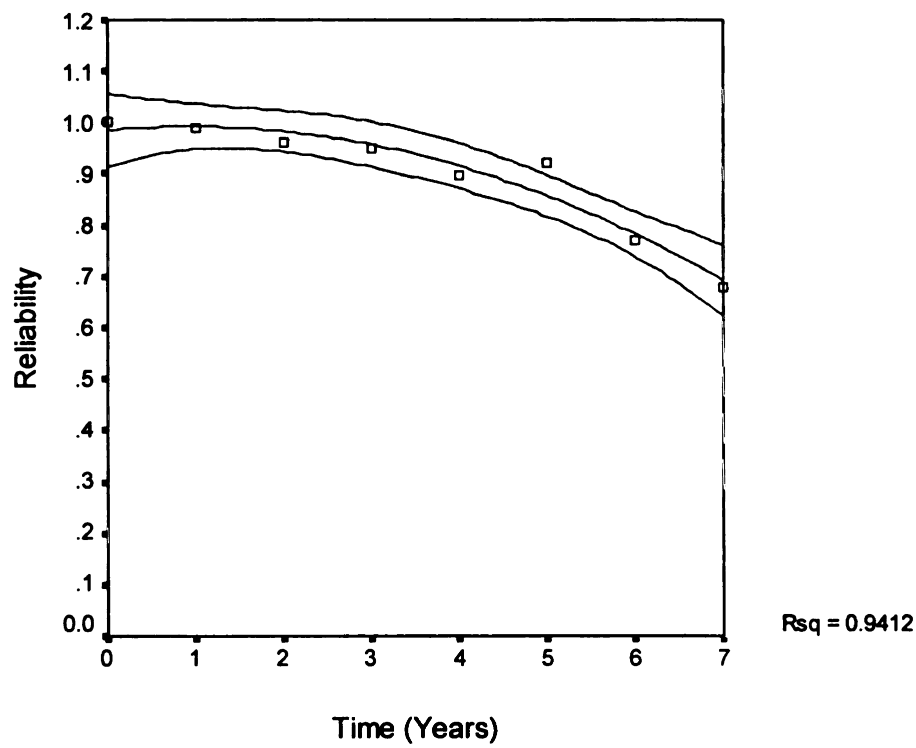

Figure 6.11 – Bituminous Crack Sealing Reliability versus Time Based on the Rehabilitation Threshold (95% Confidence Interval)

6.2.6. Overall Comparison

Table 6.1 is a first estimate of the reliability values corresponding to the different life expectancies for each preventive maintenance fix. Table 6.2 provides a summary of the reliability values of the life expectancies. The DI guidelines for preventive maintenance were used for determining these reliability values since the MDOT uses them for initiating preventive maintenance actions. The results indicate that the guidelines are reasonable. Table 6.3 provides a summary of reliability values of the life expectancies based on the rehabilitation threshold. Both of these tables will allow a highway agency to select the appropriate fix depending on the life expectancy that they are looking for along with the variability associated with certain fixes. The reliability values based on the rehabilitation threshold can be used when certain preventive maintenance projects are towards the end of their life-cycle and a rehabilitation project is planned for the future. A highway agency will then know the life expectancy of the subject treatment.

Table 6.1 - First Estimate of Reliability Values over time for the Various PM Fixes

		Time after PM Fix (Years)							
Fix Type	**DI Guidelines for PM and Rehab**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Bituminous Overlay[1]	40	100%	98%	100%	87%	97%	84%	97%	36%
	50	100%	99%	100%	92%	99%	89%	97%	50%
Mill & Fill[2]	40	100%	98%	100%	98%	76%	100%	100%	N/A
	50	100%	99%	100%	99%	91%	100%	100%	N/A
Chip Seal[3]	25	75%	83%	65%	83%	68%	45%	91%	N/A
	50	92%	94%	88%	97%	84%	67%	96%	N/A
Micro-Surface[4]	30	92%	83%	79%	76%	74%	60%	84%	N/A
	50	99%	96%	90%	83%	89%	74%	86%	N/A
Crack Seal[5]	15	76%	61%	58%	44%	43%	33%	29%	2%
	50	99%	96%	95%	90%	92%	77%	68%	23%

[1] 2 Projects at Year 7 and 1 Project at Year 8

[2] 4 Projects at Year 5, 2 Projects at Year 6 and 1 Project at Year 7

[3] 4 Projects at Year 7

[4] 3 Projects at Year 7

[5] 1 Project at Year 8

Note: Shaded cells indicate small sample sizes

Table 6.2 - Estimated Reliabilities of Life Expectancy for Various Fixes Based on MDOT's PM Guidelines (95% Confidence Interval)

		Time After PM Fix (Years)						
Fix Type	**MDOT Life Extension (Years)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Bituminous Overlay	5-10	100±10%[1]	100±10%[1]	97±10%[1]	93±10%[1]	87±10%	78±10%	N/A[2]
Mill & Fill	5-10	100±2%[1]	99±2%[1]	99±2%[1]	99±2%[1]	N/A[2]	N/A[2]	N/A[2]
Chip Seal	3-6	89±20%[1]	85±20%[1]	82±20%[1]	77±20%	68±20%	60±20%	N/A[2]
Micro-Surface	4-6	95±5%	90±5%	85±5%	80±5%	73±5%	67±5%	N/A[2]
Crack Seal	Up to 3	80±5%	67±5%	55±5%	45±5%	35±5%	29±5%	22±5%

[1]Note: The reliability cannot exceed 100%

[2]N/A: Not applicable because of small sample size

Table 6.3 – Estimated Reliabilities of Life Expectancy for Various Fixes Based on MDOT's Rehabilitation Threshold

(95% Confidence Interval)

		Time After PM Fix (Years)						
Fix Type	**MDOT Life Extension (Years)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Bituminous Overlay	5-10	100±5%[1]	100±5%[1]	99±5%[1]	97±5%[1]	94±5%	90±5%	N/A[2]
Mill & Fill	5-10	100±1%[1]	100±1%[1]	100±1%[1]	100±1%[1]	N/A[2]	N/A[2]	N/A[2]
Chip Seal	3-6	96±10%[1]	95±10%[1]	92±10%[1]	87±10%	80±10%	70±10%	N/A[2]
Micro-Surface	4-6	98±5%[1]	95±5%	90±5%	87±5%	80±5%	75±5%	N/A[2]
Crack Seal	Up to 3	100±5%[1]	98±5%[1]	95±5%	91±5%	85±5%	79±5%	69±5%

[1]Note: The reliability cannot exceed 100%

[2]N/A: Not applicable because of small sample size

6.3 Evaluation of the Guideline Values for the Treatment Types

Most preventive maintenance engineers agree that the timing of the preventive maintenance treatment is very critical. If a treatment is applied to very distressed pavements then the treatment will not give the pavement the added benefit it needs. If a treatment is applied too soon, then money is being poorly spent on a pavement that really does not need the maintenance. Therefore there is a real need to evaluate the guideline values at which a given preventive maintenance fix should be applied so that the life extension of the pavement is maximized while minimizing the cost to the highway agency.

This section will look at the effect of applying a treatment to a pavement that has a distress index that is lower than the preventive maintenance guideline value compared with applying it when the distress index is greater than the preventive maintenance guideline value. Two approaches will be looked at: (1) two sample t-test, and (2) reliability analysis.

6.3.1 Two-Sample t-test Approach

A two sample t-test was conducted in order to evaluate the DI guidelines that the MDOT imposes for the different preventive maintenance fixes. Under consideration will be the mean distress indices for two populations:

- Population One: DI values less than or equal to the DI guideline values at the time of the preventive maintenance activity.
- Population Two: DI values greater than the guideline values at the time of the preventive maintenance activity.

The mean distress indices at subsequent years for each preventive maintenance treatment were analyzed using the hypotheses formulated below:

- H_o: Mean DI at time (t_i) of population one equals mean DI at time (t_i) of population 2, or
- H_A: Mean DI at time (t_i) of population one does not equal mean DI at time (t_i) of population 2.

The next step is to select the appropriate level of significance ($1-\alpha$). An alpha value (α) of five percent (5%) was chosen in this case, which corresponds to a 95% level of significance. The results are summarized in Table 6.4.

6.3.1.1 Non-Structural Bituminous Overlay

The PM guideline for a non-structural bituminous overlay calls for a DI value less than forty (<40). The first three years of extended life for a non-structural bituminous overlay are relatively insignificant since the expected life extension according to the MDOT is from five to ten years. The results of the two sample t-test for this treatment can be seen in Table 6.4. The p-values from year five to year six are below the 5% significance level and the mean DI for population two is significantly higher than that of population one for these years. This analysis reasonably confirms that the MDOT guideline value for a non-structural bituminous overlay (DI<40) is valid. Data in year eight and beyond has a very limited population and thus analysis was not done for these years.

6.3.1.2 Surface Milling with a Non-Structural Bituminous Overlay

The PM guideline for surface milling with a non-structural bituminous overlay calls for a DI value less than forty (<40). The results of the two sample t-test for this treatment can be seen in Table 6.4. These results show that no statement can be made about the guideline value at this time since the difference in the mean DI values for both populations is not statistically different. The results are therefore inconclusive, and more performance data for later years are needed.

6.3.1.3 Single Chip Seal

The PM guideline for single chip seal calls for a DI value less than twenty-five (<25). The results of the two sample t-test for this treatment can be seen in Table 6.4. The p-values from year one to year six are below the 5% significance level, except for year seven (p-value=0.77). This anomaly can be ignored since the anticipated life extension for a single chip seal according to the MDOT is three to five years. Therefore one would not expect this treatment to last seven years. The mean values of DI after the fix are statistically different, with those from population one being lower than those from population two. This analysis confirms that the MDOT guideline value for a single chip seal (DI<25) is reasonable. Year seven was ignored due to the fact that only two projects had DI data seven years after the treatment.

6.3.1.4 Multiple Course Micro-Surfacing

The PM guideline for multiple course micro-surfacing calls for a DI value less than thirty (<30). The results of the two sample t-test for this treatment can be seen in Table 6.4. The p-values from year one to year six are below the 5% significance level, suggesting that the means of population one and two are statistically different, with those for population one being lower than those for population two, at all years. This analysis confirms that the MDOT threshold for a multiple course micro-surfacing (DI<30) is valid.

6.3.1.5 Bituminous Crack Seal

The PM guideline for bituminous crack sealing calls for a DI value less than fifteen (<15). The results of the two sample t-test for this treatment can be seen in Table 6.4. The p-values from year one to year six are below the 5% significance level, with the mean DI values for population two being clearly higher than those from population one. The p-value for year seven is higher (0.69). This can be ignored since the anticipated life extension for a bituminous crack seal according to the MDOT is up to three years only. Therefore one would not expect this treatment to last six to seven years. This analysis confirms that the MDOT guideline value for a bituminous crack seal (DI<15) is reasonable.

Table 6.4 – Two Sample t-test Results Using DI

		Time After PM Fix													
Fix Type		1 Year		2 Year		3 Year		4 Year		5 Year		6 Year		8 Year	
Bituminous Overlay		Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.
	N	540	119	545	424	494	68	526	276	242	70	111	11	95	8
	Mean	2.89	5.91	10.8	9.2	4.79	6.38	19	21.7	8.66	20.6	37.9	131	86.4	201
	Std. Dev	4.87	4.63	10.5	11.2	3.72	5.86	21.2	19.3	6.98	16.4	23.2	111	97.7	290
	T-Stat.	-6.38		2.29		-2.18		-1.83		-5.95		-2.8		-1.11	
	P-Value	0		0.022		0.033		0.067		0		0.019		0.3	
		1 Year		2 Year		3 Year		4 Year		5 Year		7 Year			
Mill & Fill		Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.
	N	47	59	490	71	56	26	355	22	5	11	2	7		
	Mean	6.13	5.59	8.1	5.5	6.27	5.81	15.82	16.5	48.3	30.4	21.8	8.62		
	Std. Dev	5.95	4.48	7.77	6.26	5.8	4	9.73	10.9	36.8	36.1	11.4	4.19		
	T-Stat.	0.52		3.16		0.41		-0.28		0.91		1.61			
	P-Value	0.6		0.002		0.68		0.78		0.39		0.35			
		1 Year		2 Year		3 Year		4 Year		5 Year		6 Year		7 Year	
Chip Seal		Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.
	N	599	352	432	618	512	368	94	151	558	196	303	45	69	22
	Mean	19.1	28.4	8.72	16.7	14.8	39.2	7.06	15.3	19.8	56.4	24.9	58.7	5.09	4.66
	Std. Dev	21.9	32.8	9.16	23.3	15.7	33.9	6.49	9.78	42.3	62.4	24.9	86.5	8.86	4.81
	T-Stat.	-4.74		-7.74		-12.88		-7.88		-7.62		-4.15		0.3	
	P-Value	0		0		0		0		0		0.0001		0.77	

Table 6.4 – Two Sample t-test Results Using DI (continued)

		Time After PM Fix													
Fix Type		1 Year		2 Year		3 Year		4 Year		5 Year		6 Year			
Micro-Surface		Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.
	N	464	26	621	34	690	45	684	141	584	18	457	37		
	Mean	12.32	37.4	10.3	27.4	15	73.4	14.5	58	16.5	57	31.4	107		
	Std. Dev	8.01	13.6	8.93	17.1	16	36.5	15.1	21	21.4	33.2	30.1	112		
	T-Stat.	-9.3		-5.77		-10.64		-23.37		-5.13		-4.1			
	P-Value	0		0		0		0		0.0001		0.0002			
		1 Year		2 Year		3 Year		4 Year		5 Year		6 Year		7 Year	
Crack Seal		Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.
	N	990	159	2010	346	610	78	1531	308	604	80	874	29	319	39
	Mean	11.24	21.8	13.3	27.9	18.1	31.4	16.4	39.3	26.5	37.9	34.6	86.6	58.3	60.3
	Std. Dev	9.37	14.8	11.8	21.2	13.3	19.2	16.3	40.7	17.1	22.7	39.6	96.2	41.3	27.2
	T-Stat.	-8.73		-12.42		-5.95		-9.73		-4.33		-2.9		-0.41	
	P-Value	0		0		0		0		0		0.0072		0.69	

*Shaded cells indicate p-values less than 5%

6.3.2. Reliability Approach

A reliability approach was also done using the same concept of having two populations and looking at how the distress index changes over time. Distributions were plotted for the two populations and at a specified point in time (i.e. 1 year, 2 years, etc. after the preventive maintenance activity). This will show the performance of the pavement when the treatment is applied correctly and when it is applied incorrectly according to the distress index criteria. The results are summarized in Table 6.5, and are discussed below. The life expectancy of a given fix type for the two populations was determined by plotting reliability versus time, fitting a quadratic function to the data points, and then plotting the 95% confidence intervals over the mean values. The figures can be used to determine the reliability in performance when a treatment is applied before or after the guideline values.

6.3.2.1 Non-Structural Bituminous Overlay

Reliability values for this treatment type along with the average distress index before the preventive maintenance treatment was applied are shown in Table 6.5 for both populations. The shaded cells indicate very small sample sizes and should therefore be ignored. Figure 6.12 and Figure 6.13 show a graph of reliability versus time for the two populations.

The results show that while the reliability values for population two are slightly lower than those of population one, and this difference increases with time, the difference is too small to make any statement on the guideline value. No conclusions can be drawn about the guideline value since the reliability level is still high for both populations to make a firm statement about the guideline value (DI<40). Future performance data are needed in order evaluate the guideline value after five years or more.

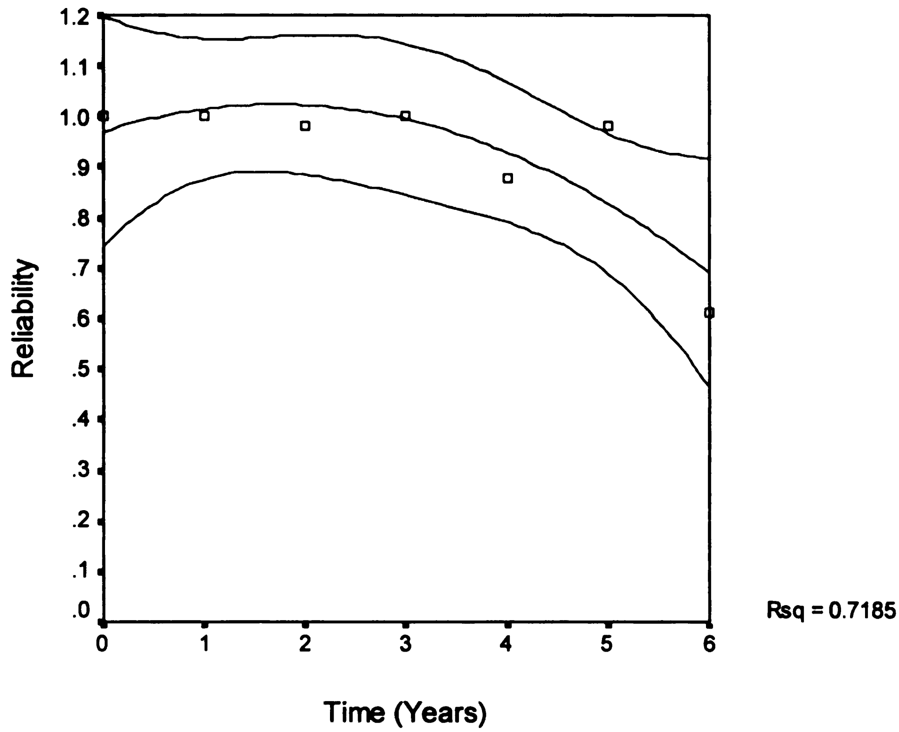

Figure 6.12 – Reliability of Life Expectancy for Non-Structural Bituminous Overlay When PM is done before the DI Guideline Value

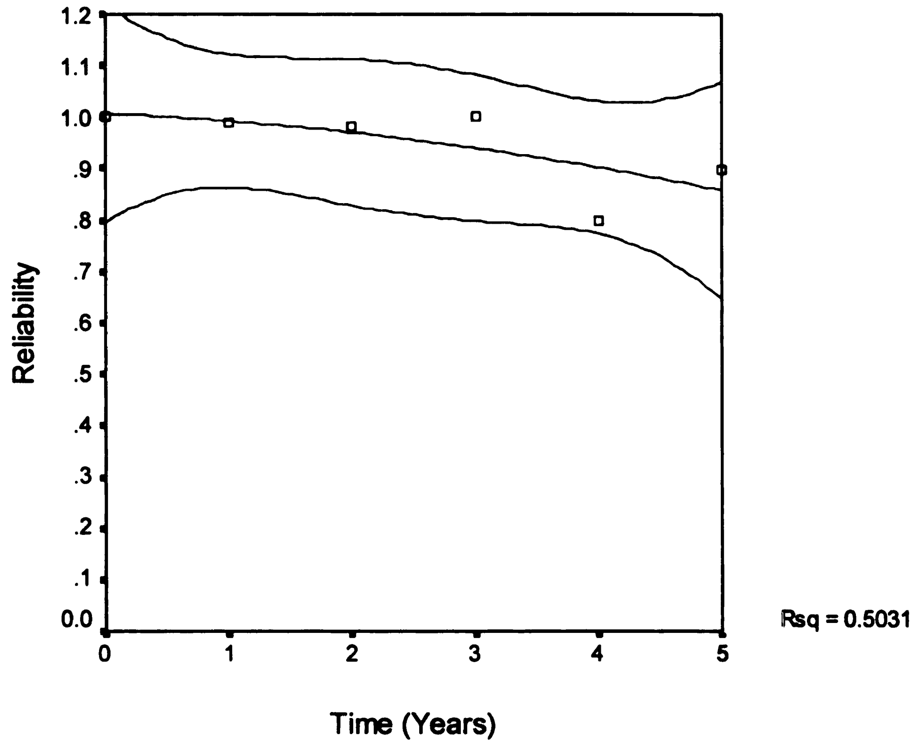

Figure 6.13 – Reliability of Life Expectancy for Non-Structural Bituminous Overlay When PM is done after the DI Guideline Value

6.3.2.2 Surface Milling with a Non-Structural Bituminous Overlay

The reliability values for this treatment type along with the average distress index before the preventive maintenance treatment was applied are shown in Table 6.5 for both populations. Figure 6.14 and Figure 6.15 show a graph of reliability versus time for the two populations.

The sample sizes for year three and later are too small to make any inferences. For the first two years, the reliability values for both populations are practically identical; this is expected since it would be too early for this fix type to show any signs of serious distress. Therefore, no conclusions can be drawn about the validity of the guideline value (DI<40) for surface milling with non-structural bituminous overlay.

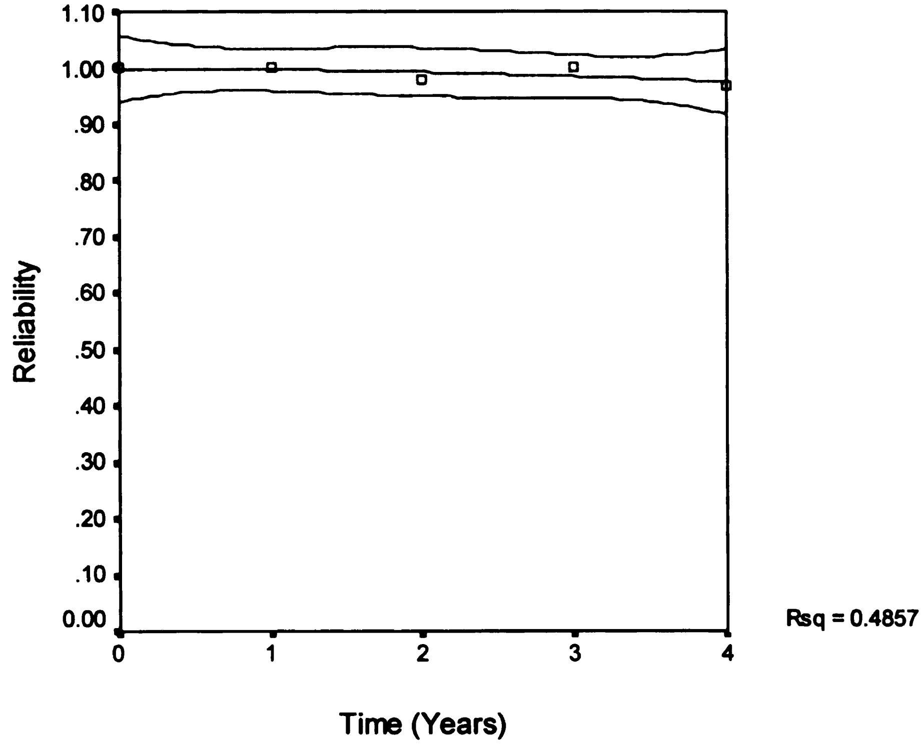

Figure 6.14 – Reliability of Life Expectancy for Surface Milling with a Non-Structural Bituminous Overlay When PM is done before the DI Guideline Value

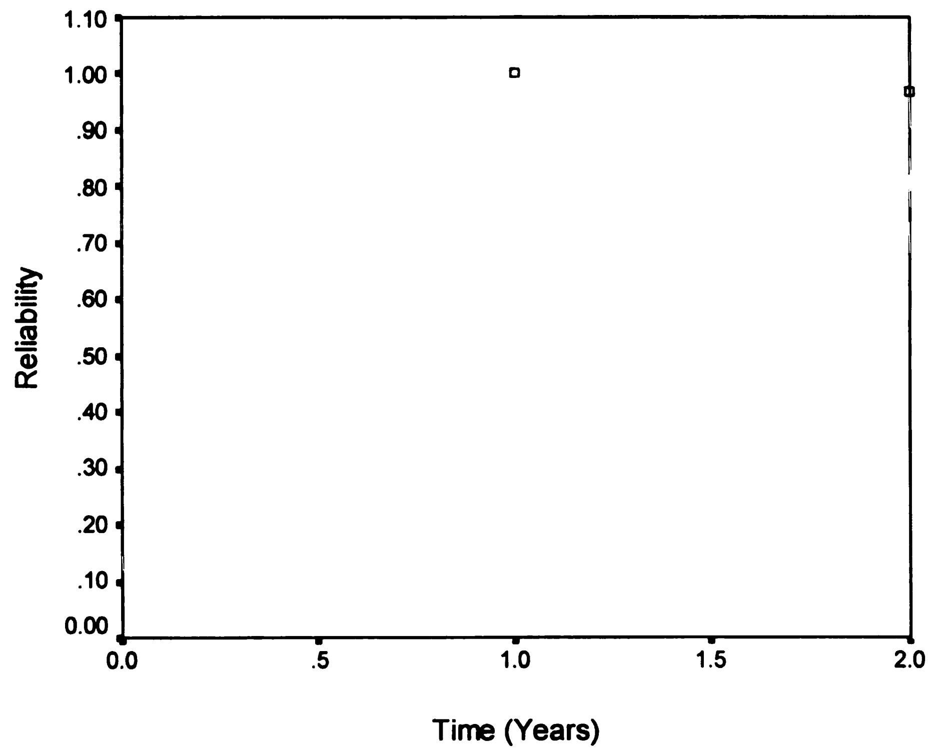

Figure 6.15 – Reliability of Life Expectancy for Surface Milling with a Non-Structural Bituminous Overlay When PM is done after the DI Guideline Value

6.3.2.3 Single Chip Seal

The reliability values for this treatment type along with the average distress index before the preventive maintenance treatment was applied are presented in Table 6.5 for both populations. Figure 6.16 and Figure 6.17 show a graph of reliability versus time for the two populations.

The results clearly show that the reliability values for population one are higher than those for population two, with the difference increasing with time. Therefore this method reasonably confirms that the MDOT guideline value (DI<25) for single chip seal is valid.

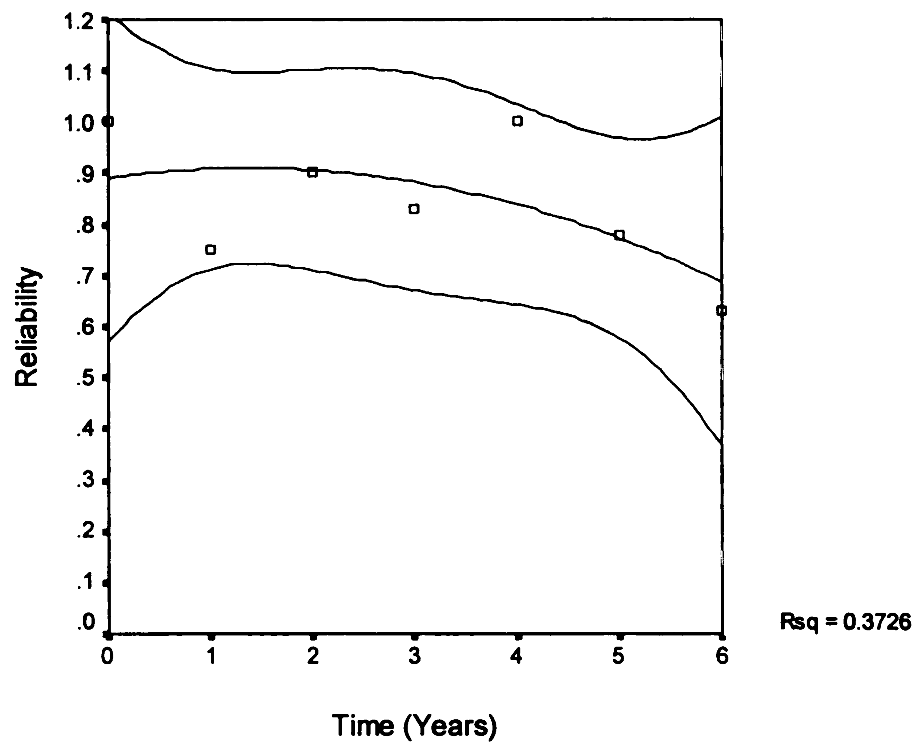

Figure 6.16 – Reliability of Life Expectancy for Single Chip Seal When PM is done before the DI Guideline Value

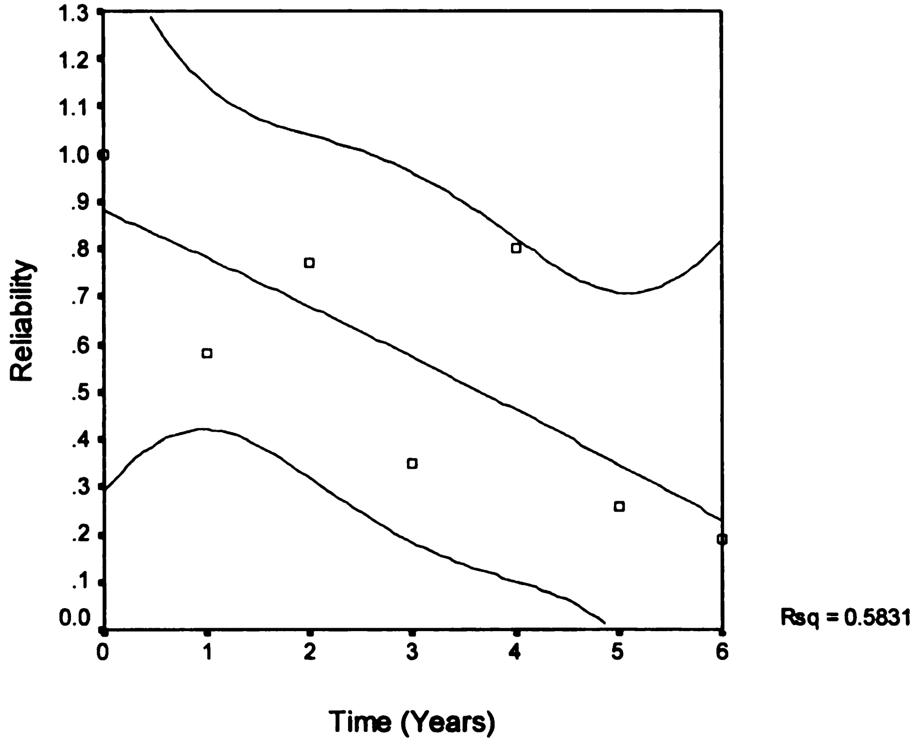

Figure 6.17 – Reliability of Life Expectancy for Single Chip Seal When PM is done after the DI Guideline Value

6.3.2.4 Multiple Course Micro-Surfacing

The reliability values for this treatment type along with the average distress index before the preventive maintenance treatment was applied are presented in Table 6.5 for both populations. Figure 6.18 and Figure 6.19 show a graph of reliability versus time for the two populations.

Despite the small sample sizes in population two for most of the years, the results clearly show that the reliability values for population two are significantly lower than those of population one. Therefore this method confirms that the MDOT guideline value (DI<30) for a multiple course micro-surfacing is reasonable.

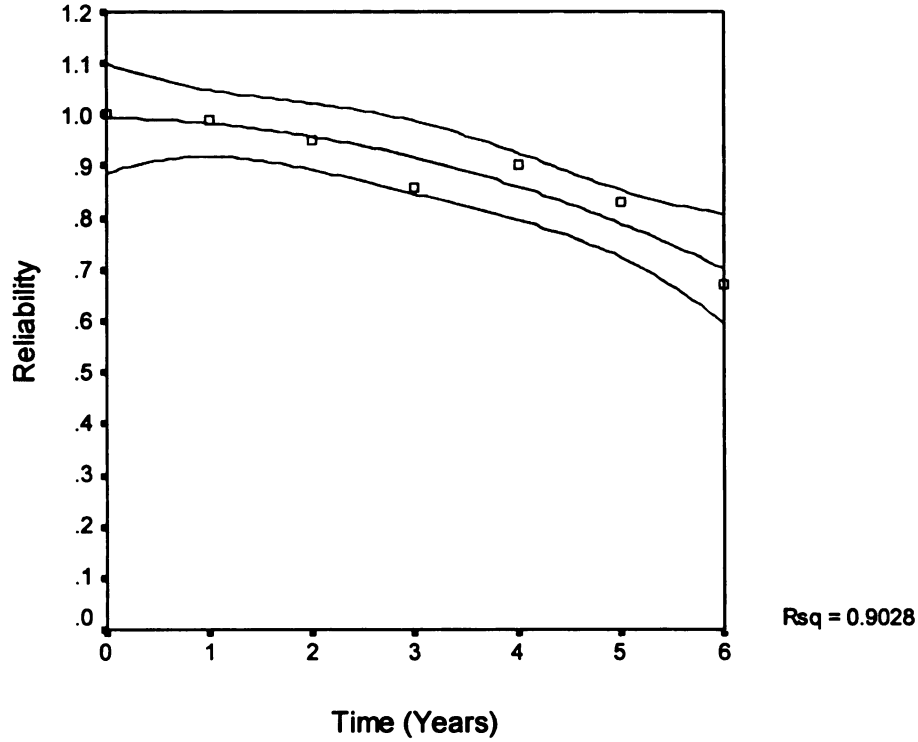

Figure 6.18 – Reliability of Life Expectancy for Multiple Course Micro-Surface When PM is done before the DI Guideline Value

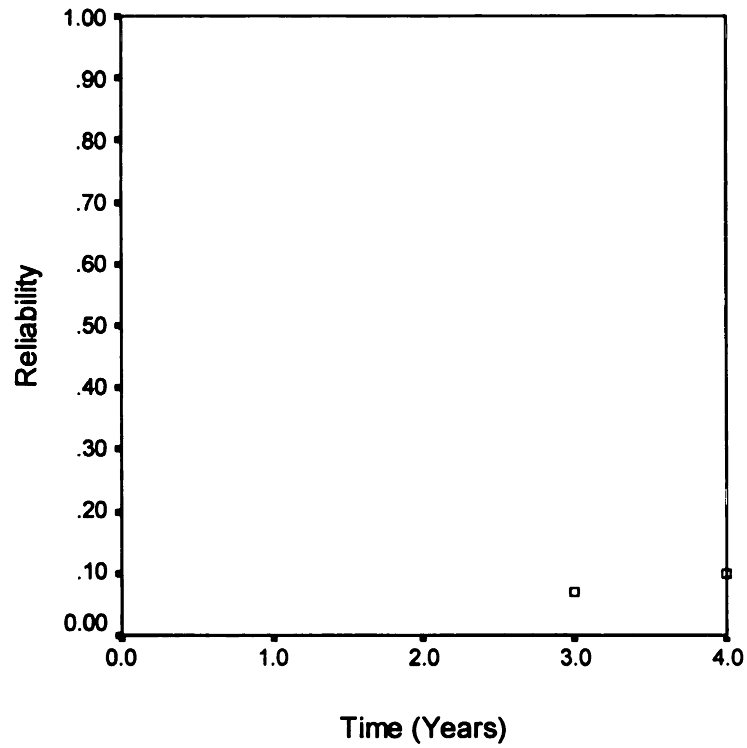

Figure 6.19 – Reliability of Life Expectancy for Multiple Course Micro-Surface When PM is done after the DI Guideline Value

6.3.2.5 Bituminous Crack Seal

The reliability values for this treatment type along with the average distress index before the preventive maintenance treatment was applied are shown in Table 6.5 for both populations. Figure 6.20 and Figure 6.21 show a graph of reliability versus time for the two populations.

The results show clearly that for year one to year five there is a significant difference in the reliability values when performing the treatment before the guideline value then when doing it after the guideline value. Therefore this method reasonably confirms that the MDOT guideline value (DI<15) for a bituminous crack seal is valid.

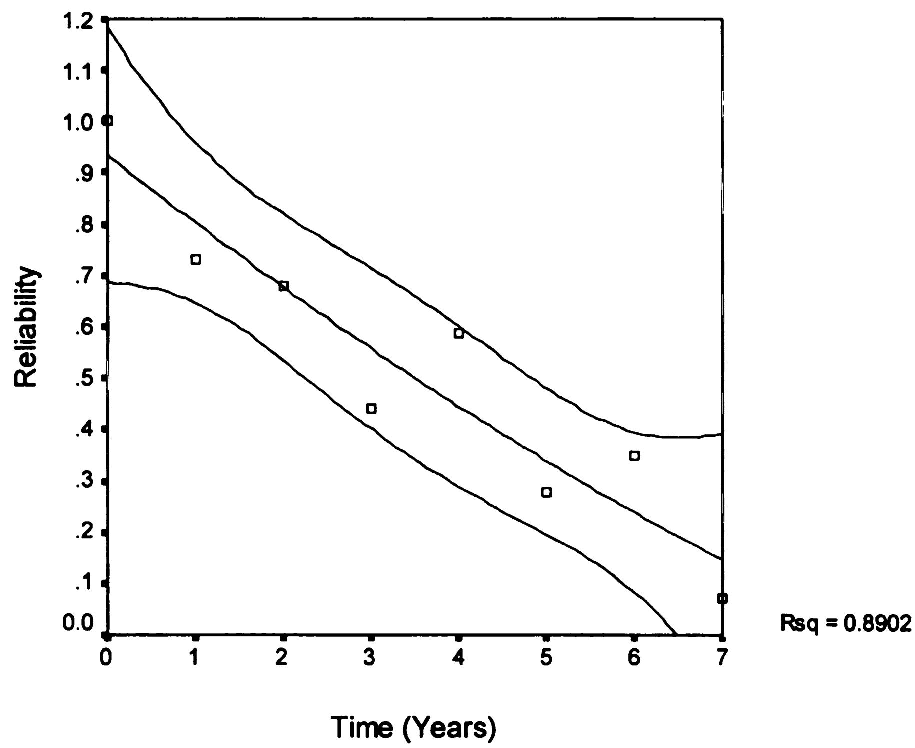

Figure 6.20 – Reliability of Life Expectancy for Bituminous Crack Seal When PM is done before the DI Guideline Value

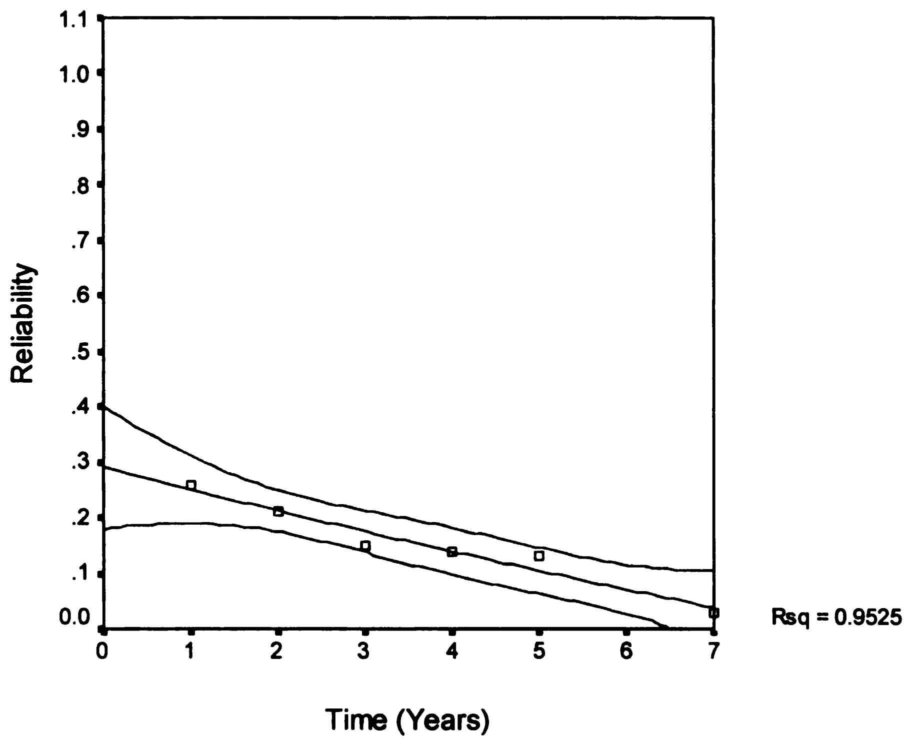

Figure 6.21 – Reliability of Life Expectancy for Bituminous Crack Seal When PM is done after the DI Guideline Value

Table 6.5 – Summary Table for Reliability Analysis on Evaluating the Guideline Values for the Treatment Types

			Time After PM Fix (Years)							
Fix Type	DI Level Before PM	Average DI Before PM	1	2	3	4	5	6	7	8
Bituminous Overlay	0-40	16.6	100%	98%	100%	88%	98%	61%	98%	37%
	>40	105.4	99%	98%	100%	82%	90%	9%	N/A	25%
Mill & Fill	0-40	16.6	100%	98%	100%	97%	60%	100%	100%	N/A
	>40	68.9	100%	97%	100%	100%	82%	N/A	100%	N/A
Chip Seal	0-25	9.9	75%	90%	83%	100%	78%	63%	91%	N/A
	>25	70.7	58%	77%	35%	80%	26%	19%	100%	N/A
Micro-Surface	0-30	8.6	99%	95%	86%	90%	83%	67%	100%	N/A
	>30	46.5	19%	59%	7%	10%	17%	18%	6%	N/A
Crack Seal	0-15	5.4	73%	68%	44%	59%	28%	35%	7%	N/A
	>15	22.2	26%	21%	15%	14%	13%	30%	3%	N/A

Note: Shaded in areas indicate small sample size

6.4 Evaluation of Ride Quality Guidelines

The ride quality of a pavement is an important aspect to the user of the road. If pavements are too rough this may accelerate the rate of distress but also accelerate damage to cars and trucks through spalled off pieces damaging windows, chipping of paint, increased wear of tires, and damage to the suspension of cars and trucks.

The evaluation of the RQI guideline values was accomplished by checking whether the RQI value at the time of application of the preventive maintenance fixes significantly affects the distress index of the pavement after the fix. A two sample t-test was conducted on the mean distress indices for two populations:

- Population One: RQI values less than or equal to the RQI guideline value at the time of the preventive maintenance activity.
- Population Two: RQI values greater than the guideline value at the time of the preventive maintenance activity.

The mean distress indices at subsequent years for each preventive maintenance treatment were analyzed using the hypotheses formulated below:

- H_o: Mean DI at time (t_i) of population one equals mean DI at time (t_i) of population 2, or
- H_A: Mean DI at time (t_i) of population one does not equal mean DI at time (t_i) of population 2.

The next step was to select the appropriate level of significance ($1-\alpha$). An alpha value (α) of five percent (5%) was chosen in this case, which corresponds to a 95% level of significance.

6.4.1 Non-Structural Bituminous Overlay

The results of the two sample t-test shown in Table 6.6 indicate that the p-values are all greater than the 5% level of significance except for year four. This implies that the difference in the mean DI after the fix of both populations is not statistically significant. Therefore the results seem to indicate that the RQI value at the time of the fix does not seem to affect the future DI values (at least up to five or six years). This is expected since overlaying a pavement will smoothen its surface so that roughness is minimized after overlaying. The anomaly seen at year four where the p-value is less than the 5% level of significance could be explained by the fact that the RQI threshold (>70) being very high may reflect serious problems in the pavement foundation layers. In that case, overlaying with a thin, non-structural layer may not solve the root cause of the pavement distress.

6.4.2 Surface Milling with a Non-Structural Bituminous Overlay

The results of the two sample t-test shown in Table 6.6 indicate that the p-values are all greater than the 5% level of significance except for year five. This implies that the difference in the mean DI after the fix of both populations is not statistically significant. These results indicate that the RQI value at the time of the fix does not seem to affect the future DI values. Again, this is expected since this fix involves milling the pavement surface, and then overlaying the pavement, thus minimizing surface roughness. The anomaly seen at year five where the p-value is less than the 5% level of significance can be attributed to the fact that a high RQI value (>70) may be indicative of more serious foundation problems that can not be fixed by a mill and fill treatment.

6.4.3 Single Chip Seal

The results of the two sample t-test shown in Table 6.6 indicate that the p-values are below the 5% level of significance. However, the mean DI values are higher for population two only after four years or more. Year six show a p-value above the 5% level of significance. However the data for year six may be ignored because of small sample size of pavements with RQI values higher than the guideline value. Therefore the results seem to indicate some effect of the RQI guideline value (>54) at later years, but they are not as conclusive as those for the DI guideline value.

6.4.4 Multiple Course Micro-Surfacing

The results of the two sample t-test shown in Table 6.6 indicate that the p-values are variable from year to year. Years one, three, and five have a p-value higher than the 5% level of significance while years two, four, and six have p-values lower than the 5% level of significance with the mean DI value for population two being higher than those for population one. Therefore the results are inconclusive, and more data are needed to confirm or disprove the hypothesis that the RQI level at the time of applying a multiple course micro-surfacing will affect the future performance of the pavement after the fix.

6.4.5 Bituminous Crack Seal

The results of the two sample t-test shown in Table 6.6 indicate that while the p-values are lower than 5%, the mean DI values for population one are higher than those of population two for years four and seven. Therefore the results are inconclusive, and more data are needed to support or disprove the hypothesis that the RQI level at the time the crack sealing is applied will affect the future performance of the pavement.

Table 6.6 – Two Sample t-test Results Based on RQI

		Time After PM Fix													
Fix Type		1 Year		2 Year		3 Year		4 Year		5 Year		6 Year		7 Year	
Bituminous Overlay		Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.
	N	232	13	470	46	233	11	244	41	186	11	213	7		
	Mean	4.92	5.08	6.8	8.16	8.79	8.17	6.33	25.2	8.14	13	14.92	13.95		
	Std. Dev	5.03	7.52	6.04	5.34	8.76	9.99	7.11	19.4	6.71	10.7	7.81	9.13		
	T-Stat.	-0.08		-1.62		0.2		-6.15		-1.49		0.28			
	P-Value	0.94		0.11		0.84		0		0.17		0.79			
		1 Year		2 Year		3 Year		4 Year		5 Year		6 Year		7 Year	
Mill & Fill		Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.
	N	46	26	115	34	79	39	73	27	46	32	8	7		
	Mean	12.21	12.5	8.77	9.68	13.06	14.5	12.49	10.11	28.89	42.9	18.89	20		
	Std. Dev	3.5	3.25	8.79	9.43	7.33	9.39	7.81	9.55	9.95	22.3	5.43	4.28		
	T-Stat.	-0.31		-0.51		-0.83		1.16		-3.1		-0.44			
	P-Value	0.75		0.61		0.41		0.25		0.0036		0.66			
		1 Year		2 Year		3 Year		4 Year		5 Year		6 Year		7 Year	
Chip Seal		Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.
	N	621	228	646	160	571	108	373	214	600	121	324	27		
	Mean	19.9	24.2	10.31	11.5	37.9	32.7	9.6	17.2	30.4	59.5	61.9	41.3		
	Std. Dev	20.7	22.4	9.86	12	29.4	21.3	10.2	13.9	53.8	45.1	62.7	69.2		
	T-Stat.	-2.5		-1.2		2.19		-6.96		-6.24		1.5			
	P-Value	0.013		0.23		0.03		0		0		0.14			

Table 6.6 – Two Sample t-test Results Based on RQI (continued)

Fix Type		Time After PM Fix													
		1 Year		2 Year		3 Year		4 Year		5 Year		6 Year		7 Year	
Micro-Surface		Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.
	N	413	58	413	182	405	52	401	159	355	44	243	116		
	Mean	11.97	10.8	10.01	30.2	8.47	8.86	10.17	35.6	17.3	19.5	31.7	60.9		
	Std. Dev	7.91	11	9.82	22.8	7.63	8.71	9.91	44.5	22.6	14	35.4	53.9		
	T-Stat.	0.79		-11.48		-0.31		-7.19		-0.92		-5.31			
	P-Value	0.43		0		0.76		0		0.36		0			
		1 Year		2 Year		3 Year		4 Year		5 Year		6 Year		7 Year	
Crack Seal		Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.	Before TH.	After TH.
	N	873	186	761	36	688	159	796	35	751	155	335	16	189	76
	Mean	11	15	8.09	13.1	15.7	20.6	18.9	15.4	23.7	26	16.2	29.6	49.9	41.6
	Std. Dev	10.3	10.1	7.34	7.31	14	8.52	17.7	10.6	18.4	13.2	12	16.7	31.5	14
	T-Stat.	-4.87		-4.05		-5.71		1.85		-1.9		-3.17		2.95	
	P-Value	0		0.0002		0		0.071		0.059		0.0063		0.0034	

*Shaded cells indicate p-values less than 5%

CHAPTER 7 - SUMMARY OF FINDINGS AND RECOMMENDATIONS

7.1 Summary of Findings

The research objective was to use the wealth of PMS performance data collected on 240 preventive maintenance (PM) projects since 1992 to perform a reliability-based analysis for the purpose of determining the life expectancy and evaluation of the guideline values for the different PM fixes. These are: (1) Non-structural bituminous overlay, (2) surface milling with a non-structural bituminous overlay, (3) single chip seal, (4) multiple course micro-surfacing, and (5) bituminous crack seal. The pavement performance parameters that MDOT collects are distress index (DI), ride quality index (RQI), and rut depth. There were insufficient rut data to perform the analysis, therefore only DI and RQI data were used.

- **Determination of the Life Expectancy for PM Fixes Using DI**

The life expectancy was determined by plotting distributions of the distress index at subsequent years after the preventive maintenance activity. The reliability was then calculated as the area under the curve to the left of the MDOT guideline value. The results were summarized in tables showing reliability values that correspond with the different life expectancies for each preventive maintenance fix. The life expectancy values estimated from the reliability-based analysis compare reasonably well with those suggested in MDOT's preventive maintenance guidelines. The reliability approach suggested in this research can be used as a pavement management tool, provided that the MDOT adopts a minimum level of reliability that would be acceptable before an action is taken.

- **Evaluation of Distress Index (DI) Guidelines**

A two sample t-test was conducted in order to evaluate the DI guidelines that the MDOT imposes for the different preventive maintenance fixes. The mean distress index was determined for two populations:

- Population One: DI values lower than or equal to the DI guideline values at the time of the preventive maintenance activity.
- Population Two: DI values greater than the guideline values at the time of the preventive maintenance activity.

For each treatment the mean distress indices at subsequent years after applying the fix from both populations were compared.

A reliability approach was also done using the same concept of having two populations and looking at how the distress index changes over time. Distributions of the distress index were plotted for the two populations at subsequent years after the preventive maintenance activity. The corresponding reliability values were then compared.

Based on the above analysis, the distress index guideline values for a non-structural bituminous overlay (<40), single chip seal (<25), multiple course micro-surfacing (<30), and bituminous crack seal (<15) were found to be reasonable. The results for surface milling with a non-structural bituminous overlay (<40) were inconclusive. This is probably due to the fact that this fix type had the smallest number of projects compared with the other fix types.

- **Evaluation of Ride Quality Index (RQI) Guidelines**

The evaluation of the RQI guidelines was done by looking at the distress index at subsequent years after the fix was applied for two populations:

- Population One: RQI values less than or equal to the RQI guideline values at the time of the preventive maintenance activity.
- Population Two: RQI values greater than the guideline values at the time of the preventive maintenance activity.

A two sample t-test was then conducted by comparing the mean distress indices at subsequent years after applying the fix from both populations.

The results for the non-structural bituminous overlay and surface milling with a non-structural bituminous overlay indicate that the RQI value at the time of the fix does not seem to affect the future DI values (at least up to five or six years for the bituminous overlay and up to four years for the mill and fill). This is expected since overlaying the pavement will smoothen its surface so that roughness is minimized after overlaying. The results for chip sealing indicate that the RQI guideline value of 54 may be warranted at later years. The results for micro-surfacing and bituminous crack seal were inconclusive and more data are needed to confirm or disprove the hypothesis that the RQI level at the time of PM action is taken will affect future performance of the pavement.

7.2 Recommendations for Future Research

The results of this study have led to the following recommendations:

- First, additional variables should be investigated. This research studied the distress index before and after the preventive maintenance action. Additional variables to be considered would be: Pavement thickness, pavement age, drainage, construction, materials, and climate. Traffic could possibly be another variable, although, these fixes are applied mainly on low to medium volume roads; it may not be a significant factor except for pavement sections with relatively high traffic levels.
- Secondly, more data should be used for plotting the distributions and calculating the reliability of life expectancies. Additional projects could be added to those used in this study to increase the database for subsequent years after the initial treatment. This will increase the dependability of the reliability tables developed for fixes such as the bituminous crack seal, single chip seal, and multiple course micro-surfacing. In order to increase the dependability of the reliability tables for the non-structural bituminous overlay and surface milling with a non-structural bituminous overlay, additional data are needed at later yearscto evaluate these treatments from five to ten years.
- Thirdly, more data are needed for pavements where the pre-existing condition is known for the distress and ride quality indices. Having more data will lead to better results with the two-sample t-test. Also, with the addition of future performance data, more conclusive results could be reached, especially for the validity of the RQI guideline values.

- Fourth, in order to do a project level analysis, one must look at the types of distresses that predominately occur in preventive maintenance projects and plot distributions of these different distresses over time while tracking the type of fix that is performed. From this analysis one can determine the reliability versus time for particular distresses. Based on some minimum level of reliability one will be able to estimate life expectancy for a given fix type with a particular distress.

APPENDICIES

APPENDIX A

HISTOGRAMS USED TO DETERMINE THE LIFE EXPECTANCY FOR THE FOLLOWING PREVENTIVE MAINTENANCE (PM) TREATMENTS BASED ON THE DISTRESS INDEX (DI)

Non-Structural Bituminous Overlay
Surface Milling with a Non-Structural Bituminous Overlay
Single Chip Seal
Multiple Course Micro-Surfacing
Bituminous Crack Seal

Non-Structural Bituminous Overlay

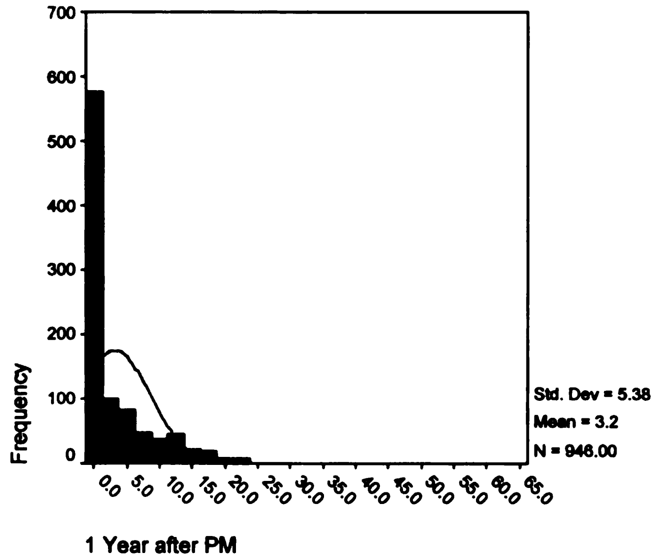

Figure A.1 - Histogram of DI 1 Year after PM

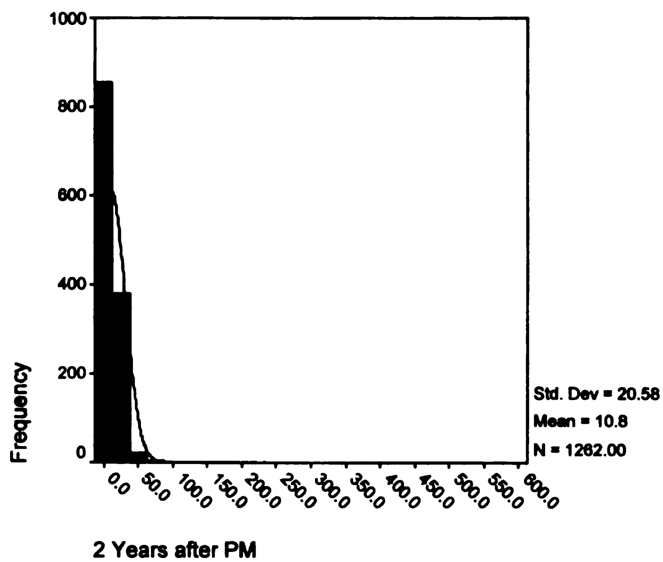

Figure A.2 - Histogram of DI 2 Years after PM

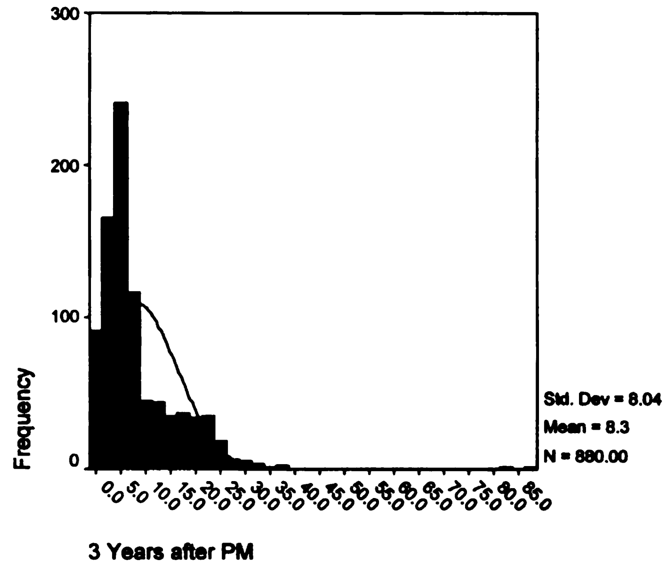

Figure A.3 - Histogram of DI 3 Years after PM

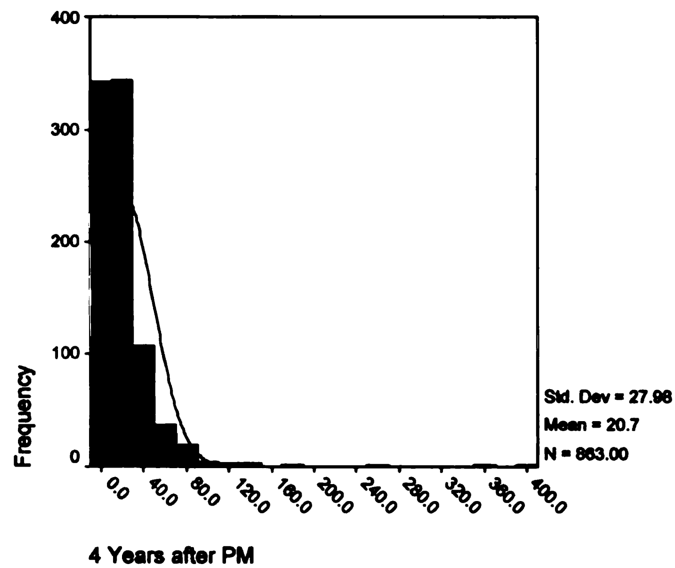

Figure A.4 - Histogram of DI 4 Years after PM

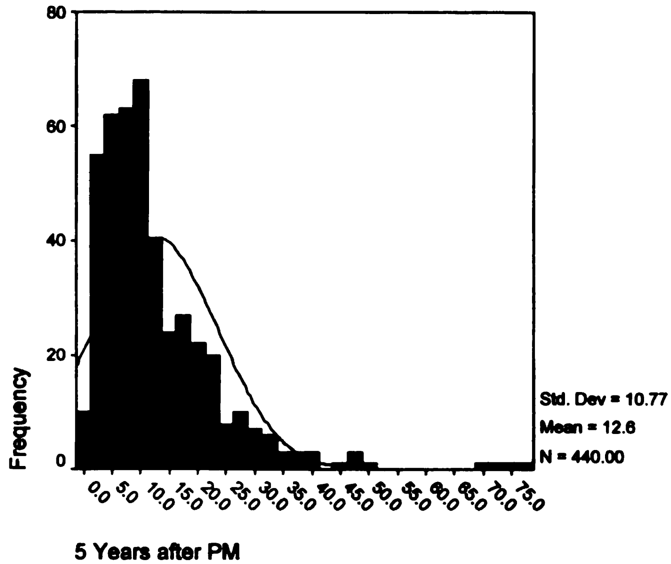

Figure A.5 - Histogram of DI 5 Years after PM

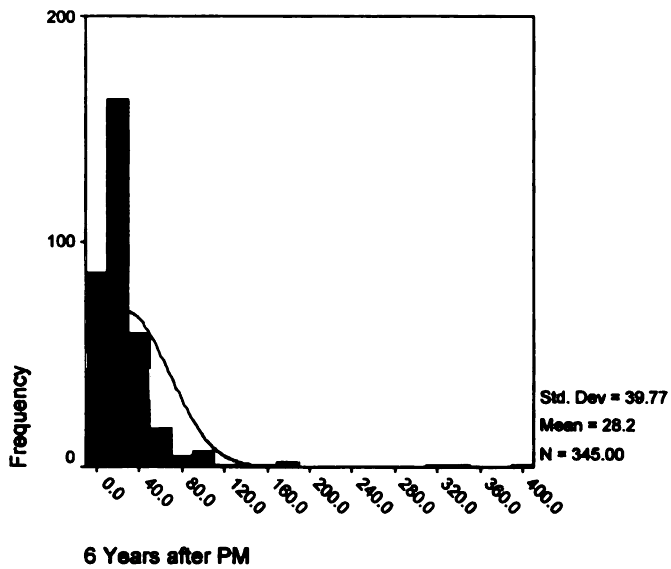

Figure A.6 - Histogram of DI 6 Years after PM

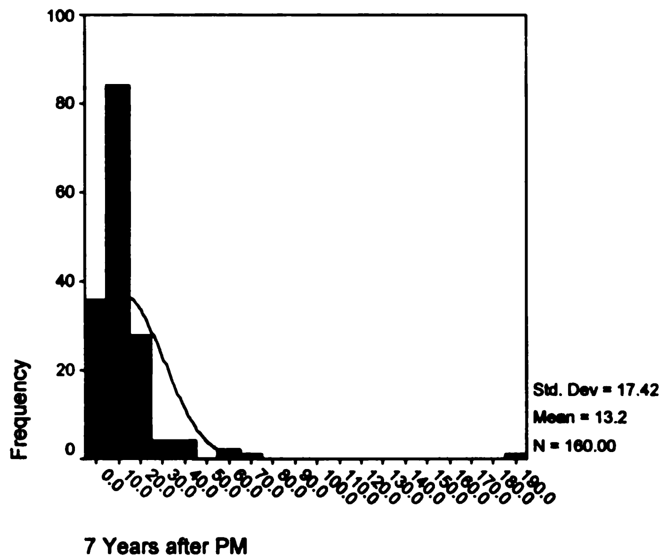

Figure A.7 - Histogram of DI 7 Years after PM

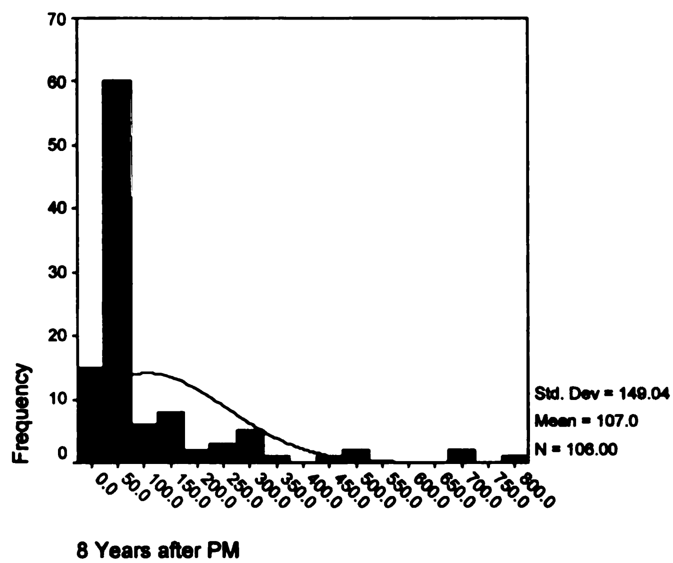

Figure A.8 - Histogram of DI 8 Years after PM

Surface Milling with a Non-Structural Bituminous Overlay

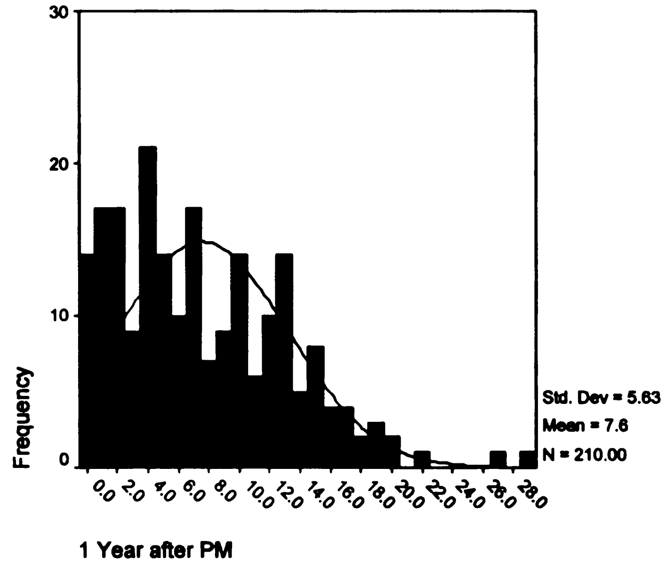

Figure A.9 - Histogram of DI 1 Years after PM

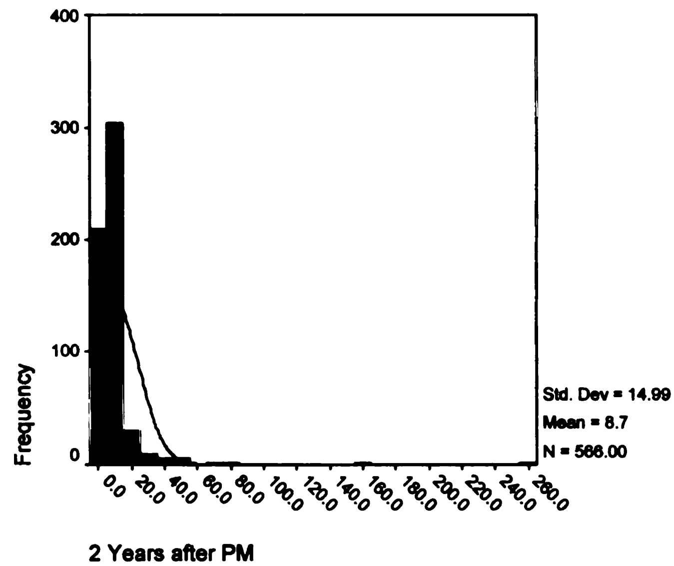

Figure A.10 - Histogram of DI 2 Years after PM

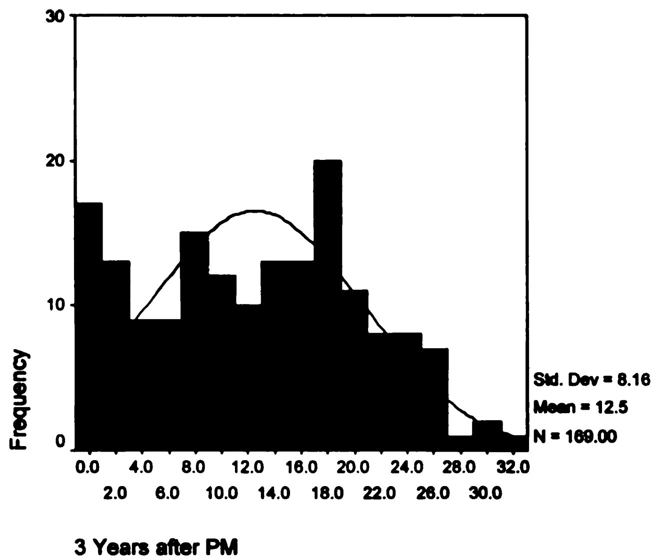

Figure A.11 - Histogram of DI 3 Years after PM

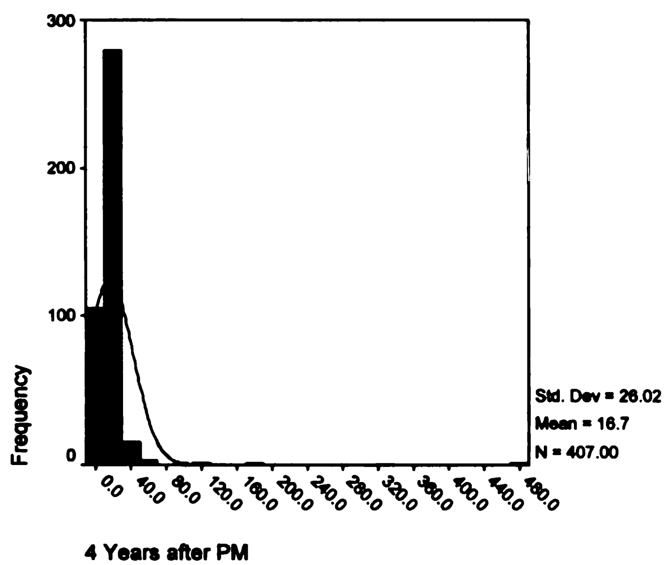

Figure A.12 - Histogram of DI 4 Years after PM

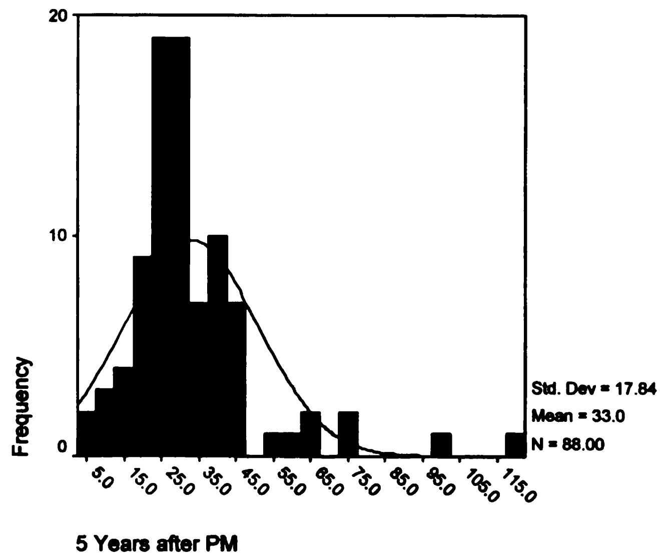

Figure A.13 - Histogram of DI 5 Years after PM

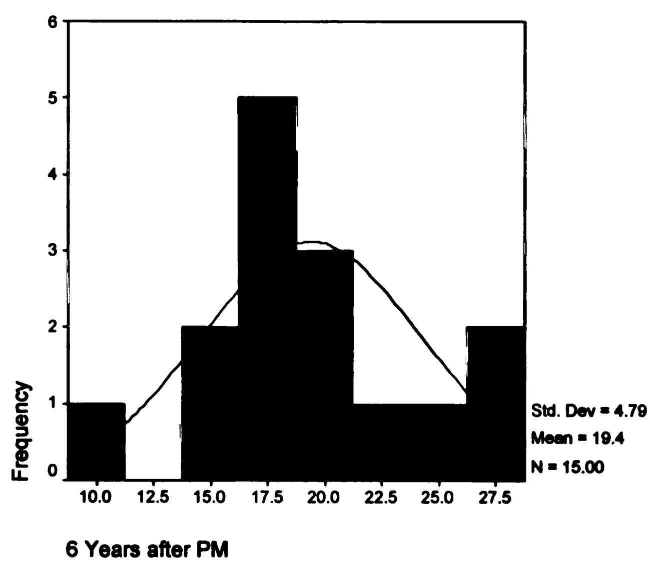

Figure A.14 - Histogram of DI 6 Years after PM

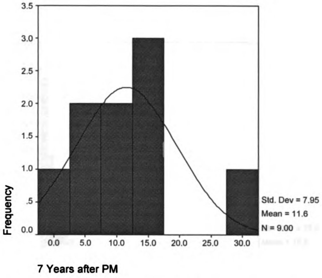

Figure A.15 - Histogram of DI 7 Years after PM

Single Chip Seal

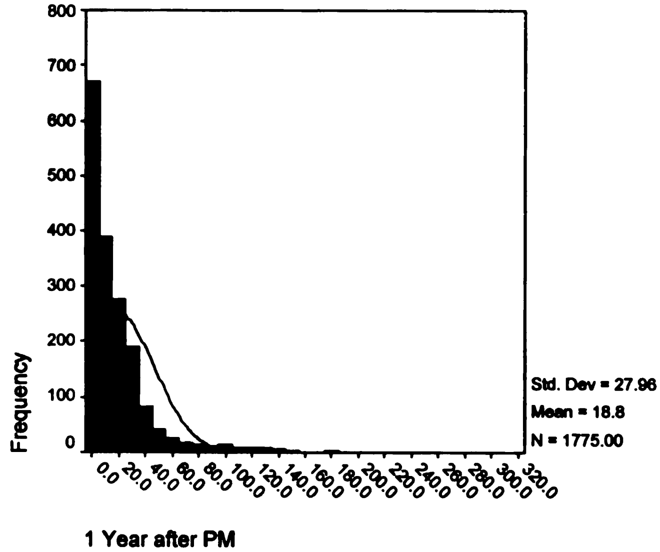

Figure A.16 - Histogram of DI 1 Years after PM

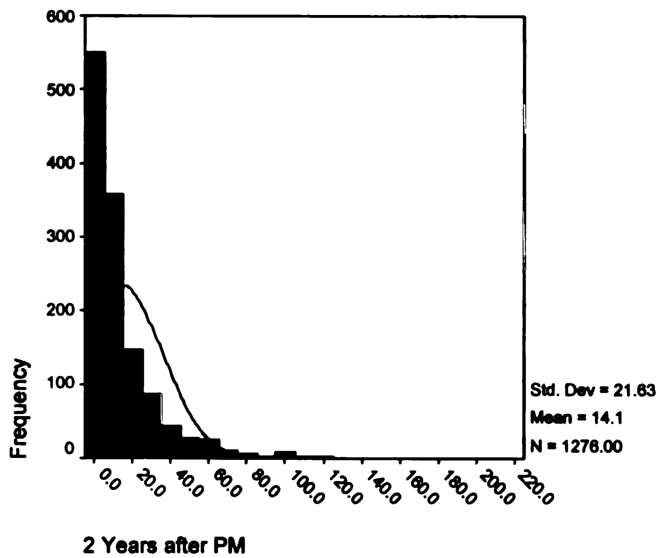

Figure A.17 - Histogram of DI 2 Years after PM

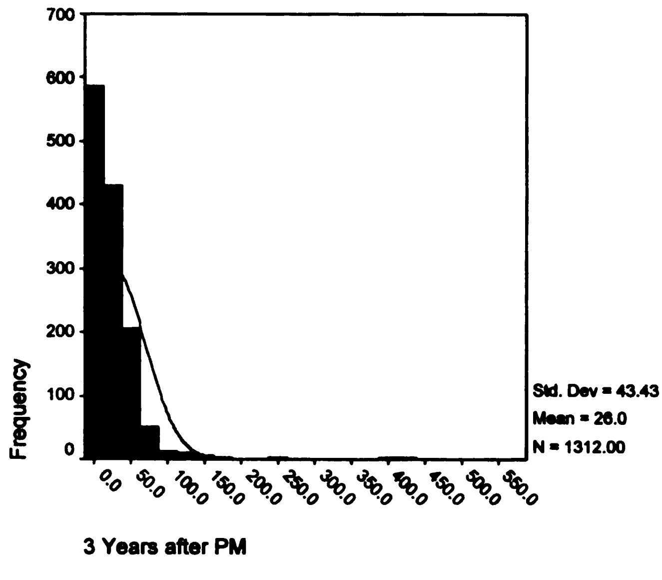

Figure A.18 - Histogram of DI 3 Years after PM

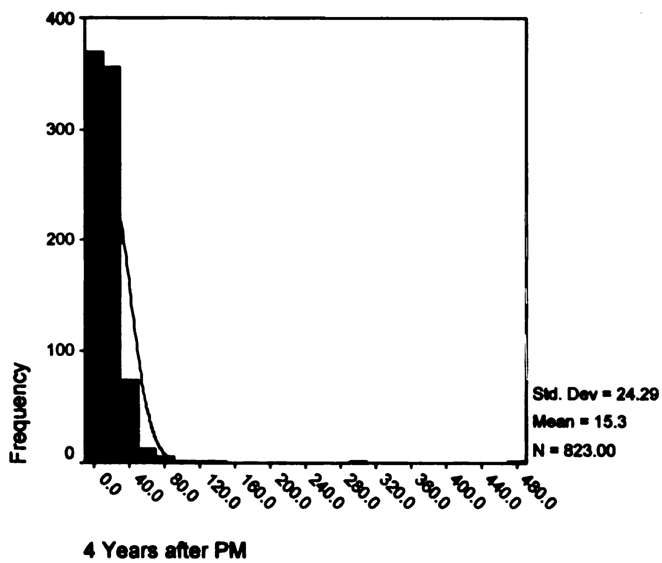

Figure A.19 - Histogram of DI 4 Years after PM

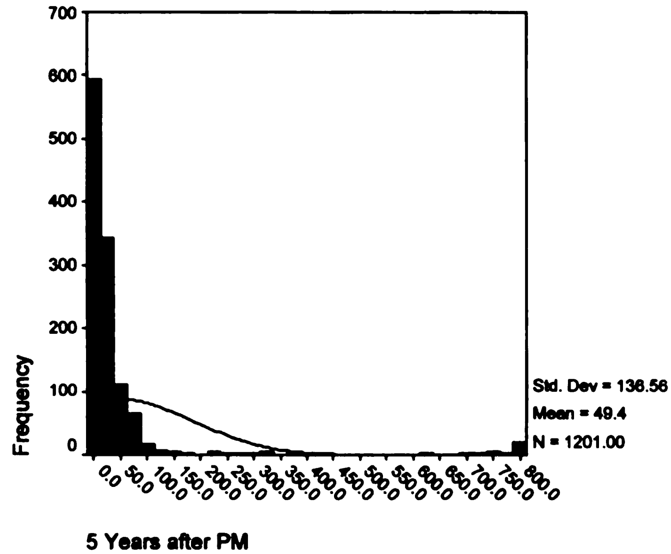

Figure A.20 - Histogram of DI 5 Years after PM

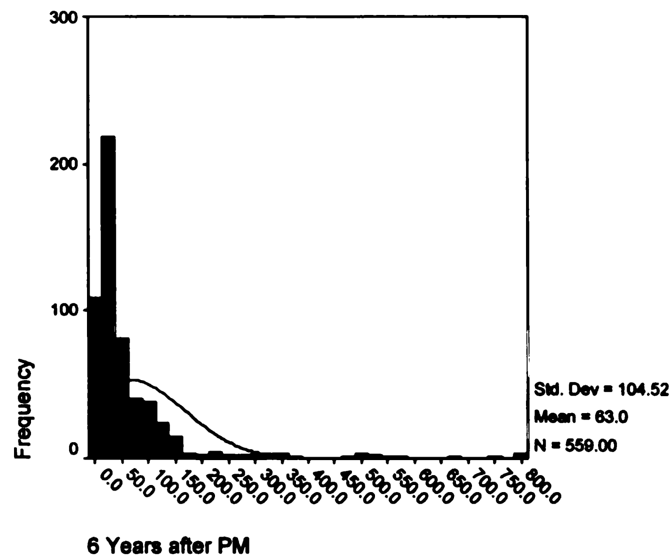

Figure A.21 - Histogram of DI 6 Years after PM

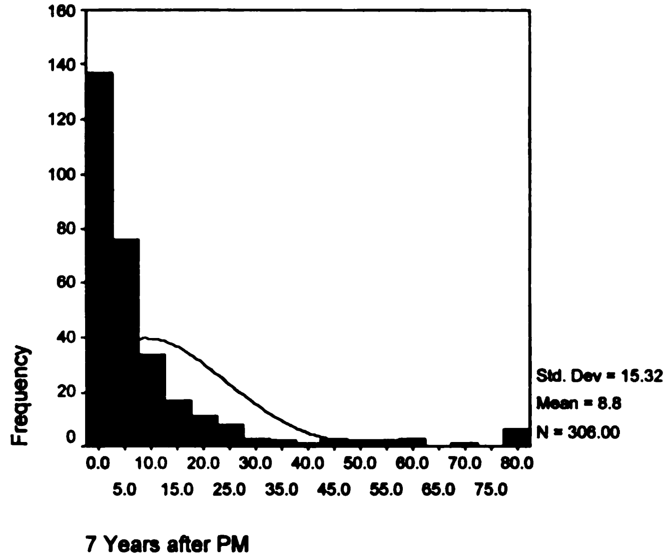

Figure A.22 - Histogram of DI 7 Years after PM

Multiple Course Micro-Surfacing

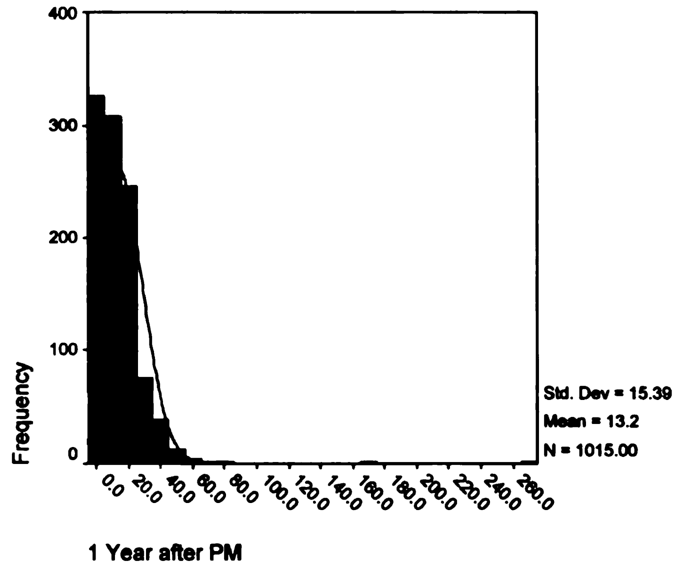

Figure A.23 - Histogram of DI 1 Years after PM

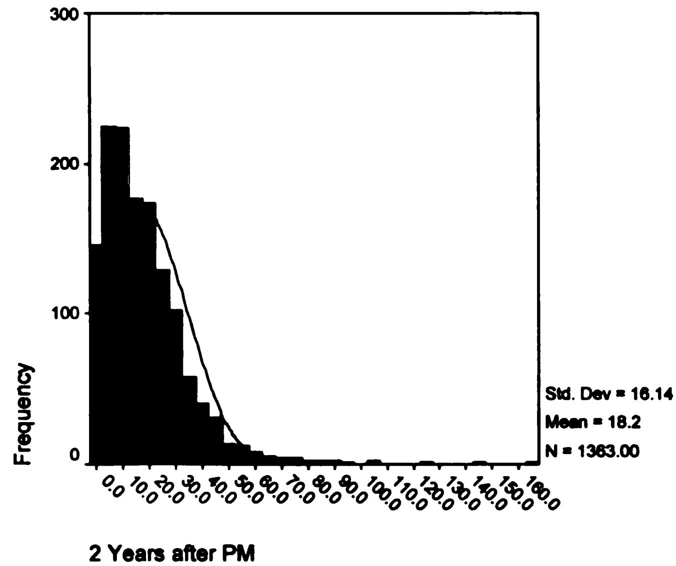

Figure A.24 - Histogram of DI 2 Years after PM

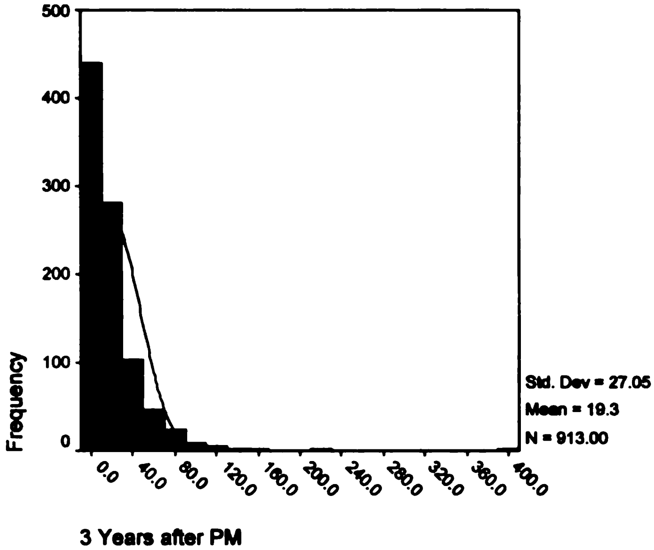

Figure A.25 - Histogram of DI 3 Years after PM

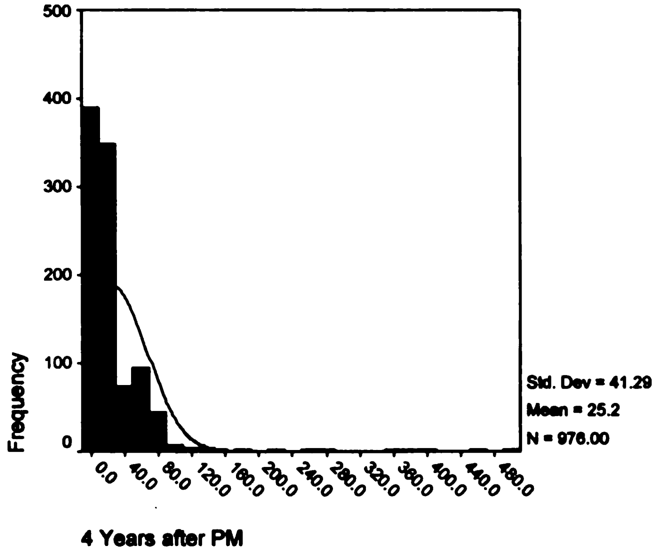

Figure A.26 - Histogram of DI 4 Years after PM

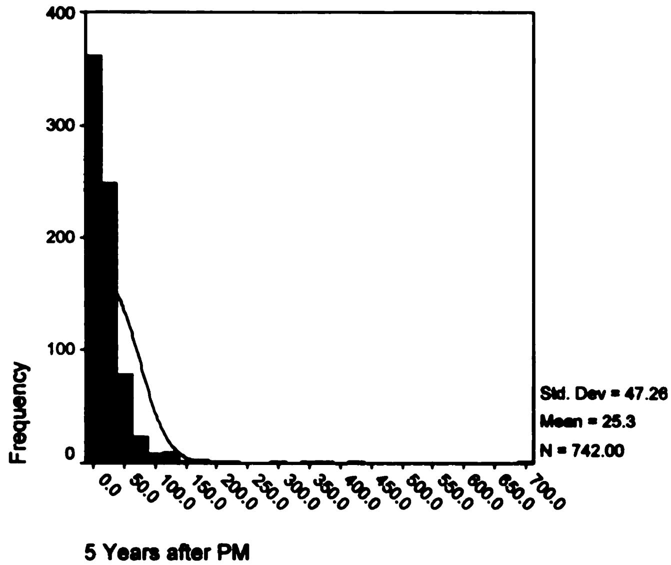

Figure A.27 - Histogram of DI 5 Years after PM

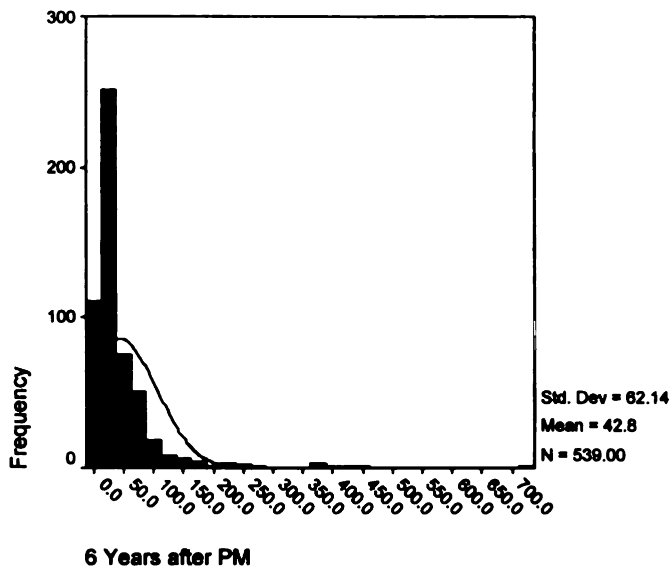

Figure A.28 - Histogram of DI 6 Years after PM

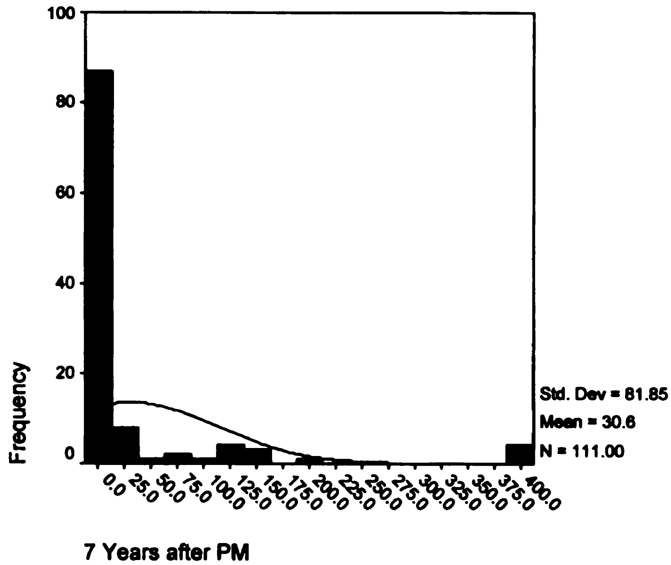

Figure A.29 - Histogram of DI 7 Years after PM

Bituminous Crack Seal

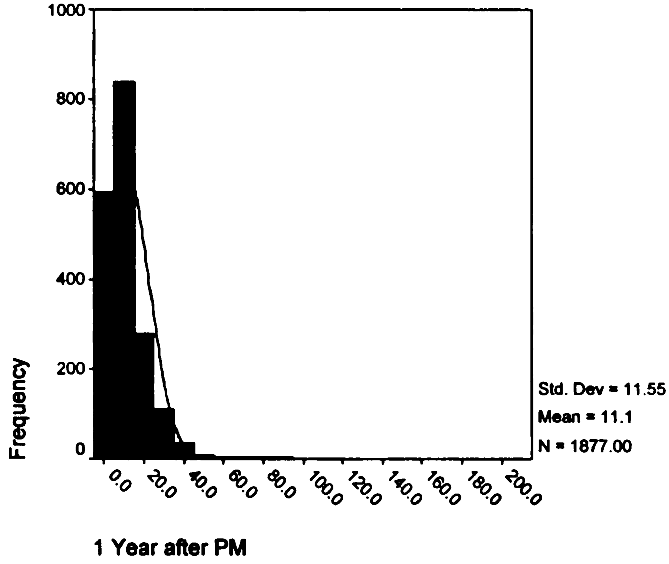

Figure A.30 - Histogram of DI 1 Years after PM

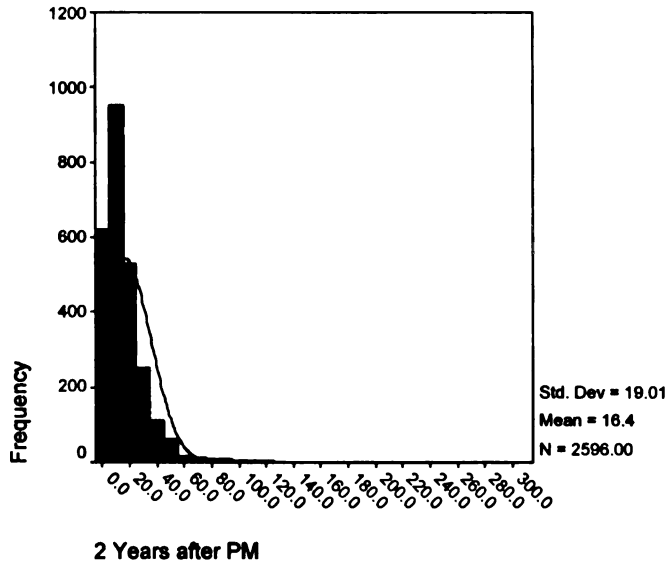

Figure A.31 - Histogram of DI 2 Years after PM

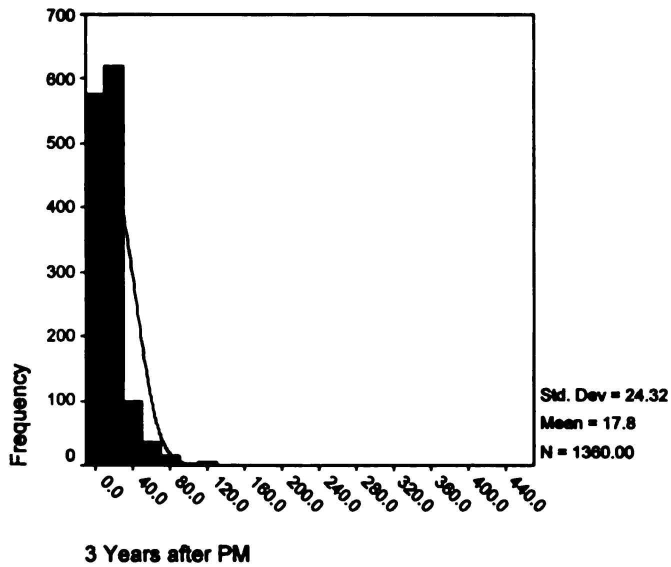

Figure A.32 - Histogram of DI 3 Years after PM

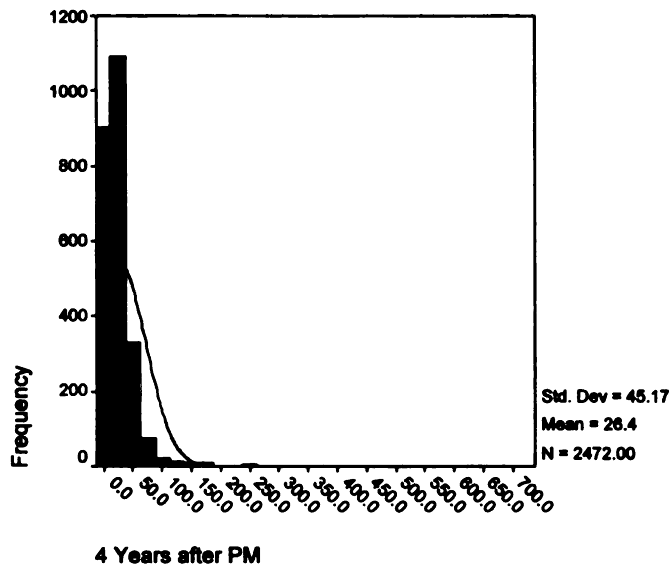

Figure A.33 - Histogram of DI 4 Years after PM

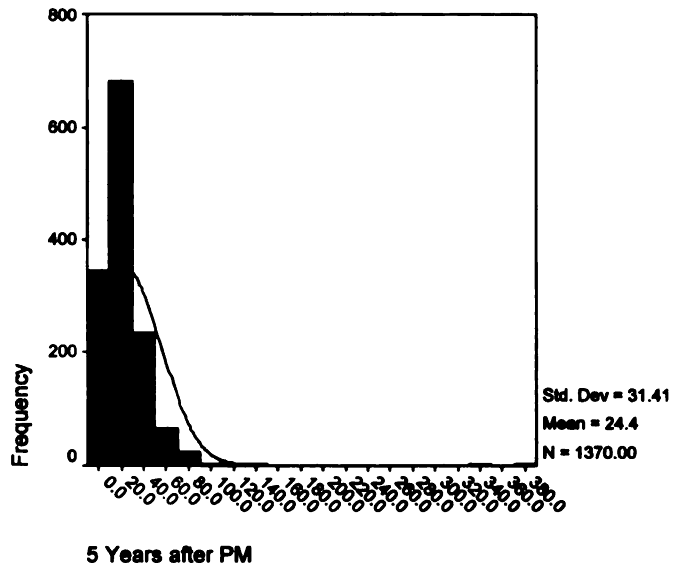

Figure A.34 - Histogram of DI 5 Years after PM

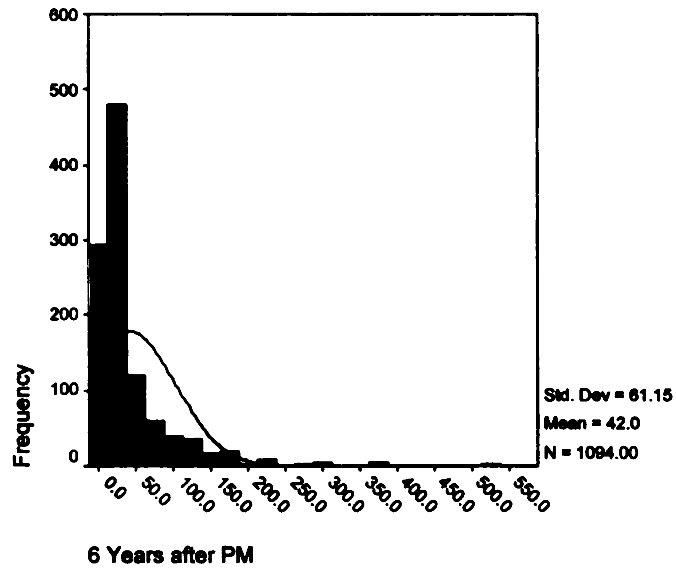

Figure A.35 - Histogram of DI 6 Years after PM

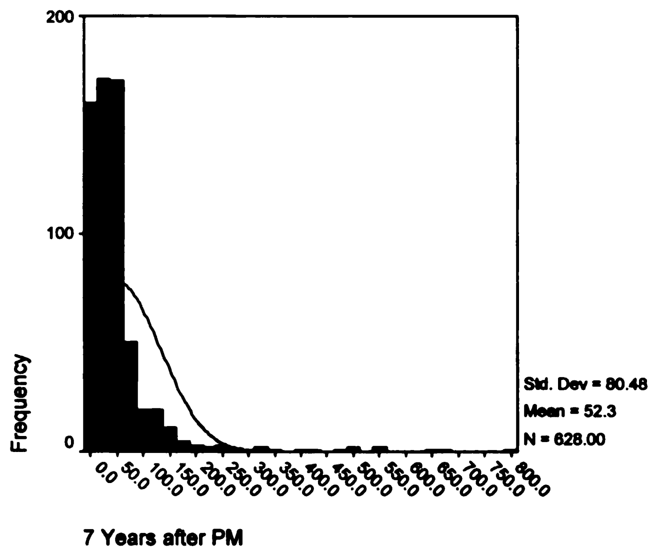

Figure A.36 - Histogram of DI 7 Years after PM

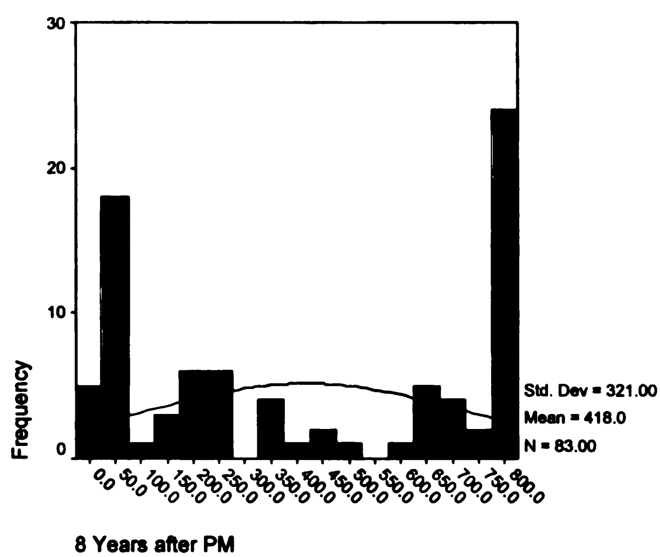

Figure A.37 – Histogram of DI 8 Years after PM

APPENDIX B

HISTOGRAMS USED TO EVALUATE THE DISTRESS INDEX (DI) PREVENTIVE MAINTENANCE (PM) GUIDELINE VALUES FOR THE FOLLOWING PM TREATMENTS

Non-Structural Bituminous Overlay
Surface Milling with a Non-Structural Bituminous Overlay
Single Chip Seal
Multiple Course Micro-Surfacing
Bituminous Crack Seal

Non-Structural Bituminous Overlay

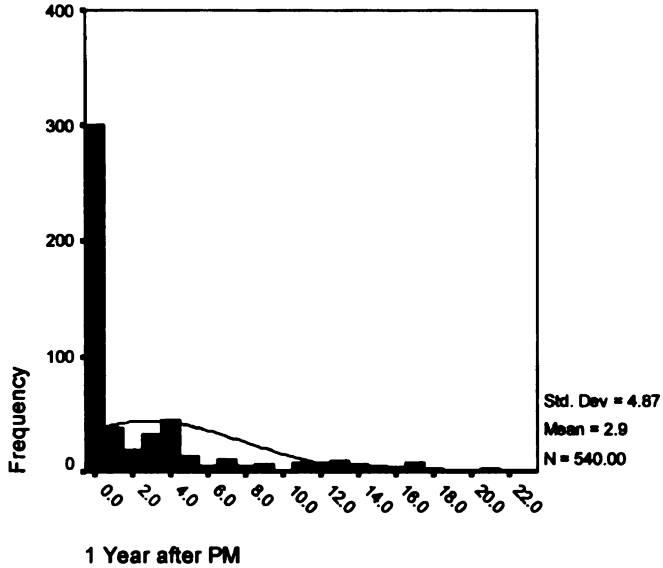

Figure B.1- Histogram of DI 1 Year after PM when the pre-existing condition is less than the guideline value

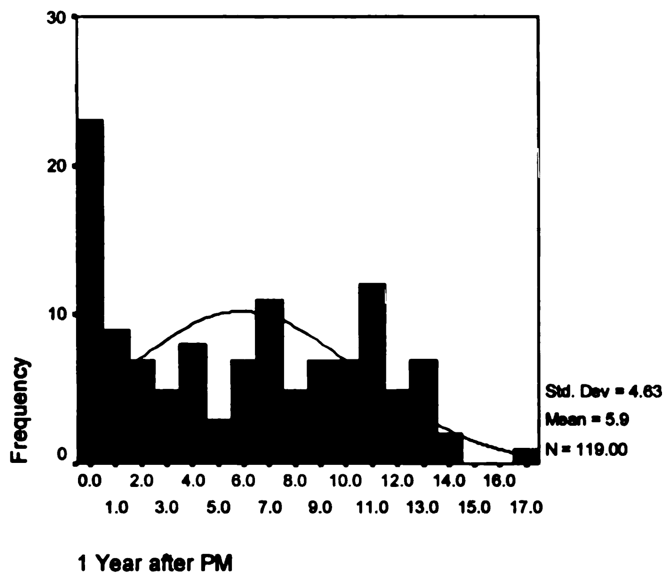

Figure B.2 - Histogram of DI 1 Year after PM when the pre-existing condition is greater than the guideline value

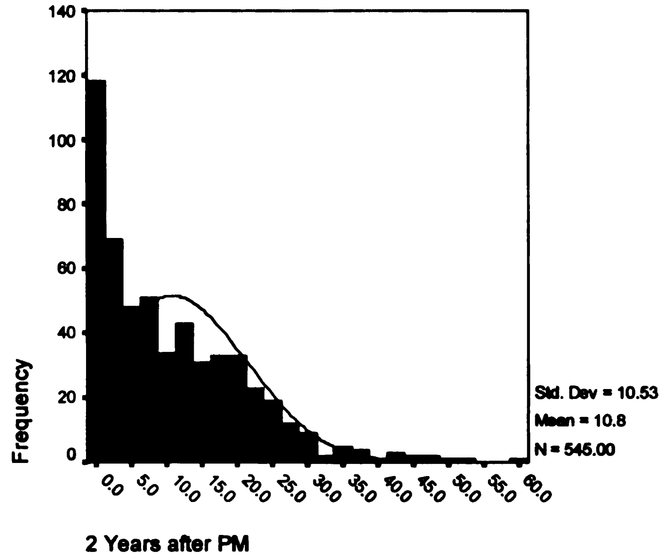

Figure B.3 - Histogram of DI 2 Years after PM when the pre-existing condition is less than the guideline value

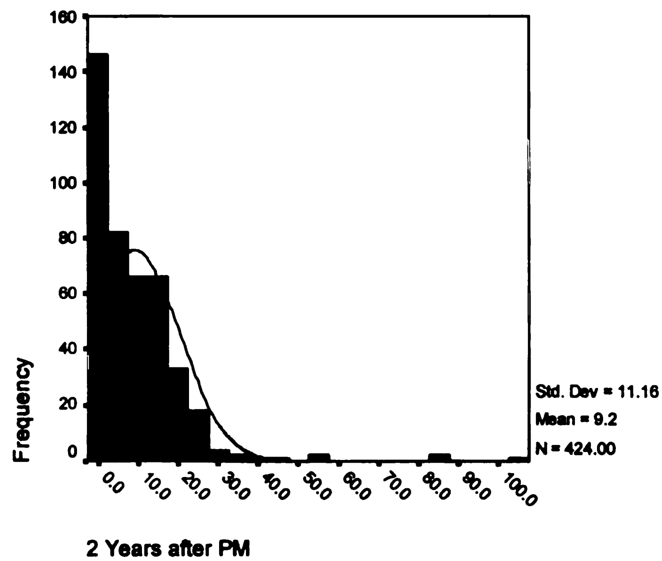

Figure B.4 - Histogram of DI 2 Years after PM when the pre-existing condition is greater than the guideline value

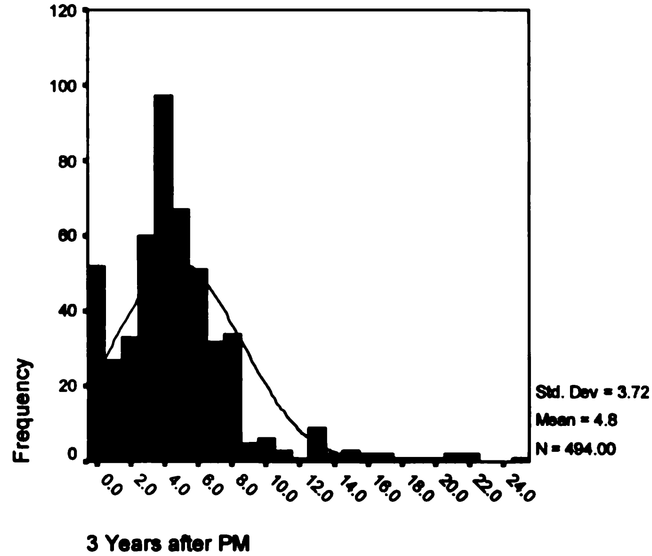

Figure B.5 - Histogram of DI 3 Years after PM when the pre-existing condition is less than the guideline value

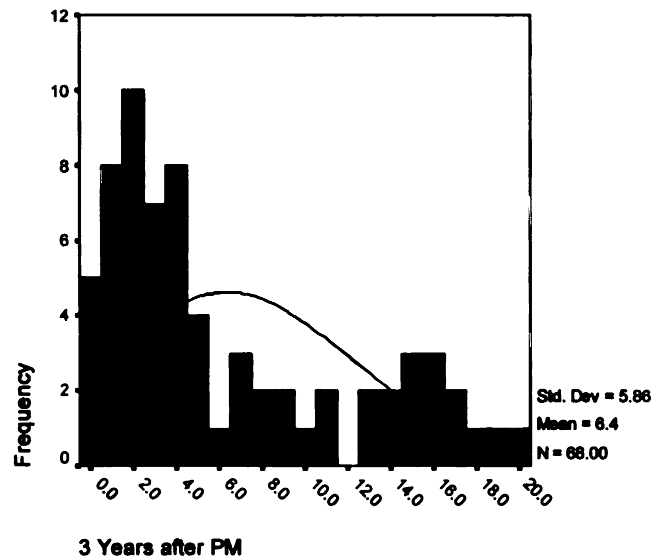

Figure B.6 - Histogram of DI 3 Years after PM when the pre-existing condition is greater than the guideline value

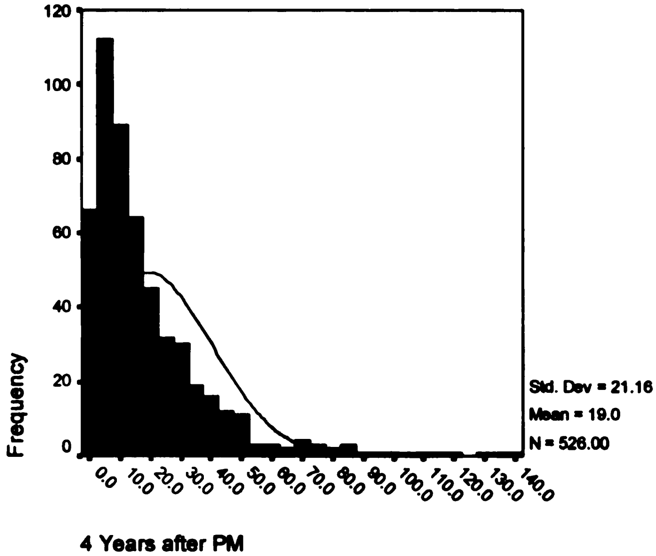

Figure B.7 - Histogram of DI 4 Years after PM when the pre-existing condition is less than the guideline value

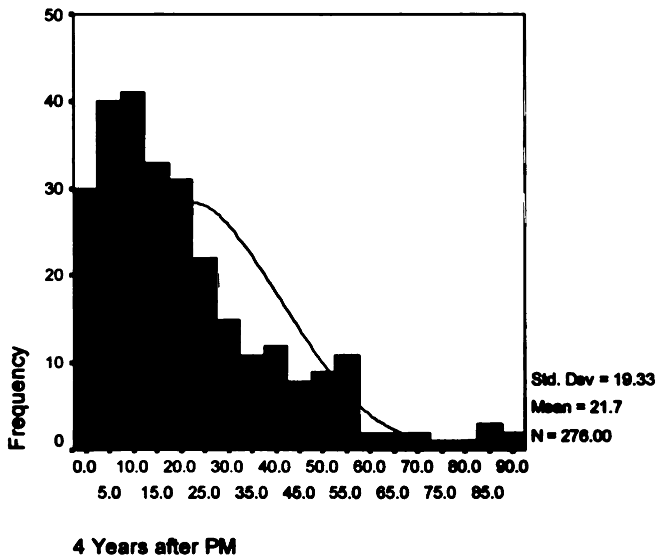

Figure B.8 - Histogram of DI 4 Years after PM when the pre-existing condition is greater than the guideline value

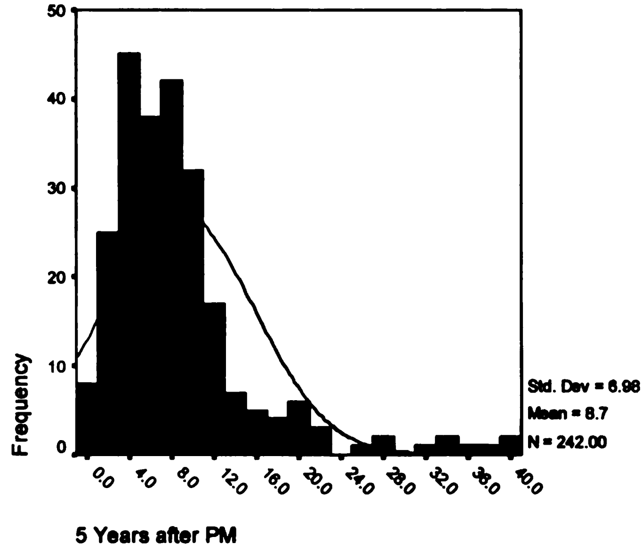

Figure B.9 - Histogram of DI 5 Years after PM when the pre-existing condition is less than the guideline value

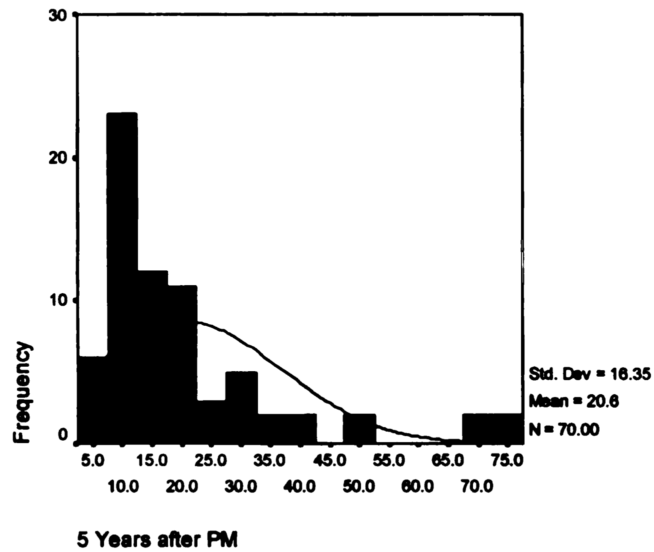

Figure B.10 - Histogram of DI 5 Years after PM when the pre-existing condition is greater than the guideline value

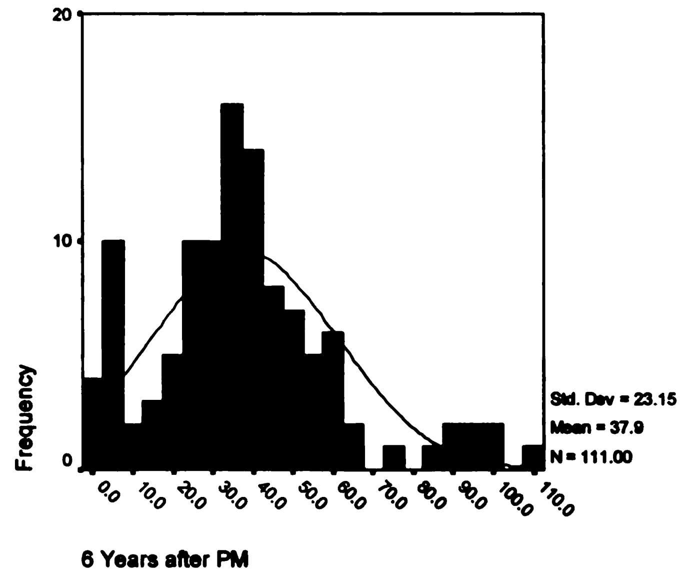

Figure B.11 - Histogram of DI 6 Years after PM when the pre-existing condition is less than the guideline value

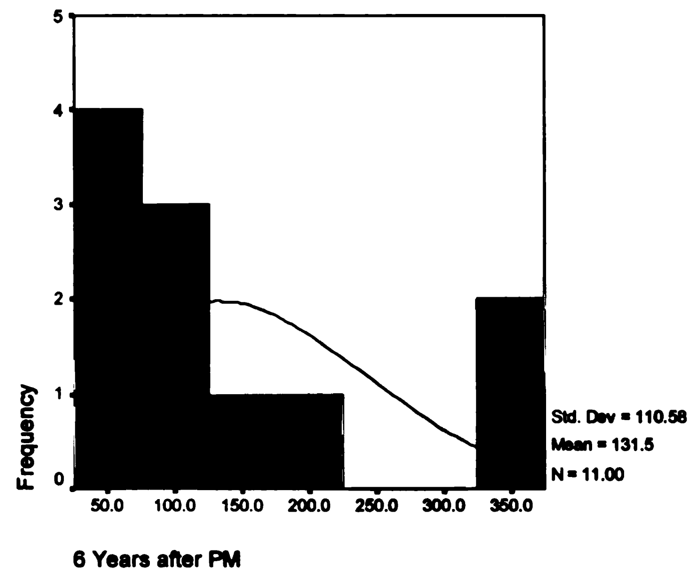

Figure B.12 - Histogram of DI 6 Years after PM when the pre-existing condition is greater than the guideline value

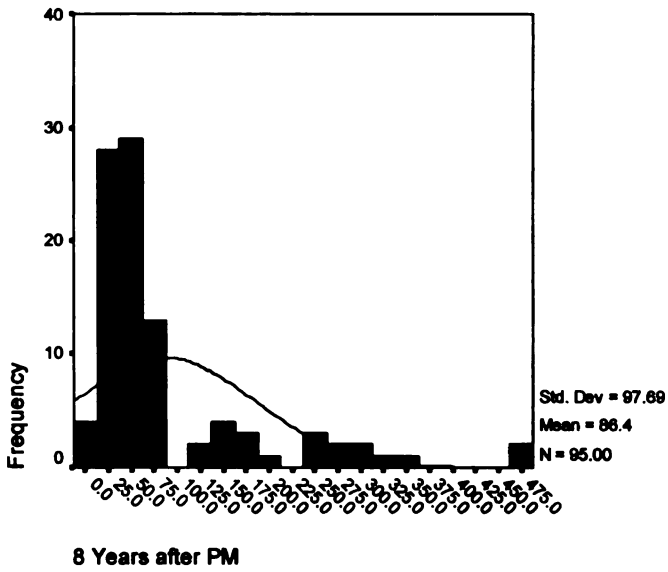

Figure B.13 - Histogram of DI 8 Years after PM when the pre-existing condition is less than the guideline value

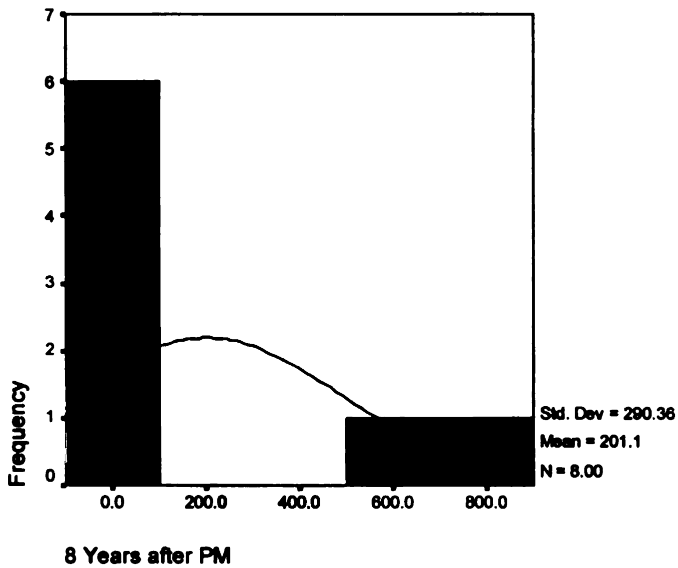

Figure B.14 - Histogram of DI 8 Years after PM when the pre-existing condition is greater than the guideline value

Surface Milling with a Non-Structural Bituminous Overlay

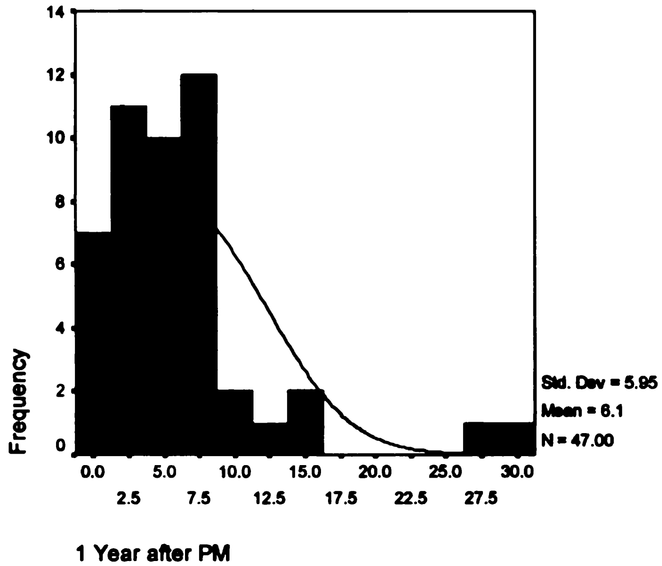

Figure B.15 - Histogram of DI 1 Year after PM when the pre-existing condition is less than the guideline value

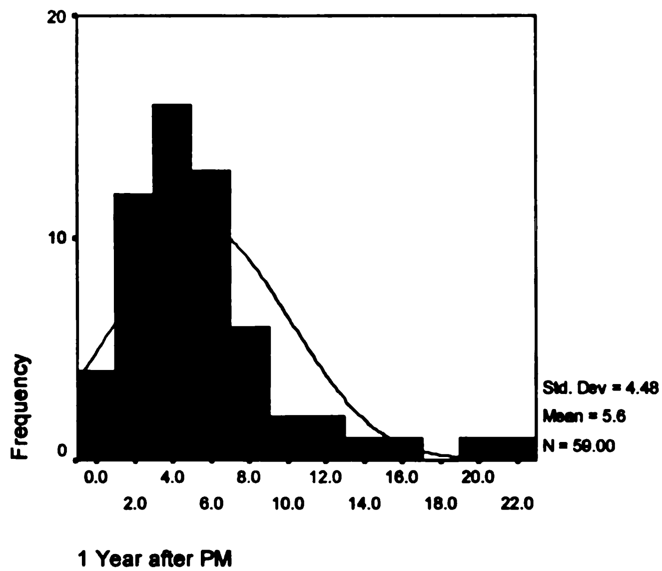

Figure B.16 - Histogram of DI 1 Year after PM when the pre-existing condition is greater than the guideline value

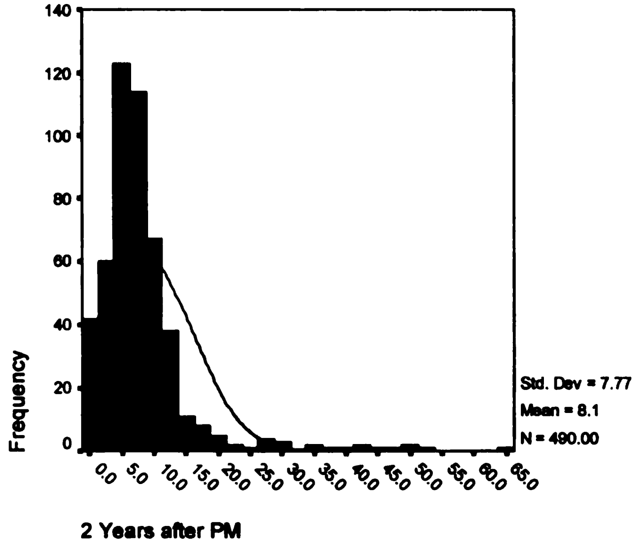

Figure B.17 - Histogram of DI 2 Years after PM when the pre-existing condition is less than the guideline value

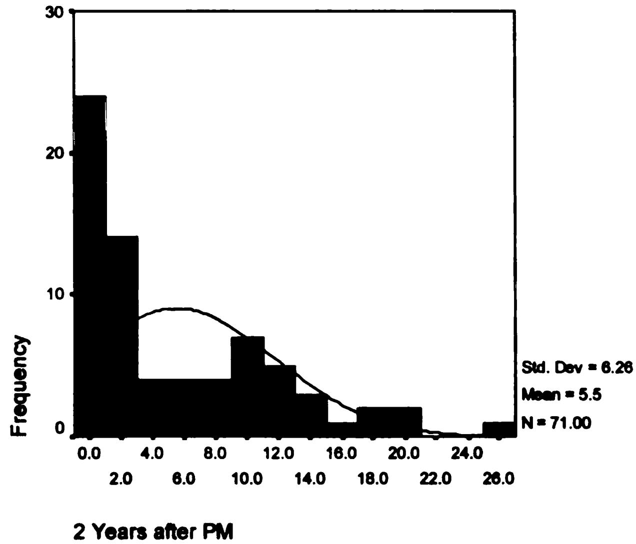

Figure B.18 - Histogram of DI 2 Years after PM when the pre-existing condition is greater than the guideline value

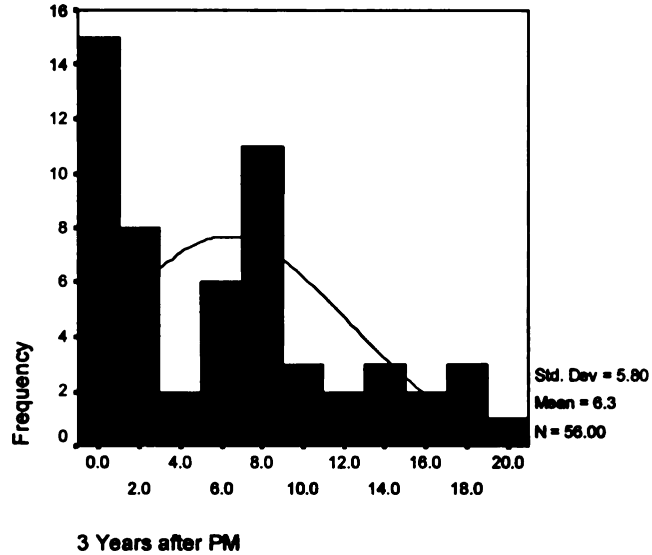

Figure B.19 - Histogram of DI 3 Years after PM when the pre-existing condition is less than the guideline value

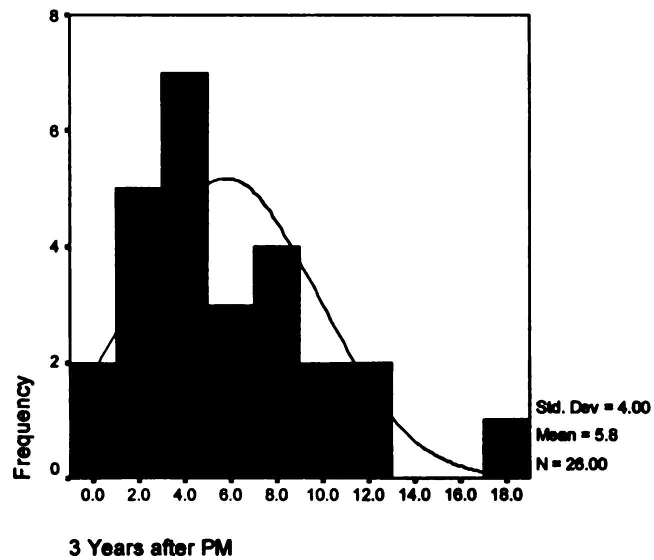

Figure B.20 - Histogram of DI 3 Years after PM when the pre-existing condition is greater than the guideline value

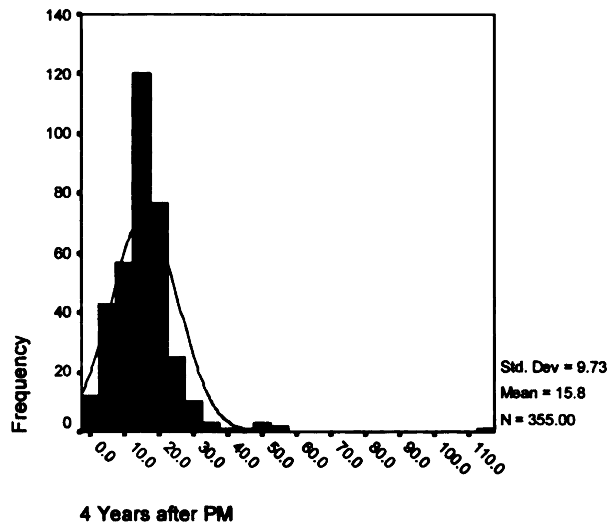

Figure B.21 - Histogram of DI 4 Years after PM when the pre-existing condition is less than the guideline value

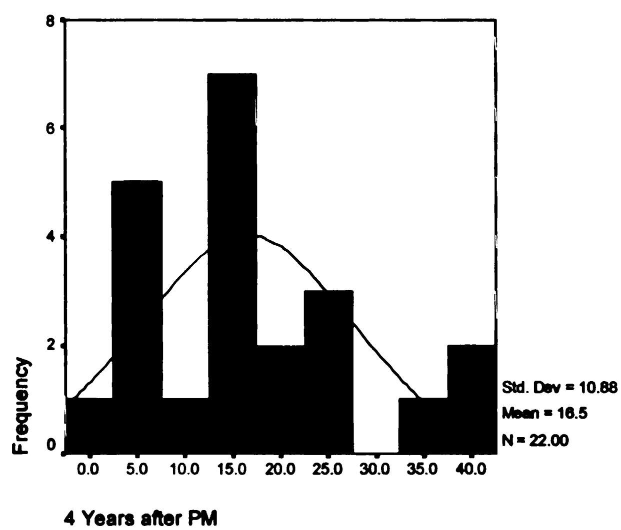

Figure B.22 - Histogram of DI 4 Years after PM when the pre-existing condition is greater than the guideline value

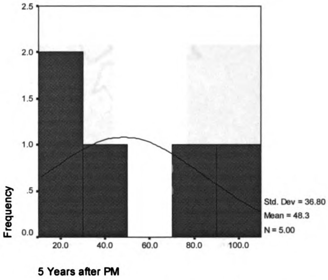

Figure B.23 - Histogram of DI 5 Years after PM when the pre-existing condition is less than the guideline value

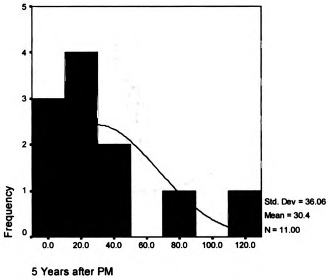

Figure B.24 - Histogram of DI 5 Years after PM when the pre-existing condition is greater than the guideline value

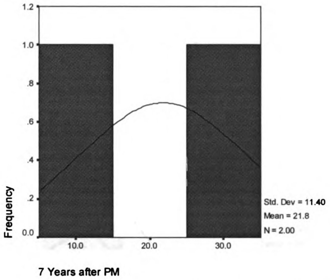

Figure B.25 - Histogram of DI 7 Years after PM when the pre-existing condition is less than the guideline value

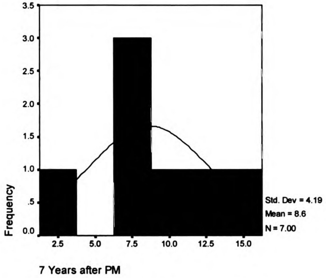

Figure B.26 - Histogram of DI 7 Years after PM when the pre-existing condition is greater than the guideline value

Single Chip Seal

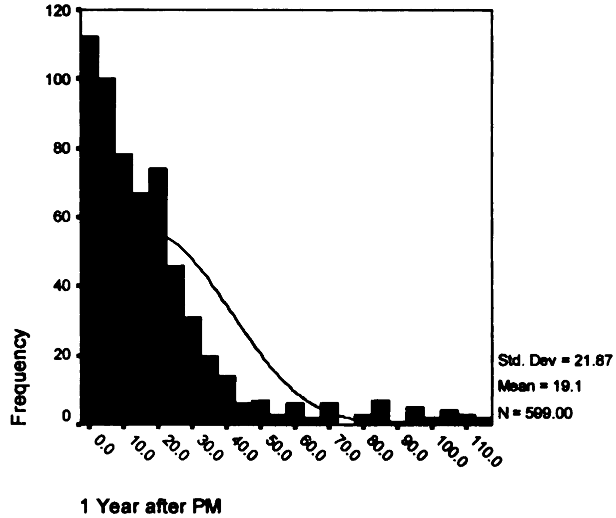

Figure B.27 - Histogram of DI 1 Year after PM when the pre-existing condition is less than the guideline value

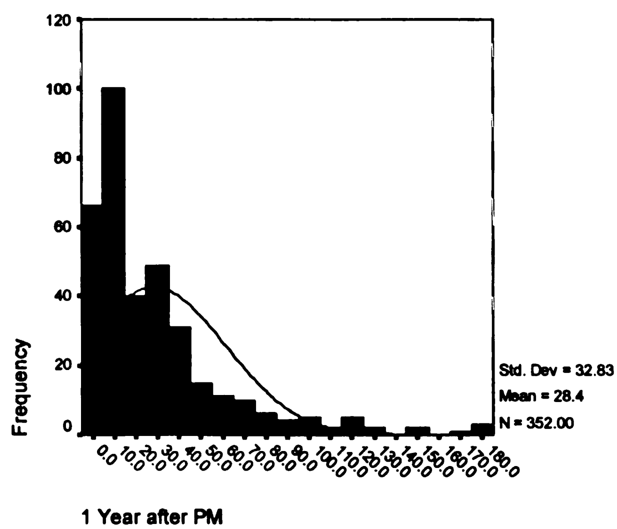

Figure B.28 - Histogram of DI 1 Year after PM when the pre-existing condition is greater than the guideline value

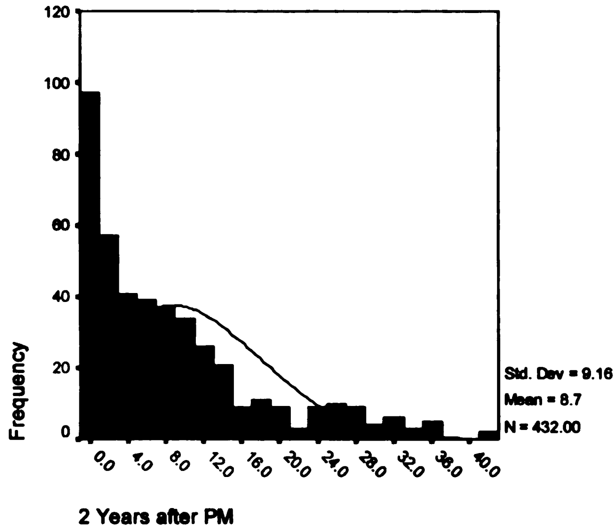

Figure B.29 - Histogram of DI 2 Years after PM when the pre-existing condition is less than the guideline value

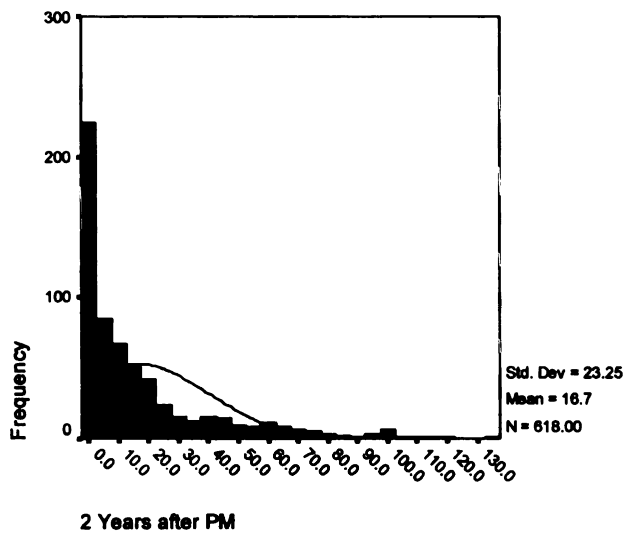

Figure B.30 - Histogram of DI 2 Years after PM when the pre-existing condition is greater than the guideline value

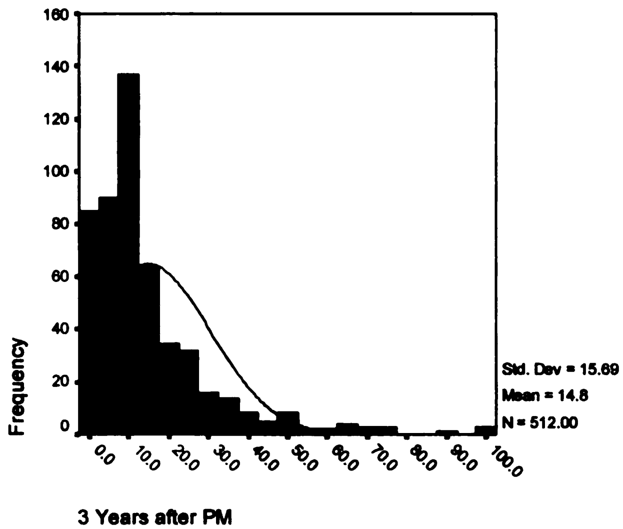

Figure B.31 - Histogram of DI 3 Years after PM when the pre-existing condition is less than the guideline value

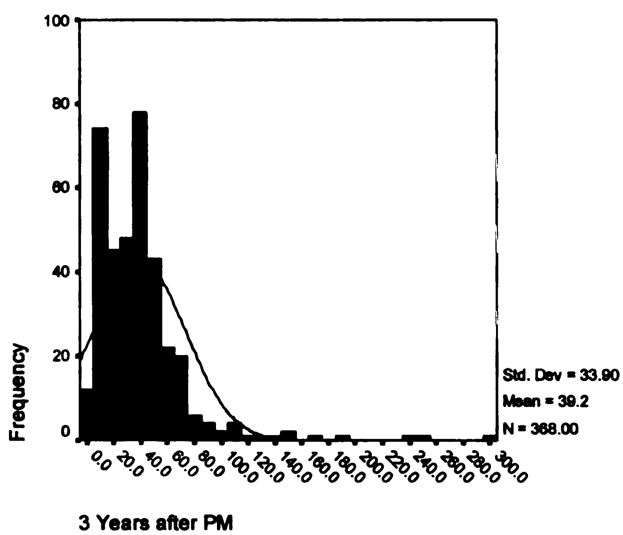

Figure B.32 - Histogram of DI 3 Years after PM when the pre-existing condition is greater than the guideline value

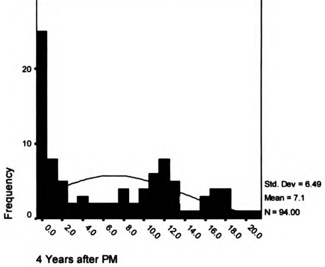

Figure B.33 - Histogram of DI 4 Years after PM when the pre-existing condition is less than the guideline value

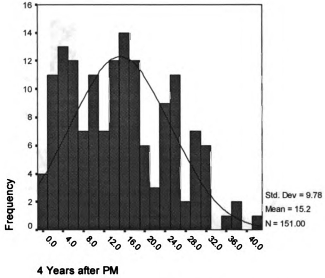

Figure B.34 - Histogram of DI 4 Years after PM when the pre-existing condition is greater than the guideline value

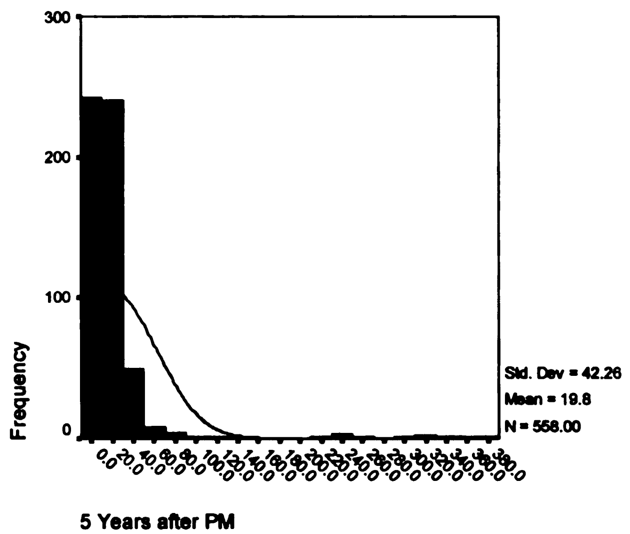

Figure B.35 - Histogram of DI 5 Years after PM when the pre-existing condition is less than the guideline value

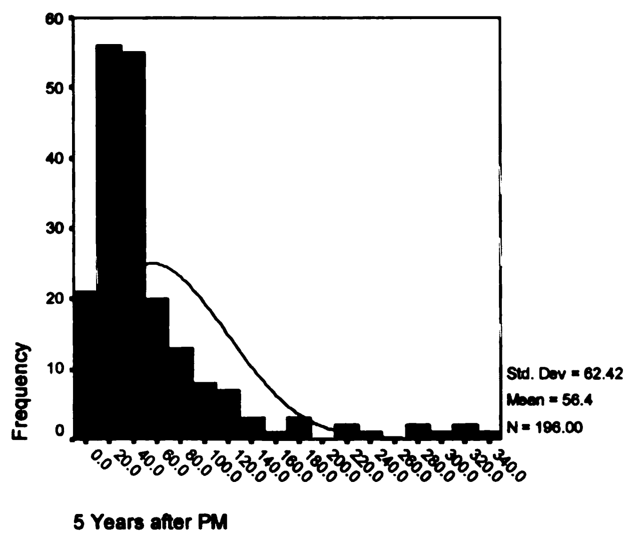

Figure B.36 - Histogram of DI 5 Years after PM when the pre-existing condition is greater than the guideline value

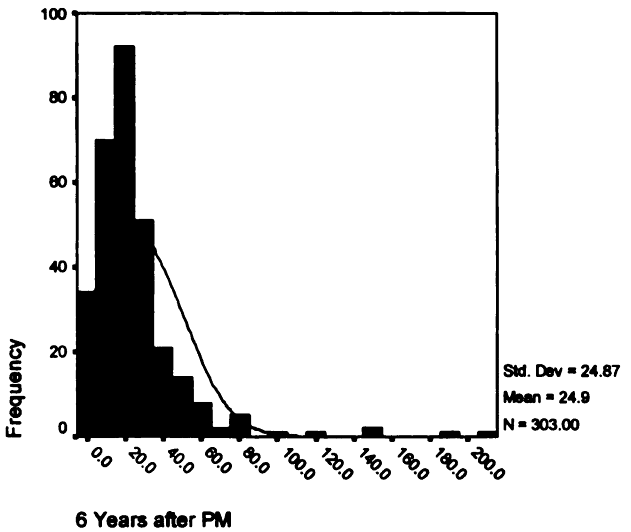

Figure B.37 - Histogram of DI 6 Years after PM when the pre-existing condition is less than the guideline value

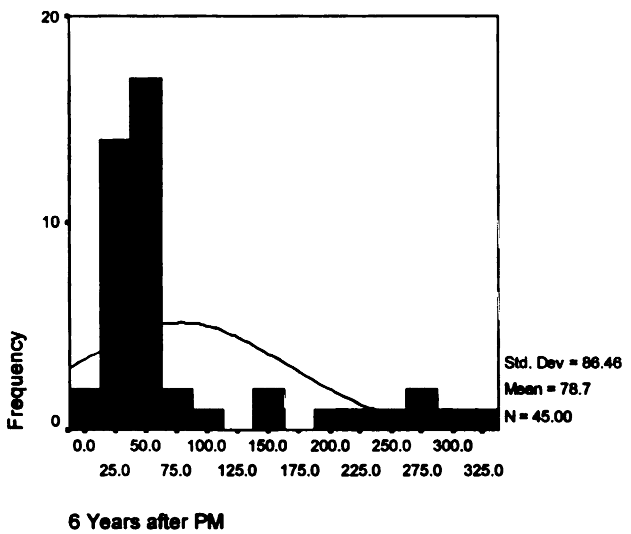

Figure B.38 - Histogram of DI 6 Years after PM when the pre-existing condition is greater than the guideline value

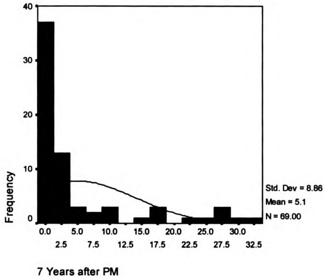

Figure B.39 - Histogram of DI 7 Years after PM when the pre-existing condition is less than the guideline value

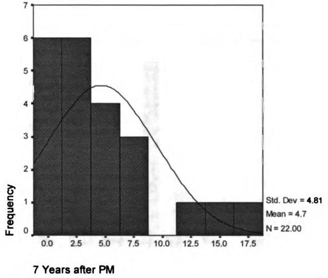

Figure B.40 - Histogram of DI 7 Years after PM when the pre-existing condition is greater than the guideline value

Multiple Course Micro-Surfacing

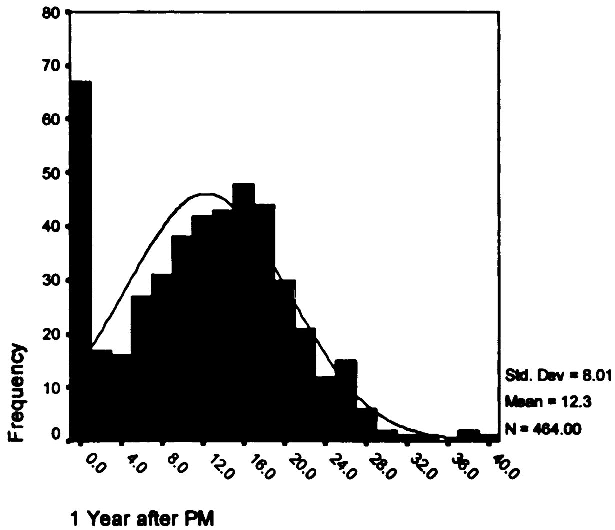

Figure B.41 - Histogram of DI 1 Year after PM when the pre-existing condition is less than the guideline value

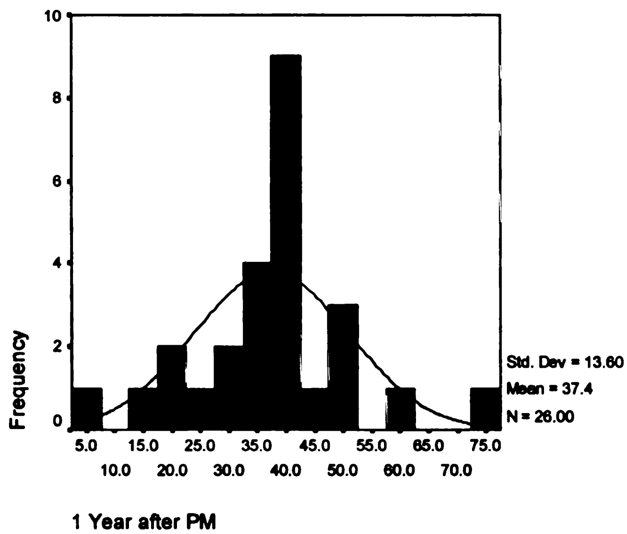

Figure B.42 - Histogram of DI 1 Year after PM when the pre-existing condition is greater than the guideline value

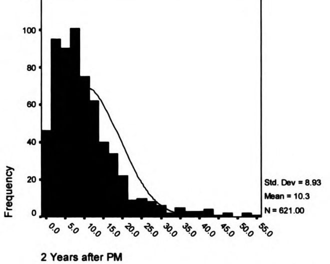

Figure B.43 - Histogram of DI 2 Years after PM when the pre-existing condition is less than the guideline value

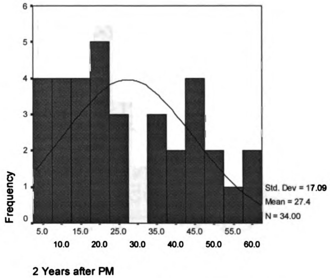

Figure B.44 - Histogram of DI 2 Years after PM when the pre-existing condition is greater than the guideline value

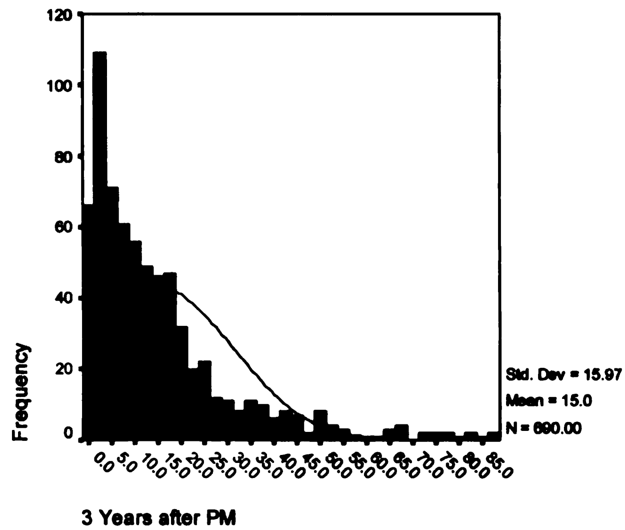

Figure B.45 - Histogram of DI 3 Years after PM when the pre-existing condition is less than the guideline value

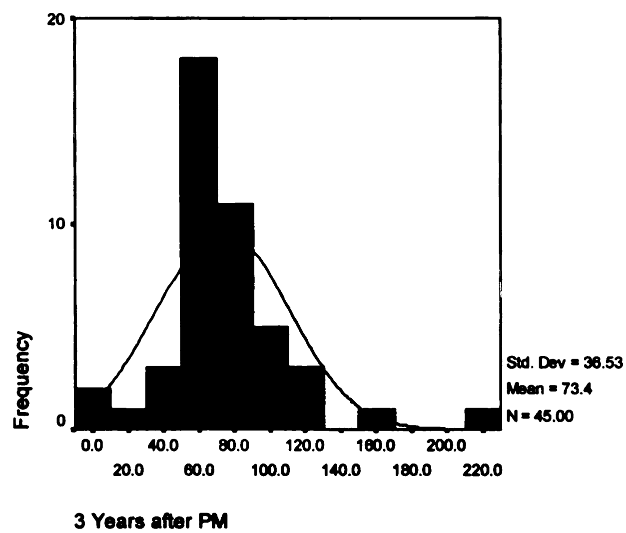

Figure B.46 - Histogram of DI 3 Years after PM when the pre-existing condition is greater than the guideline value

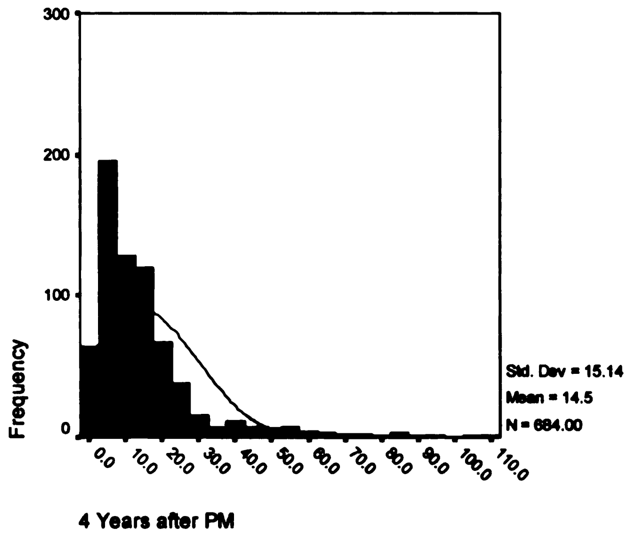

Figure B.47 - Histogram of DI 4 Years after PM when the pre-existing condition is less than the guideline value

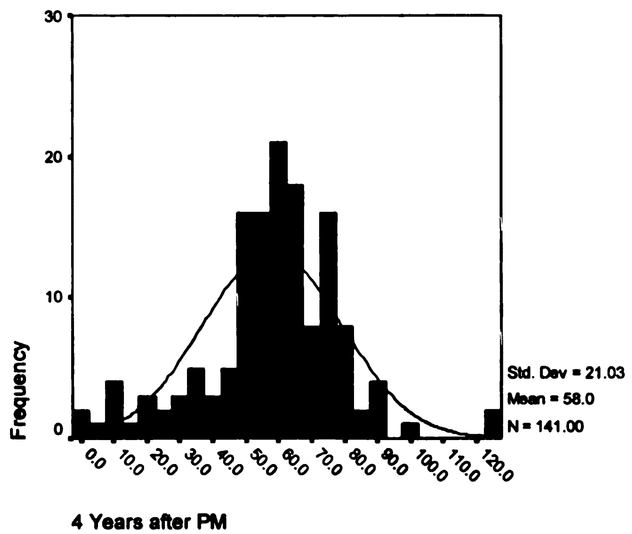

Figure B.48 - Histogram of DI 4 Years after PM when the pre-existing condition is greater than the guideline value

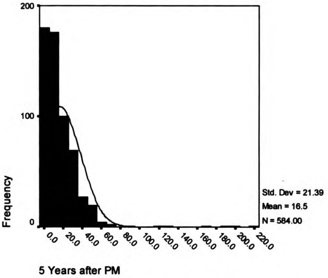

Figure B.49 - Histogram of DI 5 Years after PM when the pre-existing condition is less than the guideline value

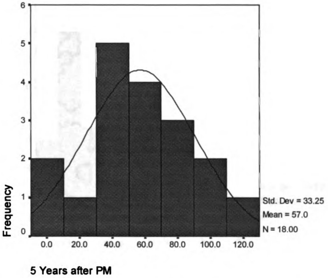

Figure B.50 - Histogram of DI 5 Years after PM when the pre-existing condition is greater than the guideline value

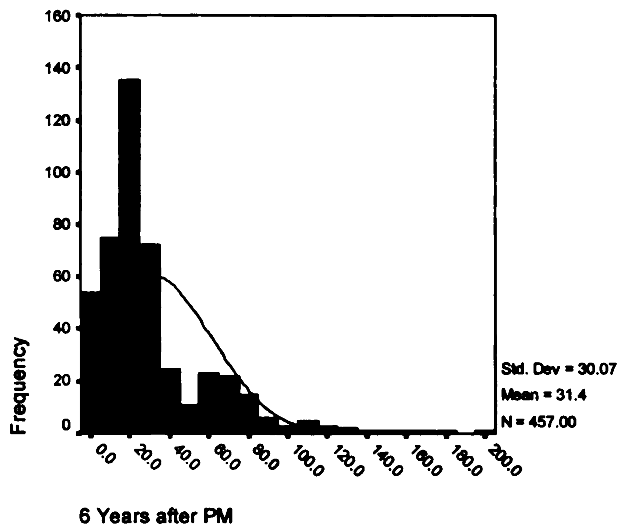

Figure B.51 - Histogram of DI 6 Years after PM when the pre-existing condition is less than the guideline value

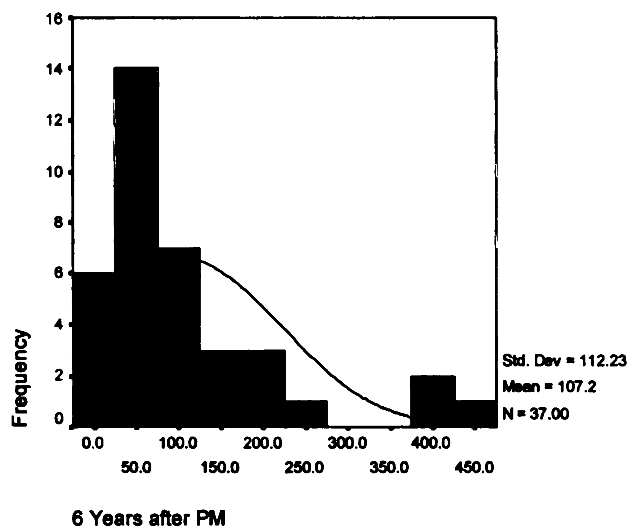

Figure B.52 - Histogram of DI 6 Years after PM when the pre-existing condition is greater than the guideline value

Bituminous Crack Seal

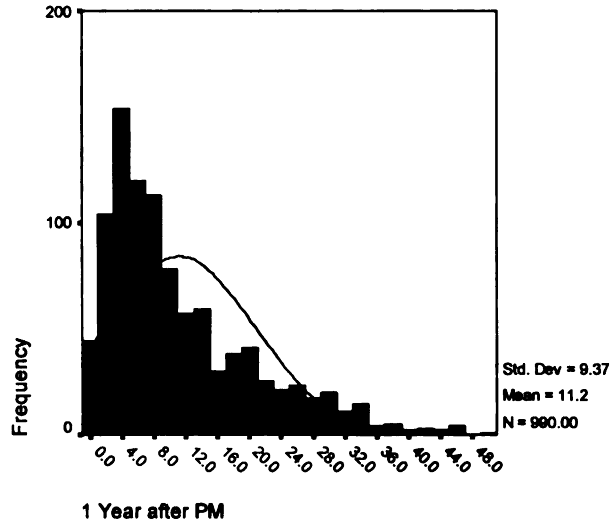

Figure B.53 - Histogram of DI 1 Year after PM when the pre-existing condition is less than the guideline value

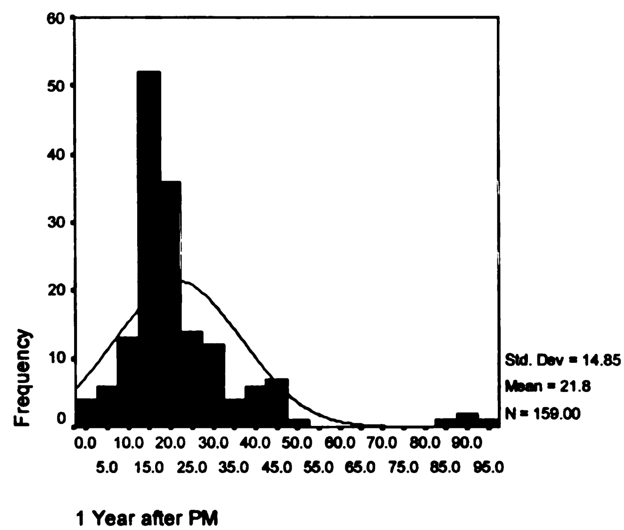

Figure B.54 - Histogram of DI 1 Year after PM when the pre-existing condition is greater than the guideline value

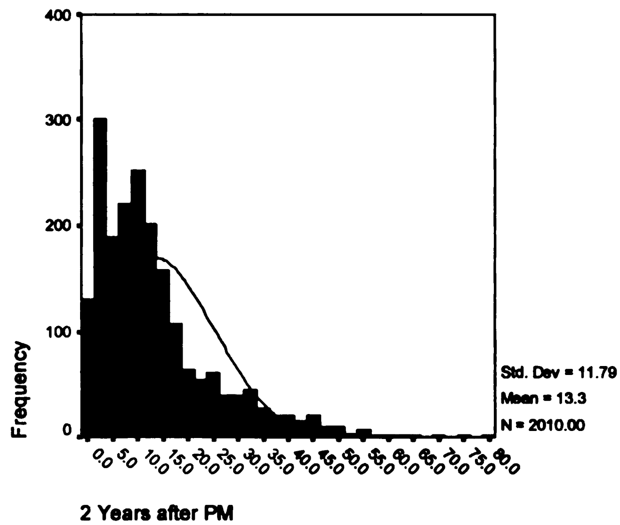

Figure B.55 - Histogram of DI 2 Years after PM when the pre-existing condition is less than the guideline value

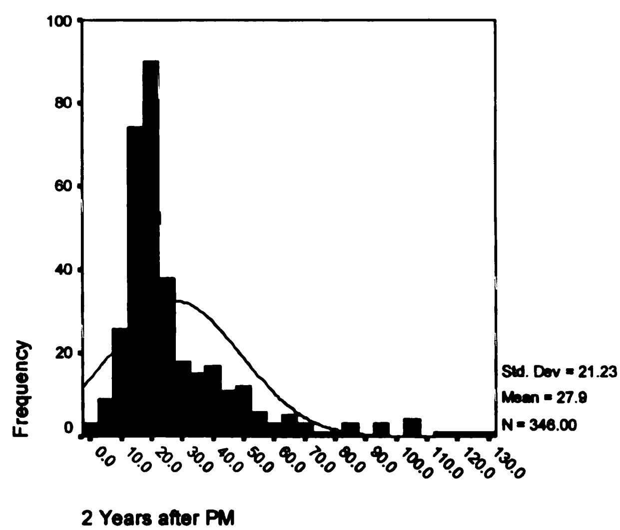

Figure B.56 - Histogram of DI 2 Years after PM when the pre-existing condition is greater than the guideline value

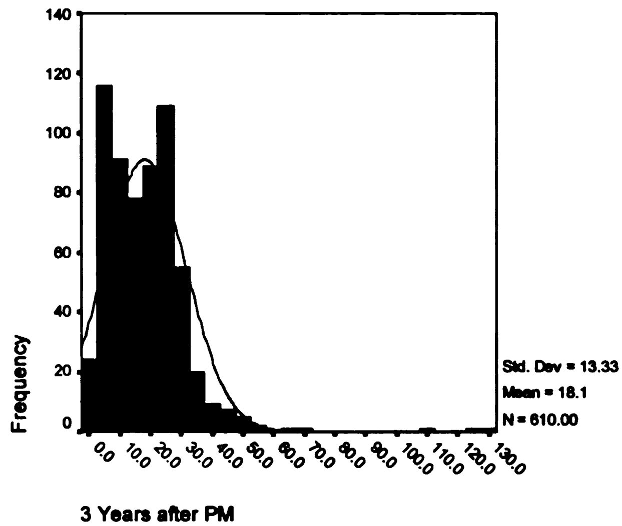

Figure B.57 - Histogram of DI 3 Years after PM when the pre-existing condition is less than the guideline value

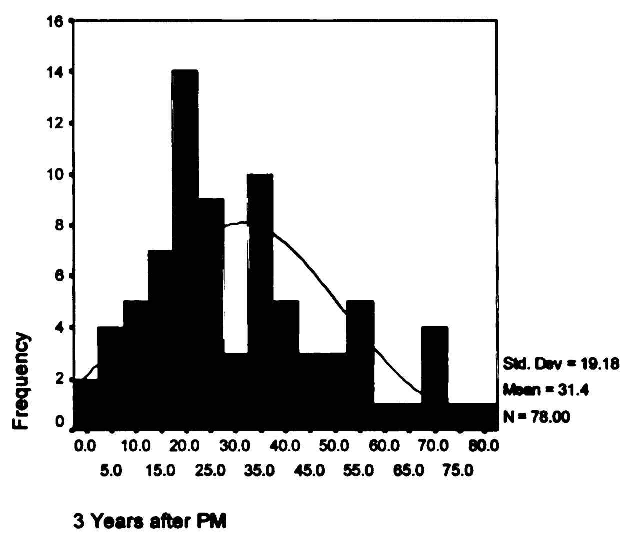

Figure B.58 - Histogram of DI 3 Years after PM when the pre-existing condition is greater than the guideline value

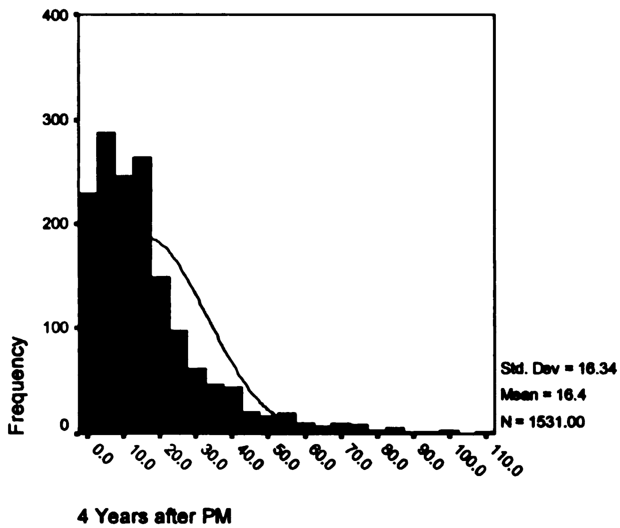

Figure B.59 - Histogram of DI 4 Years after PM when the pre-existing condition is less than the guideline value

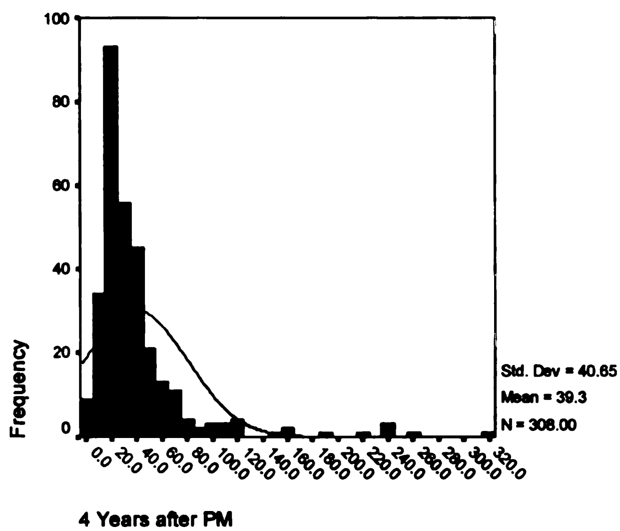

Figure B.60 - Histogram of DI 4 Years after PM when the pre-existing condition is greater than the guideline value

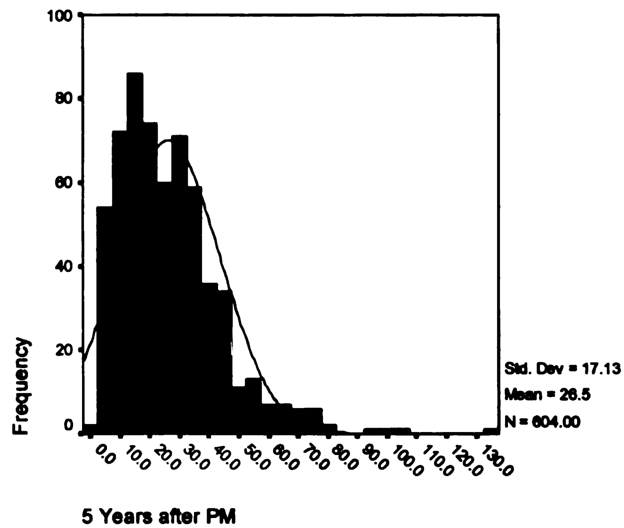

Figure B.61 - Histogram of DI 5 Years after PM when the pre-existing condition is less than the guideline value

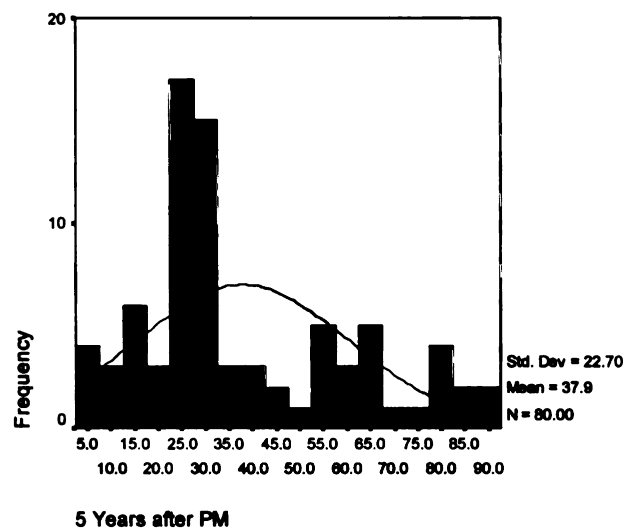

Figure B.62 - Histogram of DI 5 Years after PM when the pre-existing condition is greater than the guideline value

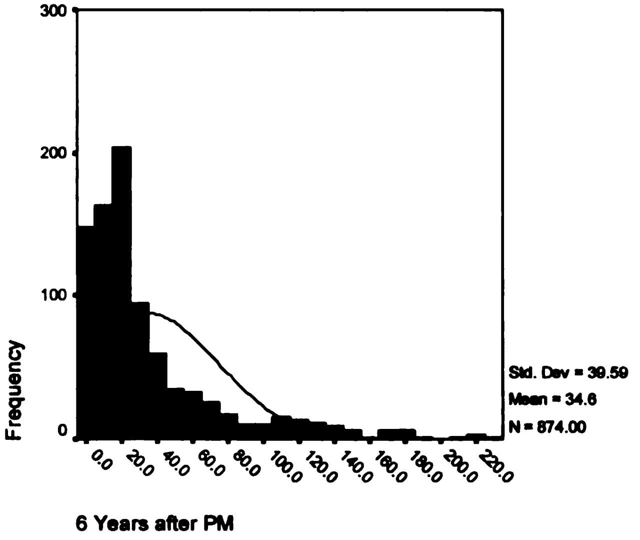

Figure B.63 - Histogram of DI 6 Years after PM when the pre-existing condition is less than the guideline value

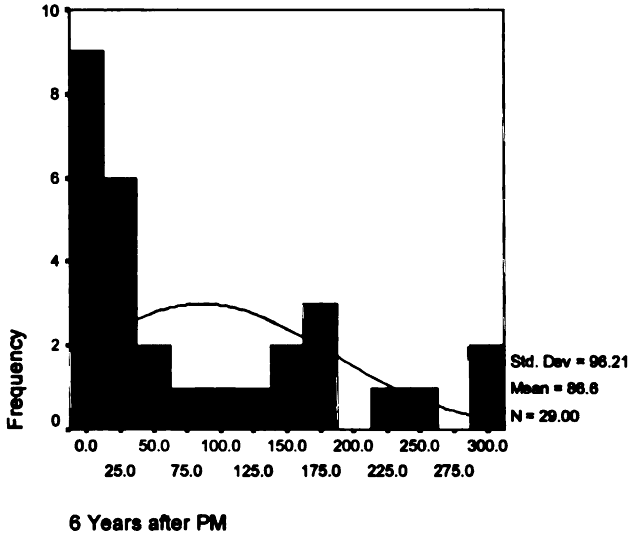

Figure B.64 - Histogram of DI 6 Years after PM when the pre-existing condition is greater than the guideline value

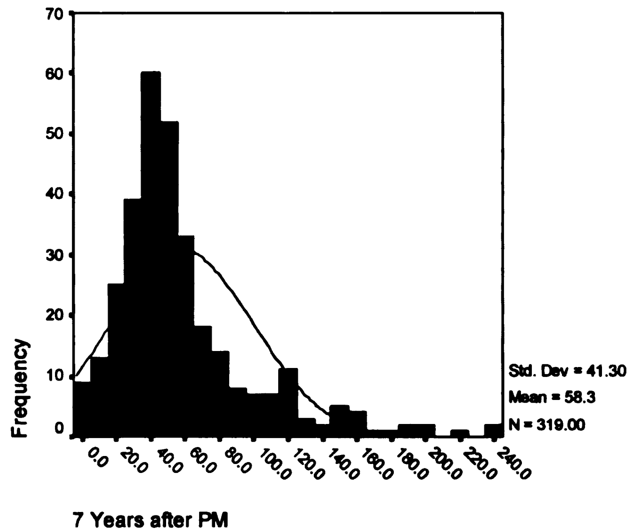

Figure B.65 - Histogram of DI 7 Years after PM when the pre-existing condition is less than the guideline value

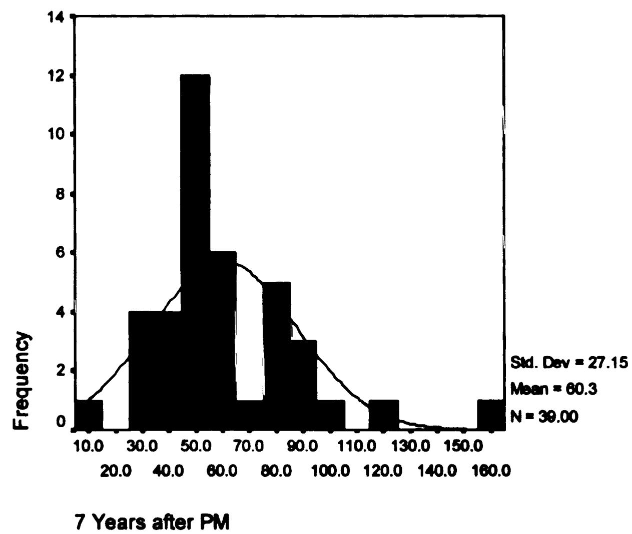

Figure B.66 - Histogram of DI 7 Years after PM when the pre-existing condition is greater than the guideline value

APPENDIX C

HISTOGRAMS USED TO EVALUATE THE RIDE QUALITY INDEX (RQI) PM GUIDELINE VALUES FOR THE FOLLOWING PREVENTIVE MAINTENANCE (PM) TREATMENTS BASED ON THE DISTRESS INDEX (DI)

Non-Structural Bituminous Overlay
Surface Milling with a Non-Structural Bituminous Overlay
Single Chip Seal
Multiple Course Micro-Surfacing
Bituminous Crack Seal

Non-Structural Bituminous Overlay

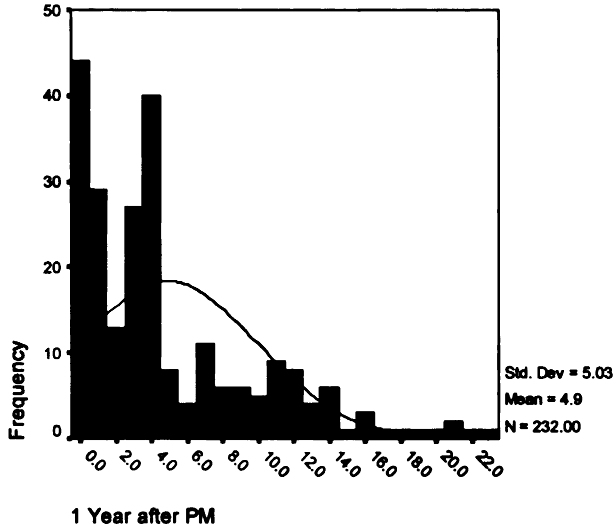

Figure C.1 - Histogram of DI 1 Year after PM when the pre-existing condition is less than the guideline value

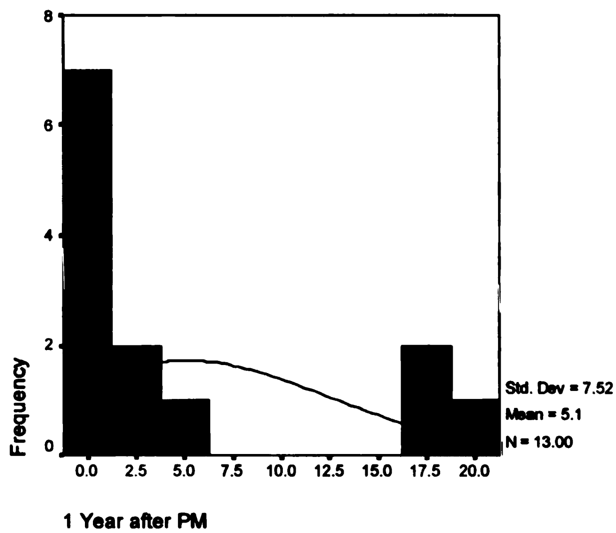

Figure C.2 - Histogram of DI 1 Year after PM when the pre-existing condition is greater than the guideline value

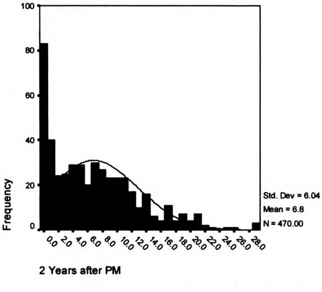

Figure C.3 - Histogram of DI 2 Years after PM when the pre-existing condition is less than the guideline value

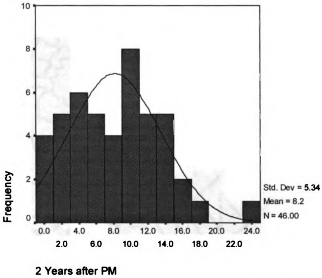

Figure C.4 - Histogram of DI 2 Years after PM when the pre-existing condition is greater than the guideline value

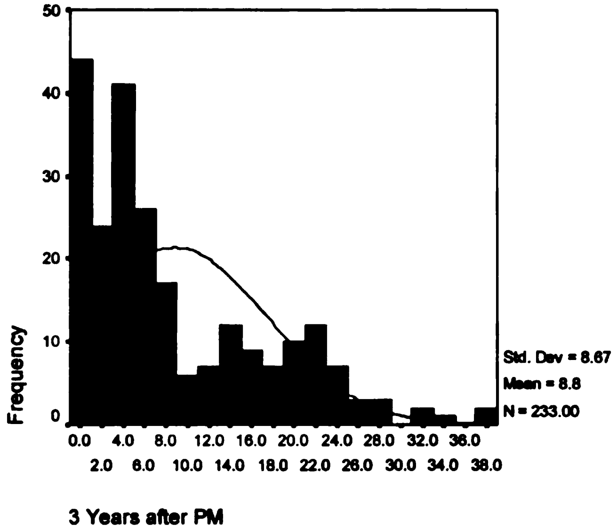

Figure C.5 - Histogram of DI 3 Years after PM when the pre-existing condition is less than the guideline value

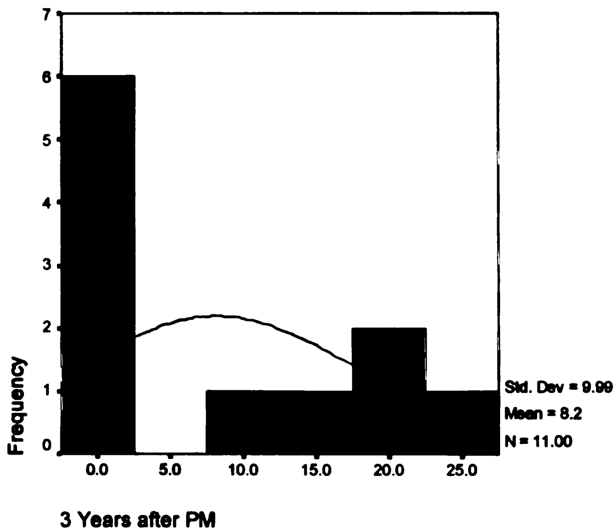

Figure C.6 - Histogram of DI 3 Years after PM when the pre-existing condition is greater than the guideline value

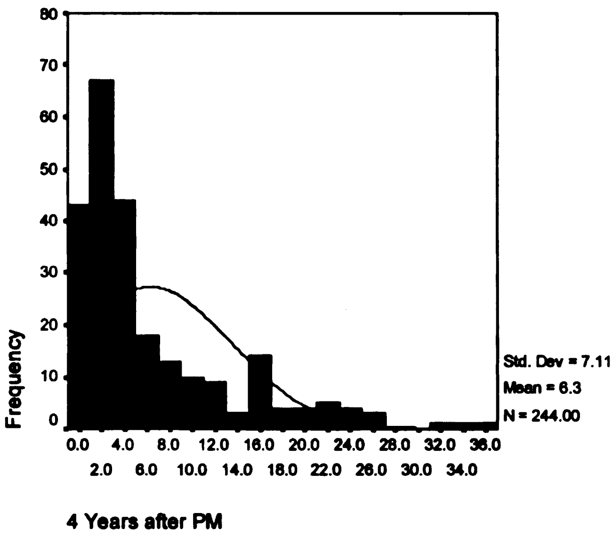

Figure C.7 - Histogram of DI 4 Years after PM when the pre-existing condition is less than the guideline value

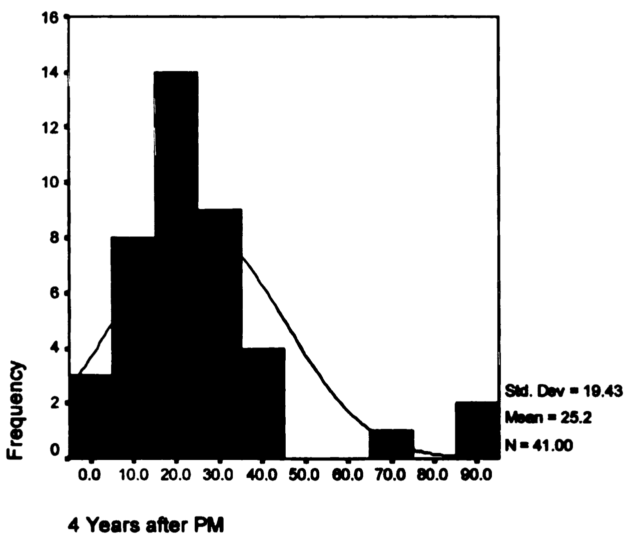

Figure C.8 - Histogram of DI 4 Years after PM when the pre-existing condition is greater than the guideline value

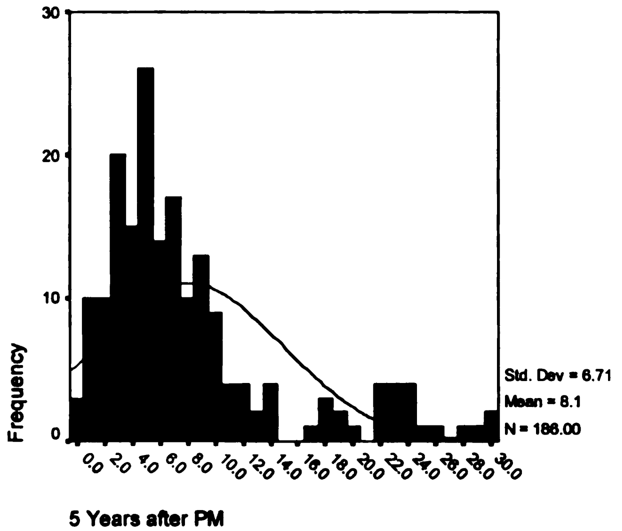

Figure C.9 - Histogram of DI 5 Years after PM when the pre-existing condition is less than the guideline value

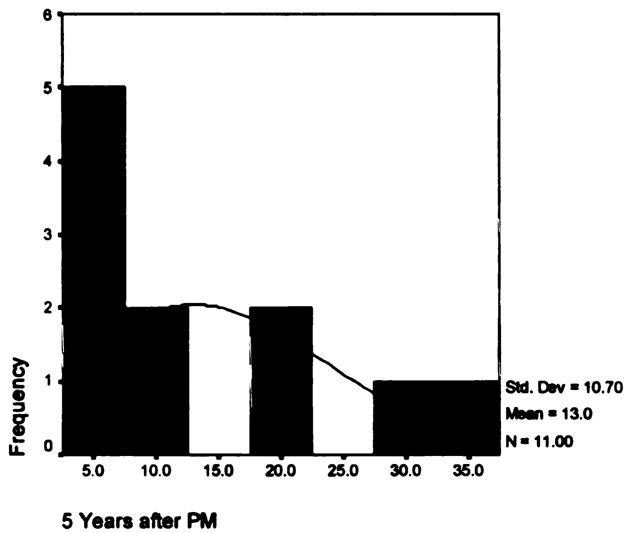

Figure C.10 - Histogram of DI 5 Years after PM when the pre-existing condition is greater than the guideline value

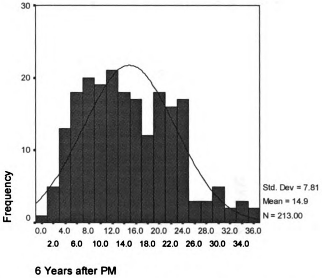

Figure C.11 - Histogram of DI 6 Years after PM when the pre-existing condition is less than the guideline value

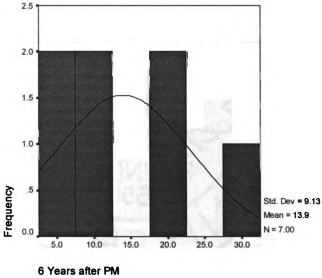

Figure C.12 - Histogram of DI 6 Years after PM when the pre-existing condition is greater than the guideline value

Surface Milling with a Non-Structural Bituminous Overlay

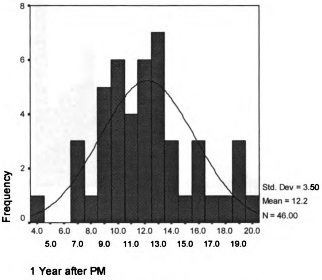

Figure C.13 - Histogram of DI 1 Year after PM when the pre-existing condition is less than the guideline value

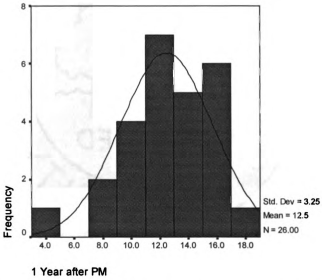

Figure C.14 - Histogram of DI 1 Year after PM when the pre-existing condition is greater than the guideline value

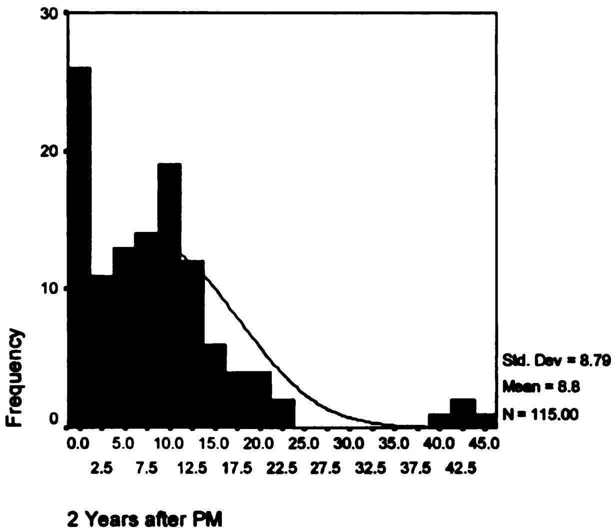

Figure C.15 - Histogram of DI 2 Years after PM when the pre-existing condition is less than the guideline value

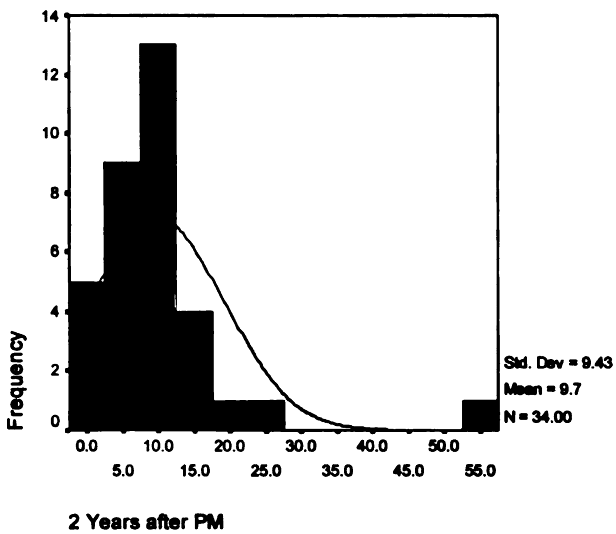

Figure C.16 - Histogram of DI 2 Years after PM when the pre-existing condition is greater than the guideline value

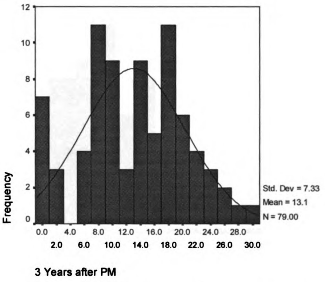

Figure C.17 - Histogram of DI 3 Years after PM when the pre-existing condition is less than the guideline value

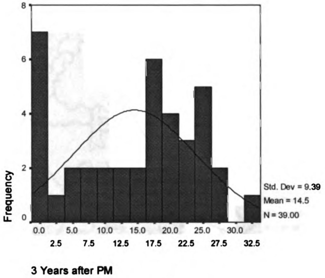

Figure C.18 - Histogram of DI 3 Years after PM when the pre-existing condition is greater than the guideline value

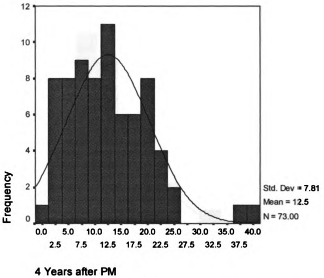

Figure C.19 - Histogram of DI 4 Years after PM when the pre-existing condition is less than the guideline value

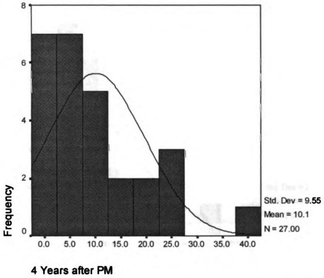

Figure C.20 - Histogram of DI 4 Years after PM when the pre-existing condition is greater than the guideline value

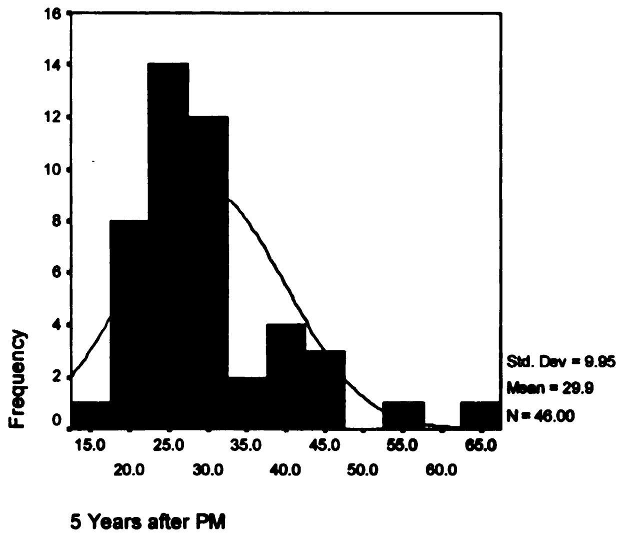

Figure C.21 - Histogram of DI 5 Years after PM when the pre-existing condition is less than the guideline value

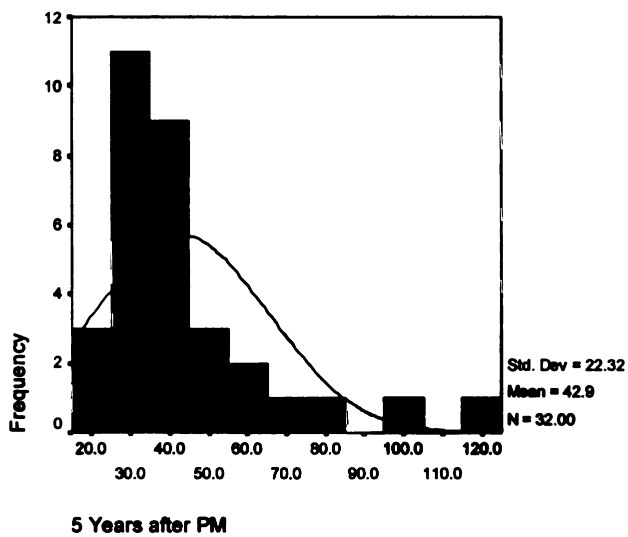

Figure C.22 - Histogram of DI 5 Years after PM when the pre-existing condition is greater than the guideline value

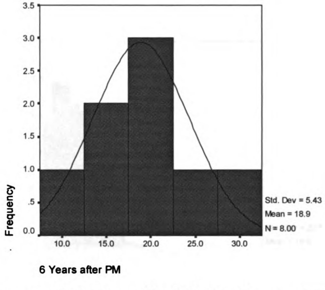

Figure C.23 - Histogram of DI 6 Years after PM when the pre-existing condition is less than the guideline value

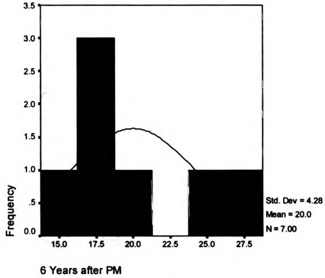

Figure C.24 - Histogram of DI 6 Years after PM when the pre-existing condition is greater than the guideline value

Single Chip Seal

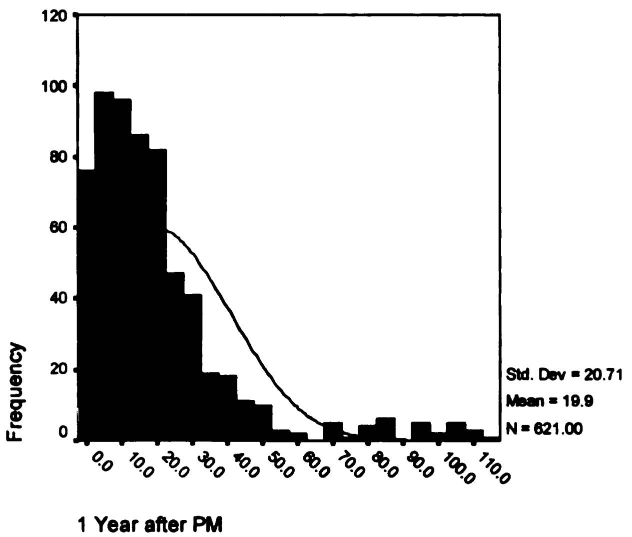

Figure C.25 - Histogram of DI 1 Year after PM when the pre-existing condition is less than the guideline value

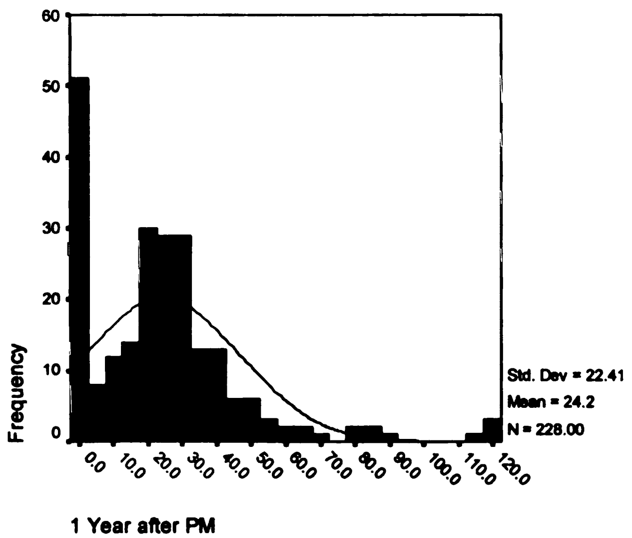

Figure C.26 - Histogram of DI 1 Year after PM when the pre-existing condition is greater than the guideline value

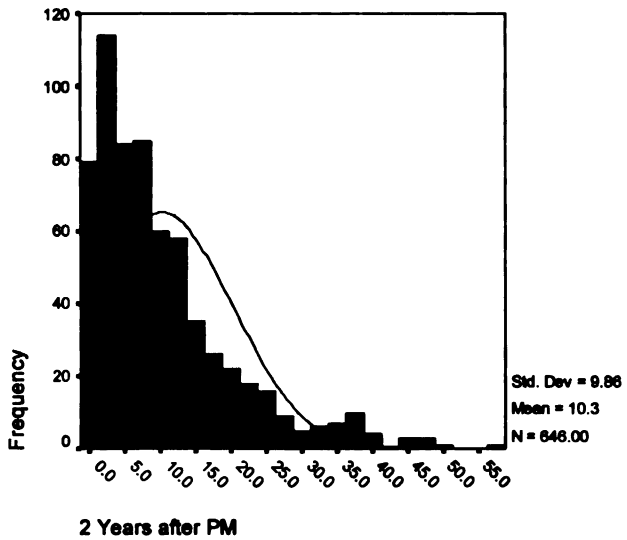

Figure C.27 - Histogram of DI 2 Years after PM when the pre-existing condition is less than the guideline value

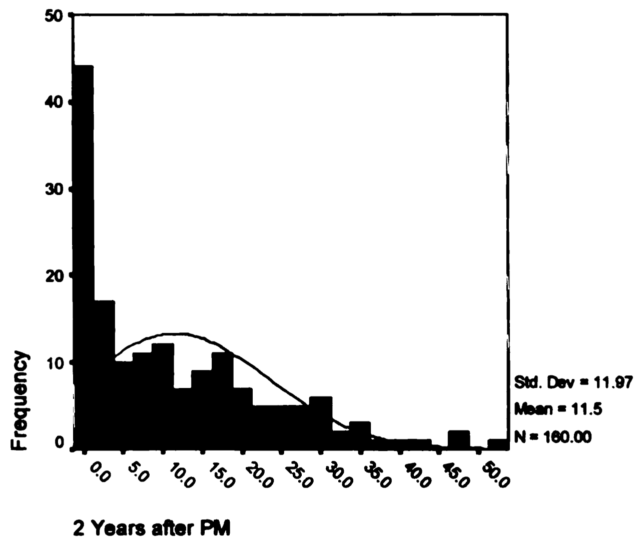

Figure C.28 - Histogram of DI 2 Years after PM when the pre-existing condition is greater than the guideline value

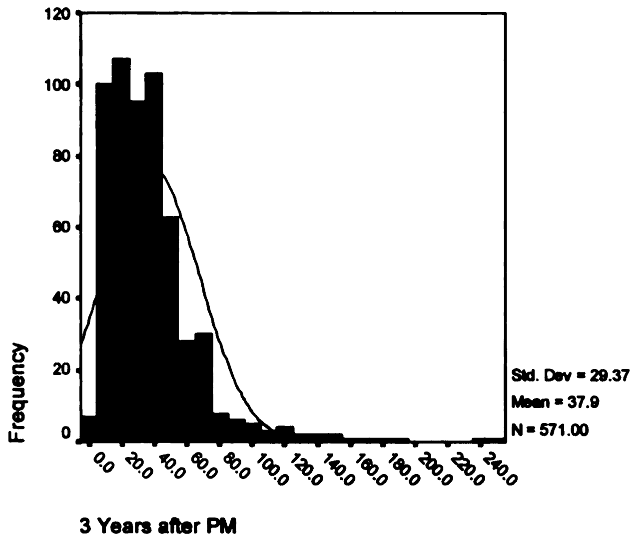

Figure C.29 - Histogram of DI 3 Years after PM when the pre-existing condition is less than the guideline value

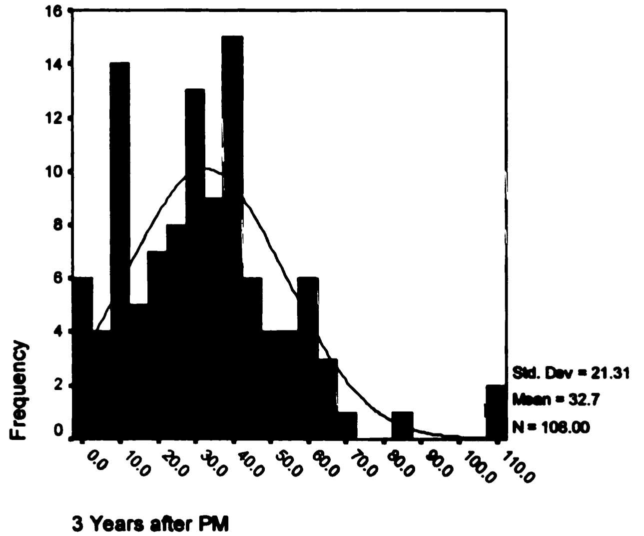

Figure C.30 - Histogram of DI 3 Years after PM when the pre-existing condition is greater than the guideline value

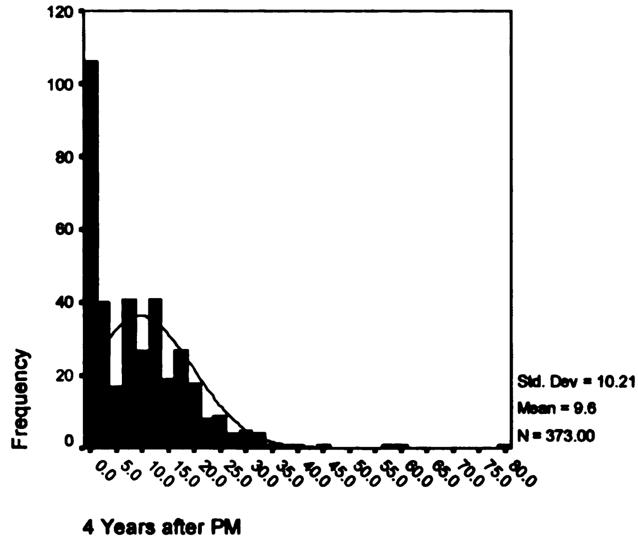

Figure C.31 - Histogram of DI 4 Years after PM when the pre-existing condition is less than the guideline value

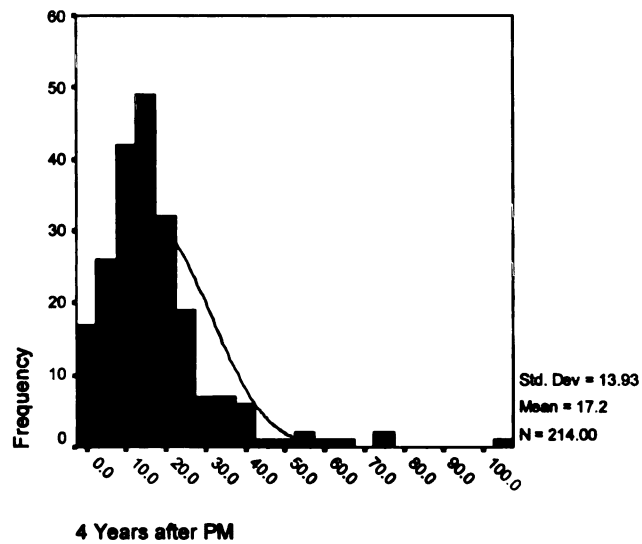

Figure C.32 - Histogram of DI 4 Years after PM when the pre-existing condition is greater than the guideline value

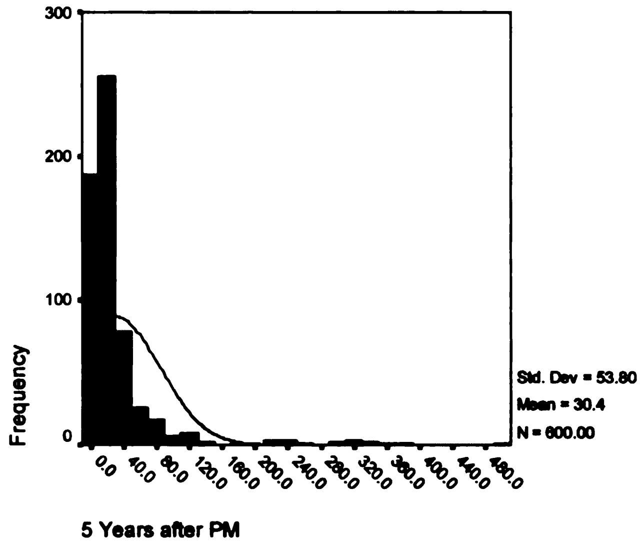

Figure C.33 - Histogram of DI 5 Years after PM when the pre-existing condition is less than the guideline value

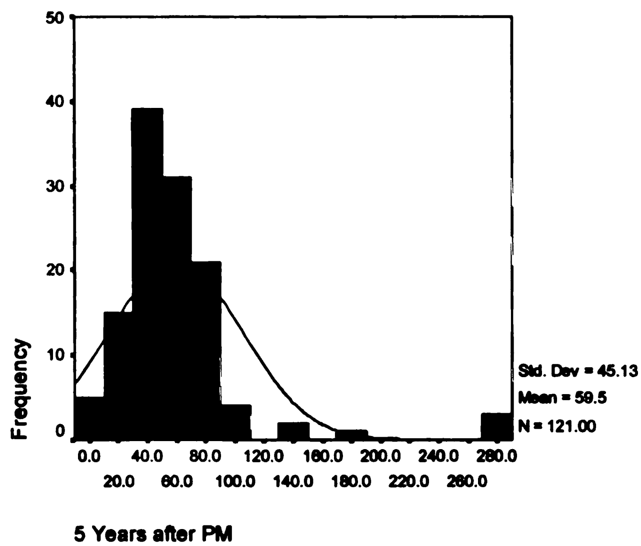

Figure C.34 - Histogram of DI 5 Years after PM when the pre-existing condition is greater than the guideline value

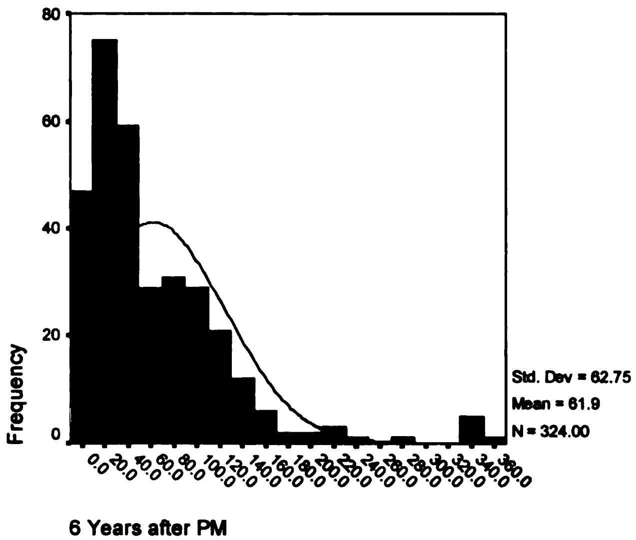

Figure C.35 - Histogram of DI 6 Years after PM when the pre-existing condition is less than the guideline value

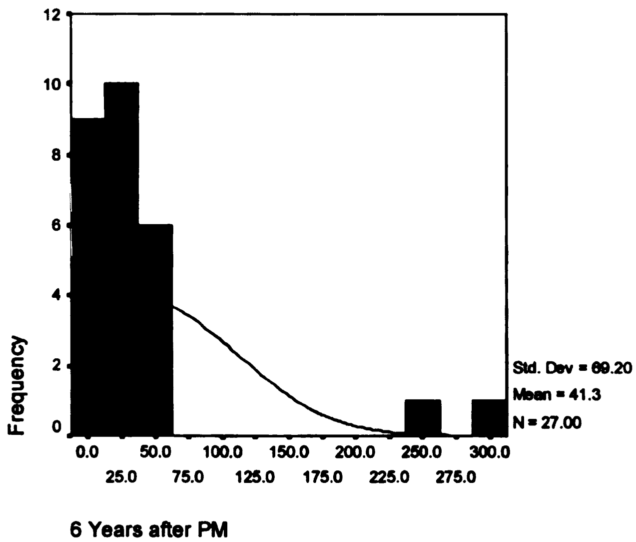

Figure C.36 - Histogram of DI 6 Years after PM when the pre-existing condition is greater than the guideline value

Multiple Course Micro-Surfacing

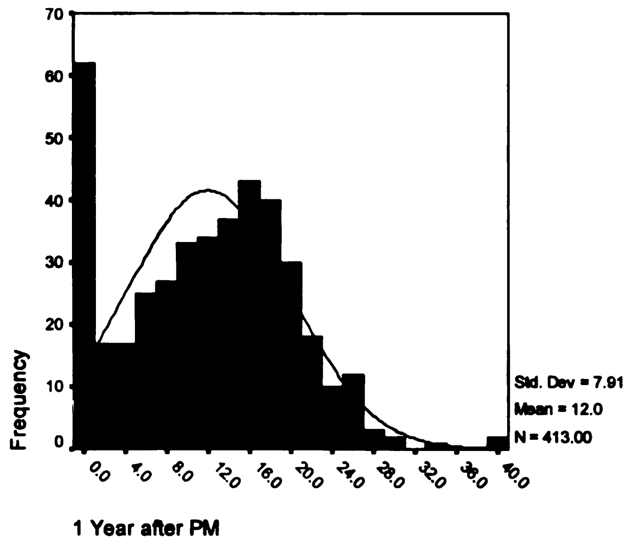

Figure C.37 - Histogram of DI 1 Year after PM when the pre-existing condition is less than the guideline value

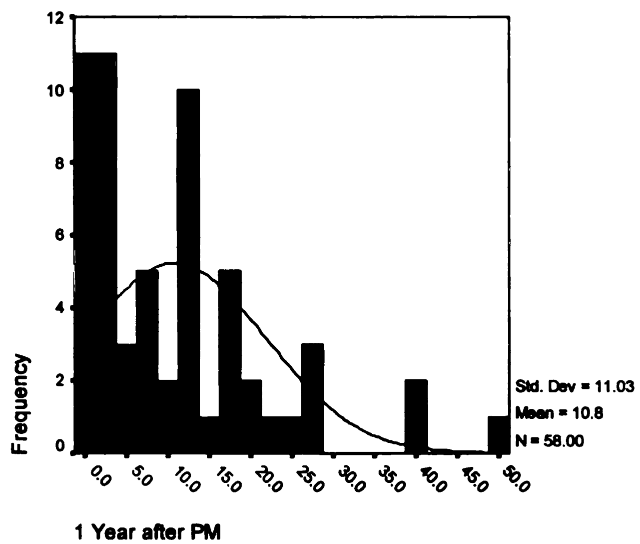

Figure C.38 - Histogram of DI 1 Year after PM when the pre-existing condition is greater than the guideline value

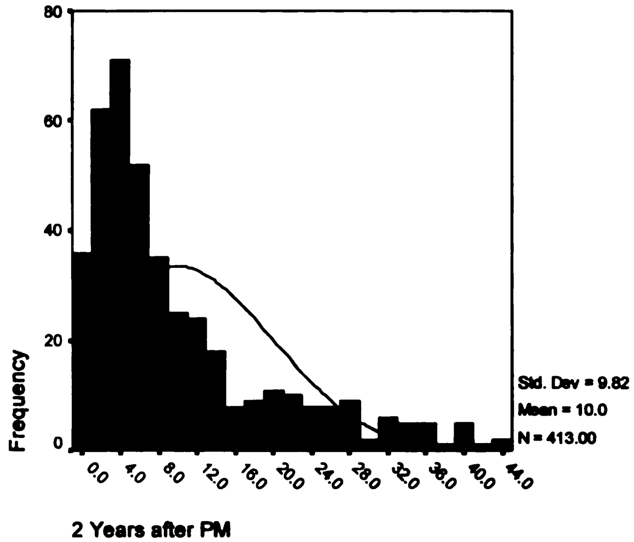

Figure C.39 - Histogram of DI 2 Years after PM when the pre-existing condition is less than the guideline value

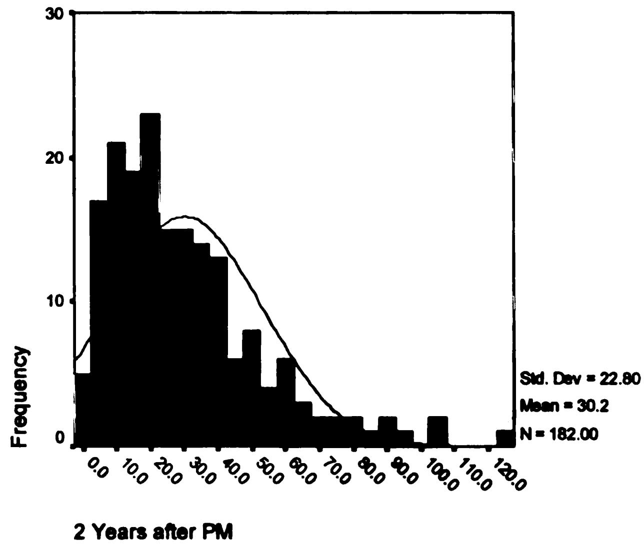

Figure C.40 - Histogram of DI 2 Years after PM when the pre-existing condition is greater than the guideline value

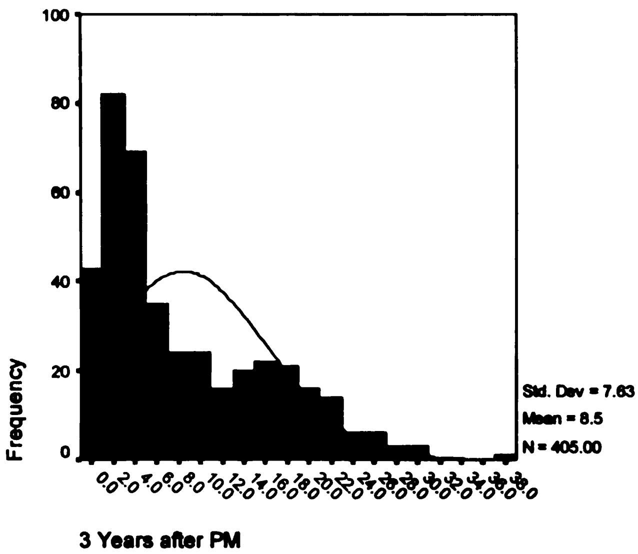

Figure C.41 - Histogram of DI 3 Years after PM when the pre-existing condition is less than the guideline value

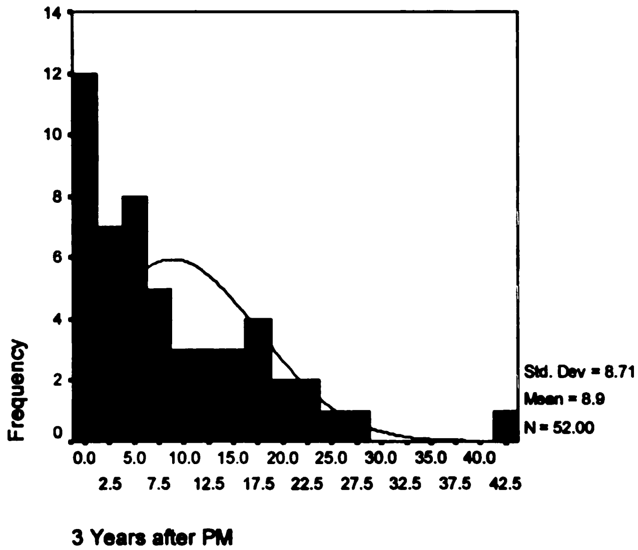

Figure C.42 - Histogram of DI 3 Years after PM when the pre-existing condition is greater than the guideline value

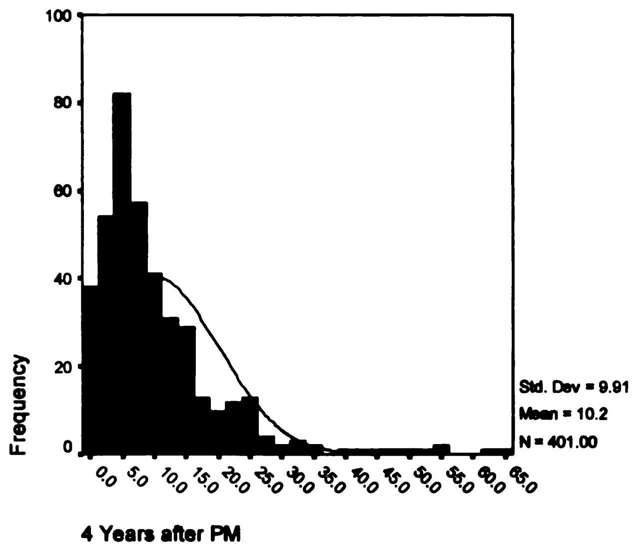

Figure C.43 - Histogram of DI 4 Years after PM when the pre-existing condition is less than the guideline value

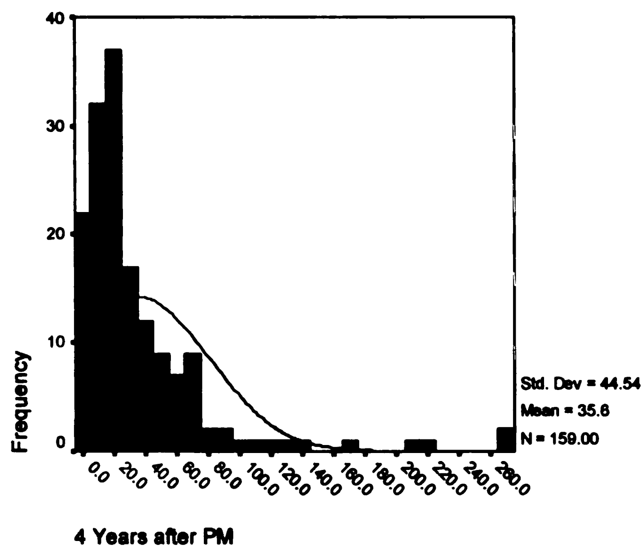

Figure C.44 - Histogram of DI 4 Years after PM when the pre-existing condition is greater than the guideline value

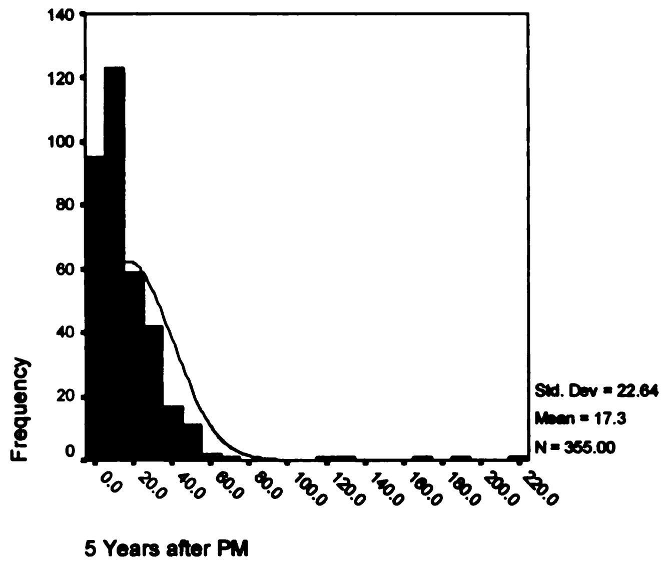

Figure C.45 - Histogram of DI 5 Years after PM when the pre-existing condition is less than the guideline value

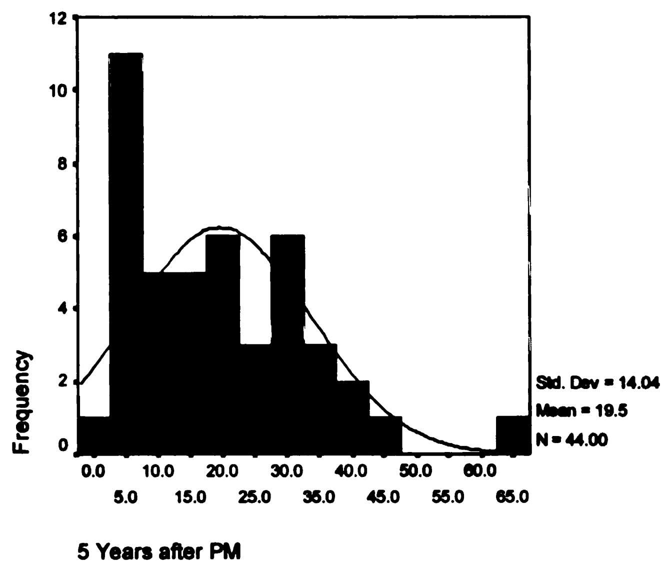

Figure C.46 - Histogram of DI 5 Years after PM when the pre-existing condition is greater than the guideline value

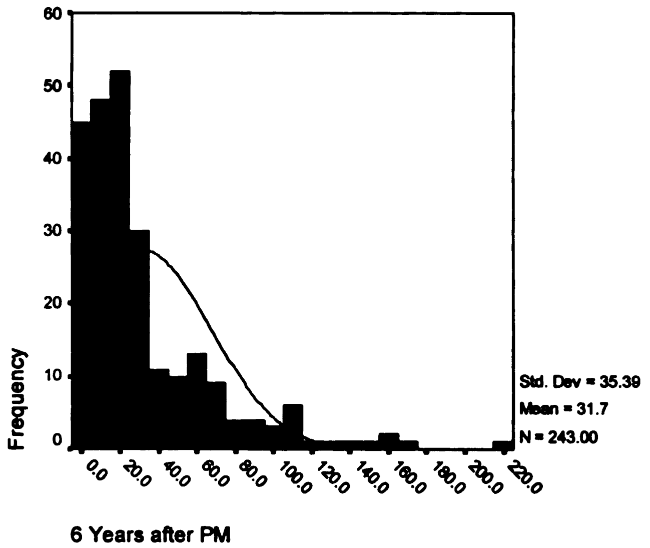

Figure C.47 - Histogram of DI 6 Years after PM when the pre-existing condition is less than the guideline value

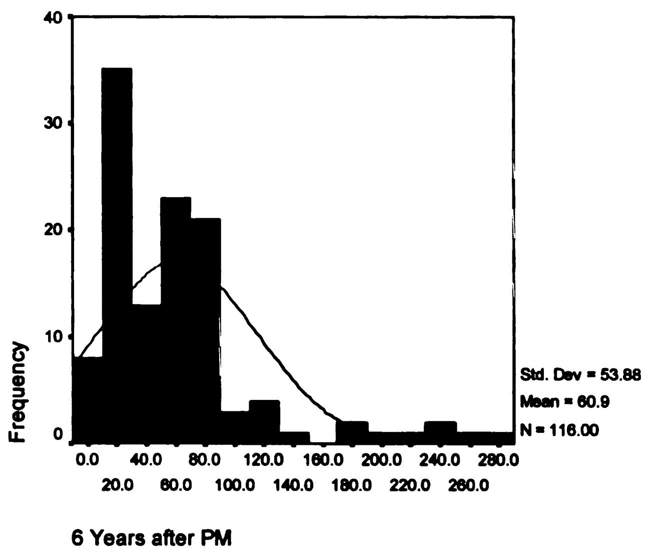

Figure C.48 - Histogram of DI 6 Years after PM when the pre-existing condition is greater than the guideline value

Bituminous Crack Seal

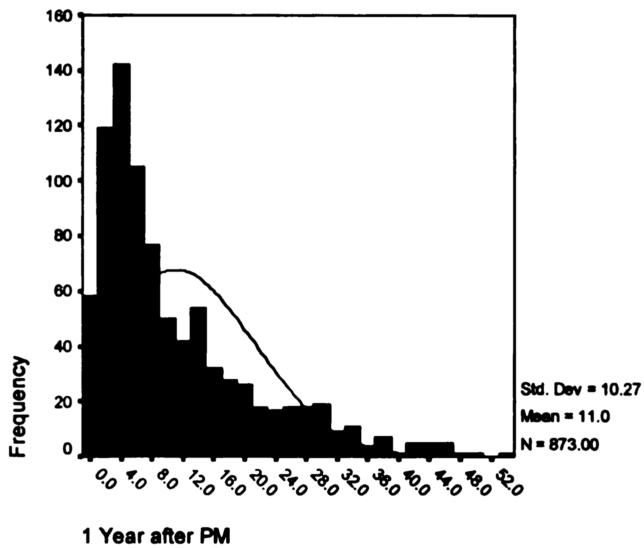

Figure C.49 - Histogram of DI 1 Year after PM when the pre-existing condition is less than the guideline value

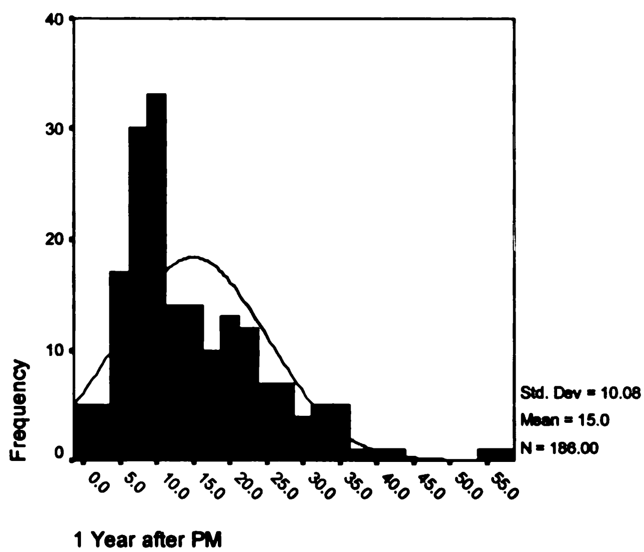

Figure C.50 - Histogram of DI 1 Year after PM when the pre-existing condition is greater than the guideline value

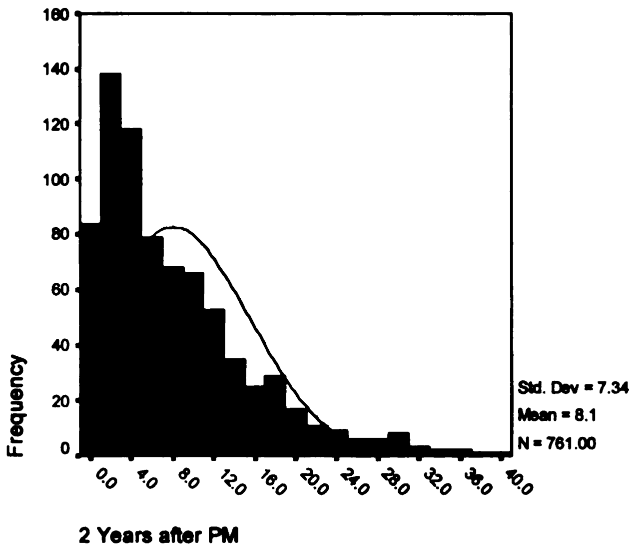

Figure C.51 - Histogram of DI 2 Years after PM when the pre-existing condition is less than the guideline value

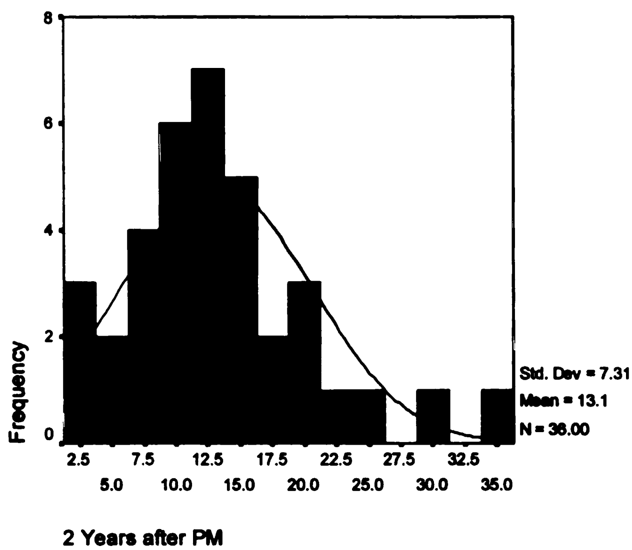

Figure C.52 - Histogram of DI 2 Years after PM when the pre-existing condition is greater than the guideline value

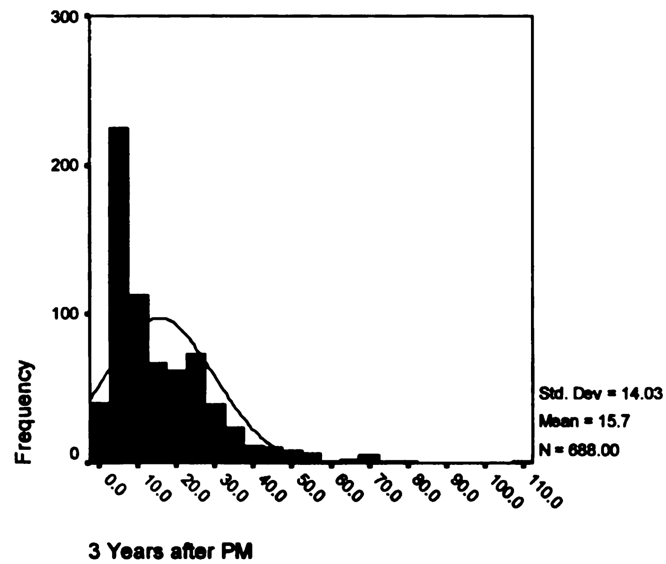

Figure C.53 - Histogram of DI 3 Years after PM when the pre-existing condition is less than the guideline value

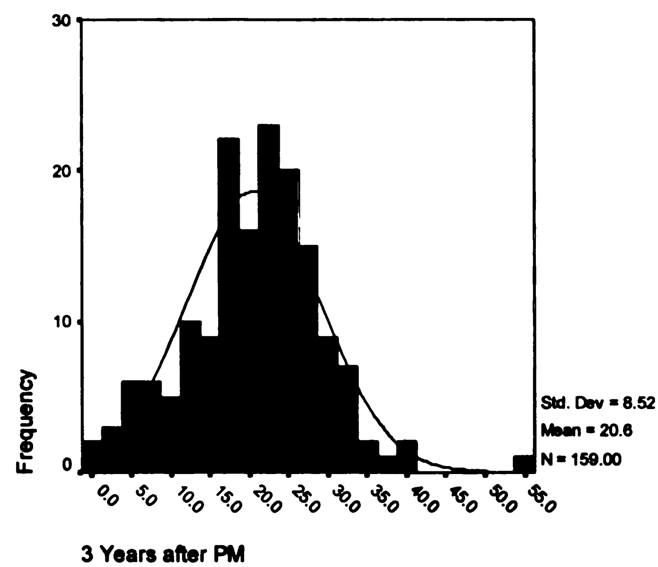

Figure C.54 - Histogram of DI 3 Years after PM when the pre-existing condition is greater than the guideline value

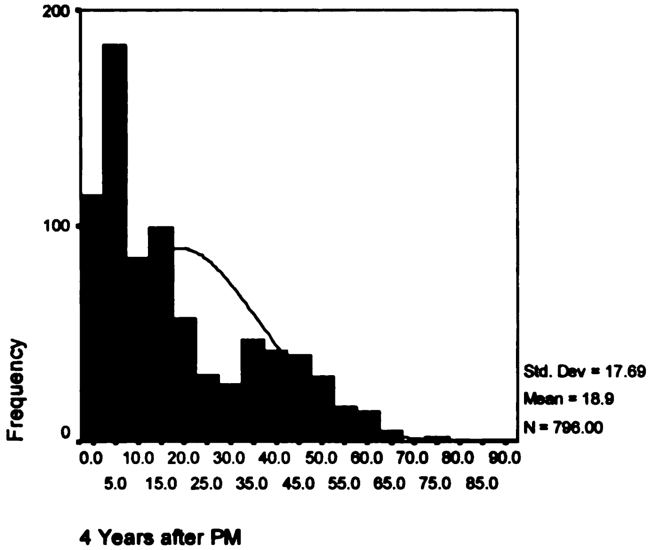

Figure C.55 - Histogram of DI 4 Years after PM when the pre-existing condition is less than the guideline value

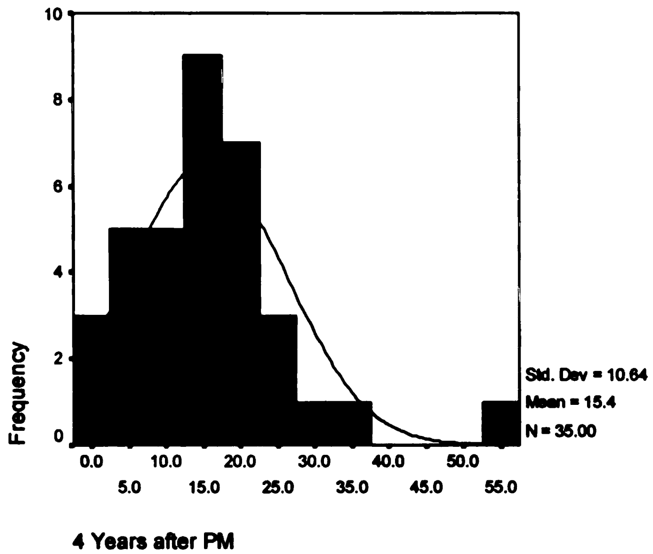

Figure C.56 - Histogram of DI 4 Years after PM when the pre-existing condition is greater than the guideline value

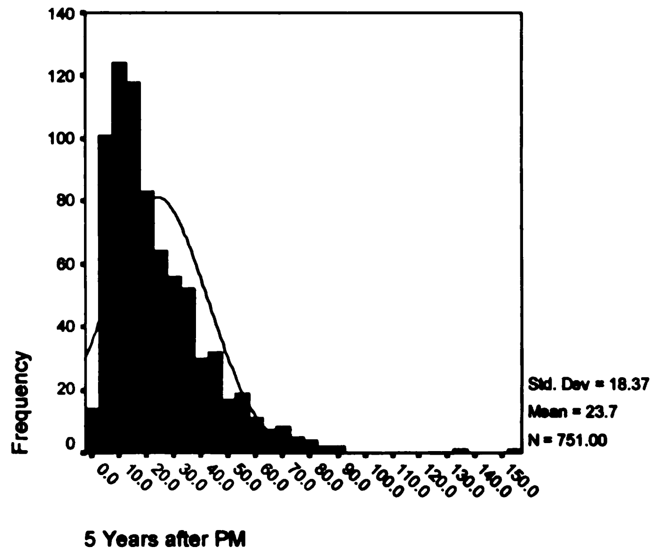

Figure C.57 - Histogram of DI 5 Years after PM when the pre-existing condition is less than the guideline value

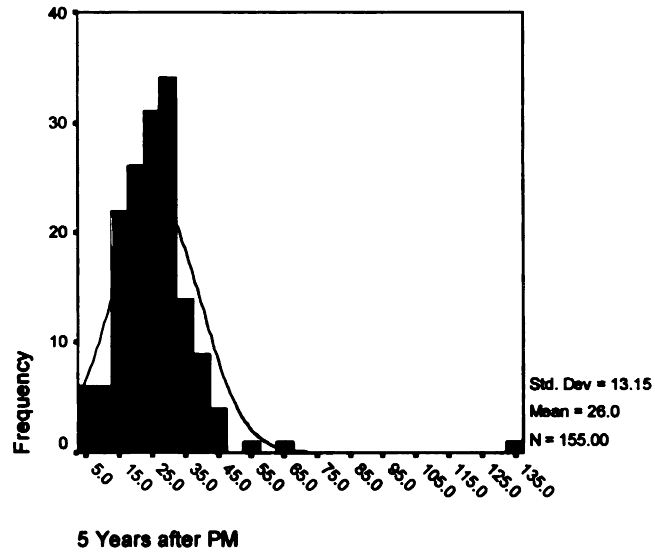

Figure C.58 - Histogram of DI 5 Years after PM when the pre-existing condition is greater than the guideline value

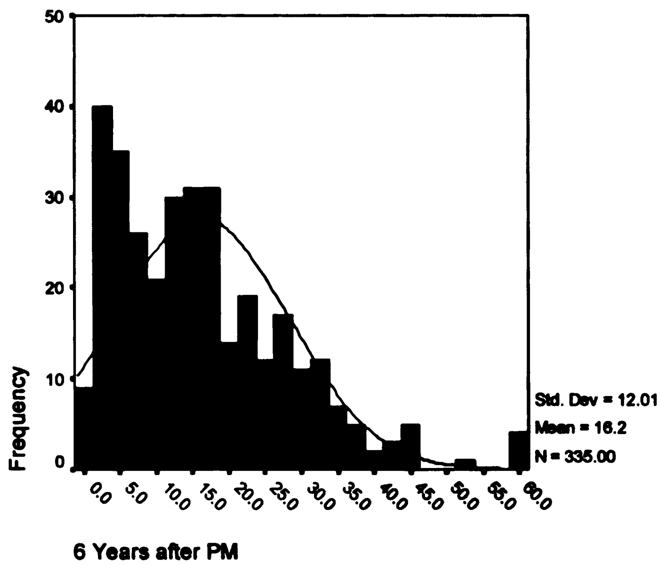

Figure C.59 - Histogram of DI 6 Years after PM when the pre-existing condition is less than the guideline value

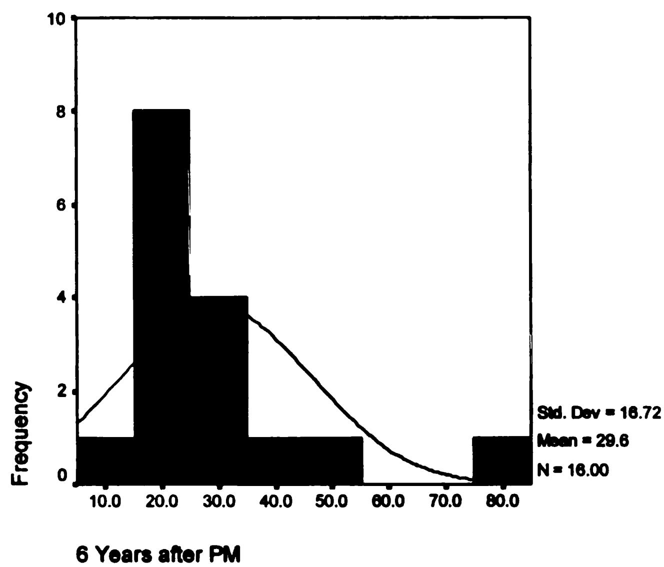

Figure C.60 - Histogram of DI 6 Years after PM when the pre-existing condition is greater than the guideline value

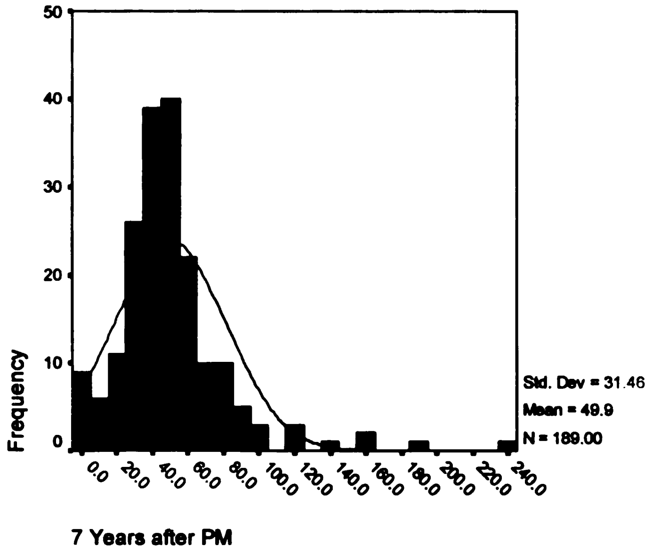

Figure C.61 - Histogram of DI 7 Years after PM when the pre-existing condition is less than the guideline value

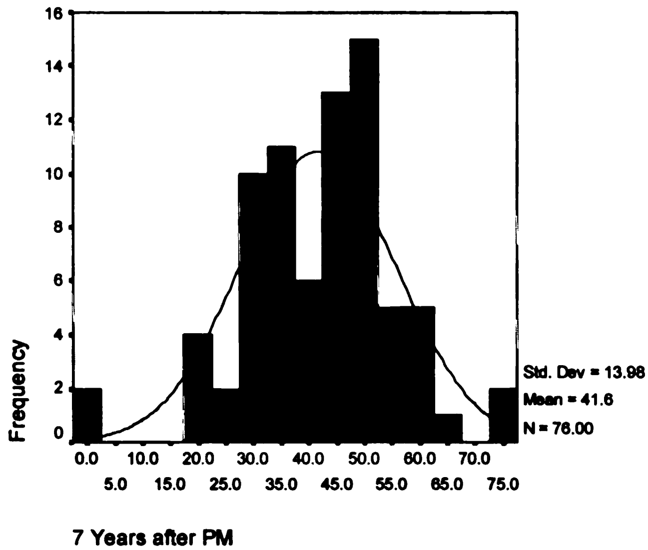

Figure C.62 - Histogram of DI 7 Years after PM when the pre-existing condition is greater than the guideline value

APPENDIX D

TWO SAMPLE T-TEST RESULTS FROM MINI-TAB USED TO EVALUATE THE DISTRESS INDEX (DI) PREVENTIVE MAINTENANCE (PM) GUIDELINE VALUES FOR THE FOLLOWING PM TREATMENTS

Non-Structural Bituminous Overlay
Surface Milling with a Non-Structural Bituminous Overlay
Single Chip Seal
Multiple Course Micro-Surfacing
Bituminous Crack Seal

Non-Structural Bituminous Overlay

Two Sample T-Test and Confidence Interval

Two sample T for 1 Year_B vs 1 Year_A

	N	Mean	StDev	SE Mean
1 Year_B	540	2.89	4.87	0.21
1 Year_A	119	5.91	4.63	0.42

95% CI for mu 1 Year_B - mu 1 Year_A: (-3.95, -2.08)
T-Test mu 1 Year_B = mu 1 Year_A (vs not =): T= -6.38 P=0.0000 DF= 180

Two Sample T-Test and Confidence Interval

Two sample T for 2 Year_B vs 2 Year_A

	N	Mean	StDev	SE Mean
2 Year_B	545	10.8	10.5	0.45
2 Year_A	424	9.2	11.2	0.54

95% CI for mu 2 Year_B - mu 2 Year_A: (0.23, 3.00)
T-Test mu 2 Year_B = mu 2 Year_A (vs not =): T= 2.29 P=0.022 DF= 882

Two Sample T-Test and Confidence Interval

Two sample T for 3 Year_B vs 3 Year_A

	N	Mean	StDev	SE Mean
3 Year_B	494	4.79	3.72	0.17
3 Year_A	68	6.38	5.86	0.71

95% CI for mu 3 Year_B - mu 3 Year_A: (-3.04, -0.13)
T-Test mu 3 Year_B = mu 3 Year_A (vs not =): T= -2.18 P=0.033 DF= 74

Two Sample T-Test and Confidence Interval

Two sample T for 4 Year_B vs 4 Year_A

	N	Mean	StDev	SE Mean
4 Year_B	526	19.0	21.2	0.92
4 Year_A	276	21.7	19.3	1.2

95% CI for mu 4 Year_B - mu 4 Year_A: (-5.64, 0.2)
T-Test mu 4 Year_B = mu 4 Year_A (vs not =): T= -1.83 P=0.067 DF= 604

Two Sample T-Test and Confidence Interval

Two sample T for 5 Year_B vs 5 Year_A

	N	Mean	StDev	SE Mean

	N	Mean	StDev	SE Mean
5 Year_B	242	8.66	6.98	0.45
5 Year_A	70	20.6	16.4	2.0

95% CI for mu 5 Year_B - mu 5 Year_A: (-15.93, -7.9)
T-Test mu 5 Year_B = mu 5 Year_A (vs not =): T= -5.95 P=0.0000 DF= 76

Two Sample T-Test and Confidence Interval

Two sample T for 6 Year_B vs 6 Year_A

	N	Mean	StDev	SE Mean
6 Year_B	111	37.9	23.2	2.2
6 Year_A	11	131	111	33

95% CI for mu 6 Year_B - mu 6 Year_A: (-168.0, -19)
T-Test mu 6 Year_B = mu 6 Year_A (vs not =): T= -2.80 P=0.019 DF= 10

Two Sample T-Test and Confidence Interval

Two sample T for 8 Year_B vs 8 Year_A

	N	Mean	StDev	SE Mean
8 Year_B	95	86.4	97.7	10
8 Year_A	8	201	290	103

95% CI for mu 8 Year_B - mu 8 Year_A: (-359, 129)
T-Test mu 8 Year_B = mu 8 Year_A (vs not =): T= -1.11 P=0.30 DF= 7

Surface Milling with a Non-Structural Bituminous Overlay

Two Sample T-Test and Confidence Interval

Two sample T for 1 Year_B vs 1 Year_A

	N	Mean	StDev	SE Mean
1 Year_B	47	6.13	5.95	0.87
1 Year_A	59	5.59	4.48	0.58

95% CI for mu 1 Year_B - mu 1 Year_A: (-1.54, 2.62)
T-Test mu 1 Year_B = mu 1 Year_A (vs not =): T= 0.52 P=0.60 DF= 83

Two Sample T-Test and Confidence Interval

Two sample T for 2 Year_B vs 2 Year_A

	N	Mean	StDev	SE Mean
2 Year_B	490	8.10	7.77	0.35
2 Year_A	71	5.50	6.26	0.74

95% CI for mu 2 Year_B - mu 2 Year_A: (0.97, 4.23)
T-Test mu 2 Year_B = mu 2 Year_A (vs not =): T= 3.16 P=0.0020 DF= 103

Two Sample T-Test and Confidence Interval

Two sample T for 3 Year_B vs 3 Year_A

	N	Mean	StDev	SE Mean
3 Year_B	56	6.27	5.80	0.78
3 Year_A	26	5.81	4.00	0.78

95% CI for mu 3 Year_B - mu 3 Year_A: (-1.75, 2.66)
T-Test mu 3 Year_B = mu 3 Year_A (vs not =): T= 0.41 P=0.68 DF= 68

Two Sample T-Test and Confidence Interval

Two sample T for 4 Year_B vs 4 Year_A

	N	Mean	StDev	SE Mean
4 Year_B	355	15.82	9.73	0.52
4 Year_A	22	16.5	10.9	2.3

95% CI for mu 4 Year_B - mu 4 Year_A: (-5.59, 4.2)
T-Test mu 4 Year_B = mu 4 Year_A (vs not =): T= -0.28 P=0.78 DF= 23

Two Sample T-Test and Confidence Interval

Two sample T for 5 Year_B vs 5 Year_A

	N	Mean	StDev	SE Mean

	N	Mean	StDev	SE Mean
5 Year_B	5	48.3	36.8	16
5 Year_A	11	30.4	36.1	11

95% CI for mu 5 Year_B - mu 5 Year_A: (-29, 65)
T-Test mu 5 Year_B = mu 5 Year_A (vs not =): T= 0.91 P=0.39 DF= 7

Two Sample T-Test and Confidence Interval

Two sample T for 7 Year_B vs 7 Year_A

	N	Mean	StDev	SE Mean
7 Year_B	2	21.8	11.4	8.1
7 Year_A	7	8.62	4.19	1.6

95% CI for mu 7 Year_B - mu 7 Year_A: (-91.2, 117.6)
T-Test mu 7 Year_B = mu 7 Year_A (vs not =): T= 1.61 P=0.35 DF= 1

Single Chip Seal

Two Sample T-Test and Confidence Interval

Two sample T for 1 Year_B vs 1 Year_A

	N	Mean	StDev	SE Mean
1 Year_B	599	19.1	21.9	0.89
1 Year_A	352	28.4	32.8	1.7

95% CI for mu 1 Year_B - mu 1 Year_A: (-13.18, -5.5)
T-Test mu 1 Year_B = mu 1 Year_A (vs not =): T= -4.74 P=0.0000 DF= 536

Two Sample T-Test and Confidence Interval

Two sample T for 2 Year_B vs 2 Year_A

	N	Mean	StDev	SE Mean
2 Year_B	432	8.72	9.16	0.44
2 Year_A	618	16.7	23.3	0.94

95% CI for mu 2 Year_B - mu 2 Year_A: (-10.03, -5.97)
T-Test mu 2 Year_B = mu 2 Year_A (vs not =): T= -7.74 P=0.0000 DF= 860

Two Sample T-Test and Confidence Interval

Two sample T for 3 Year_B vs 3 Year_A

	N	Mean	StDev	SE Mean
3 Year_B	512	14.8	15.7	0.69
3 Year_A	368	39.2	33.9	1.8

95% CI for mu 3 Year_B - mu 3 Year_A: (-28.18, -20.7)
T-Test mu 3 Year_B = mu 3 Year_A (vs not =): T= -12.88 P=0.0000 DF= 480

Two Sample T-Test and Confidence Interval

Two sample T for 4 Year_B vs 4 Year_A

	N	Mean	StDev	SE Mean
4 Year_B	94	7.06	6.49	0.67
4 Year_A	151	15.25	9.78	0.80

95% CI for mu 4 Year_B - mu 4 Year_A: (-10.24, -6.14)
T-Test mu 4 Year_B = mu 4 Year_A (vs not =): T= -7.88 P=0.0000 DF= 241

Two Sample T-Test and Confidence Interval

Two sample T for 5 Year_B vs 5 Year_A

	N	Mean	StDev	SE Mean

	N	Mean	StDev	SE Mean
5 Year_B	558	19.8	42.3	1.8
5 Year_A	196	56.4	62.4	4.5

95% CI for mu 5 Year_B - mu 5 Year_A: (-46.1, -27.1)
T-Test mu 5 Year_B = mu 5 Year_A (vs not =): T= -7.62 P=0.0000 DF= 260

Two Sample T-Test and Confidence Interval

Two sample T for 6 Year_B vs 6 Year_A

	N	Mean	StDev	SE Mean
6 Year_B	303	24.9	24.9	1.4
6 Year_A	45	78.7	86.5	13

95% CI for mu 6 Year_B - mu 6 Year_A: (-80.0, -28)
T-Test mu 6 Year_B = mu 6 Year_A (vs not =): T= -4.15 P=0.0001 DF= 45

Two Sample T-Test and Confidence Interval

Two sample T for 7 Year_B vs 7 Year_A

	N	Mean	StDev	SE Mean
7 Year_B	69	5.09	8.86	1.1
7 Year_A	22	4.66	4.81	1.0

95% CI for mu 7 Year_B - mu 7 Year_A: (-2.5, 3.4)
T-Test mu 7 Year_B = mu 7 Year_A (vs not =): T= 0.30 P=0.77 DF= 66

Multiple Course Micro-Surfacing

Two Sample T-Test and Confidence Interval

Two sample T for 1 Year_B vs 1 Year_A

	N	Mean	StDev	SE Mean
1 Year_B	464	12.32	8.01	0.37
1 Year_A	26	37.4	13.6	2.7

95% CI for mu 1 Year_B - mu 1 Year_A: (-30.60, -19.5)
T-Test mu 1 Year_B = mu 1 Year_A (vs not =): T= -9.30 P=0.0000 DF= 25

Two Sample T-Test and Confidence Interval

Two sample T for 2 Year_B vs 2 Year_A

	N	Mean	StDev	SE Mean
2 Year_B	621	10.30	8.93	0.36
2 Year_A	34	27.4	17.1	2.9

95% CI for mu 2 Year_B - mu 2 Year_A: (-23.06, -11.0)
T-Test mu 2 Year_B = mu 2 Year_A (vs not =): T= -5.77 P=0.0000 DF= 33

Two Sample T-Test and Confidence Interval

Two sample T for 3 Year_B vs 3 Year_A

	N	Mean	StDev	SE Mean
3 Year_B	690	15.0	16.0	0.61
3 Year_A	45	73.4	36.5	5.4

95% CI for mu 3 Year_B - mu 3 Year_A: (-69.34, -47.3)
T-Test mu 3 Year_B = mu 3 Year_A (vs not =): T= -10.64 P=0.0000 DF= 45

Two Sample T-Test and Confidence Interval

Two sample T for 4 Year_B vs 4 Year_A

	N	Mean	StDev	SE Mean
4 Year_B	684	14.5	15.1	0.58
4 Year_A	141	58.0	21.0	1.8

95% CI for mu 4 Year_B - mu 4 Year_A: (-47.21, -39.9)
T-Test mu 4 Year_B = mu 4 Year_A (vs not =): T= -23.37 P=0.0000 DF= 171

Two Sample T-Test and Confidence Interval

Two sample T for 5 Year_B vs 5 Year_A

	N	Mean	StDev	SE Mean

	N	Mean	StDev	SE Mean
5 Year_B	584	16.5	21.4	0.89
5 Year_A	18	57.0	33.2	7.8

95% CI for mu 5 Year_B - mu 5 Year_A: (-57.13, -23.9)
T-Test mu 5 Year_B = mu 5 Year_A (vs not =): T= -5.13 P=0.0001 DF= 17

Two Sample T-Test and Confidence Interval

Two sample T for 6 Year_B vs 6 Year_A

	N	Mean	StDev	SE Mean
6 Year_B	457	31.4	30.1	1.4
6 Year_A	37	107	112	18

95% CI for mu 6 Year_B - mu 6 Year_A: (-113.4, -38)
T-Test mu 6 Year_B = mu 6 Year_A (vs not =): T= -4.10 P=0.0002 DF= 36

Bituminous Crack Seal

Two Sample T-Test and Confidence Interval

Two sample T for 1 Year_B vs 1 Year_A

	N	Mean	StDev	SE Mean
1 Year_B	990	11.24	9.37	0.30
1 Year_A	159	21.8	14.8	1.2

95% CI for mu 1 Year_B - mu 1 Year_A: (-13.00, -8.2)
T-Test mu 1 Year_B = mu 1 Year_A (vs not =): T= -8.73 P=0.0000 DF= 178

Two Sample T-Test and Confidence Interval

Two sample T for 2 Year_B vs 2 Year_A

	N	Mean	StDev	SE Mean
2 Year_B	2010	13.3	11.8	0.26
2 Year_A	346	27.9	21.2	1.1

95% CI for mu 2 Year_B - mu 2 Year_A: (-16.85, -12.2)
T-Test mu 2 Year_B = mu 2 Year_A (vs not =): T= -12.42 P=0.0000 DF= 382

Two Sample T-Test and Confidence Interval

Two sample T for 3 Year_B vs 3 Year_A

	N	Mean	StDev	SE Mean
3 Year_B	610	18.1	13.3	0.54
3 Year_A	78	31.4	19.2	2.2

95% CI for mu 3 Year_B - mu 3 Year_A: (-17.76, -8.9)
T-Test mu 3 Year_B = mu 3 Year_A (vs not =): T= -5.95 P=0.0000 DF= 86

Two Sample T-Test and Confidence Interval

Two sample T for 4 Year_B vs 4 Year_A

	N	Mean	StDev	SE Mean
4 Year_B	1531	16.4	16.3	0.42
4 Year_A	308	39.3	40.7	2.3

95% CI for mu 4 Year_B - mu 4 Year_A: (-27.52, -18.3)
T-Test mu 4 Year_B = mu 4 Year_A (vs not =): T= -9.73 P=0.0000 DF= 327

Two Sample T-Test and Confidence Interval

Two sample T for 5 Year_B vs 5 Year_A

	N	Mean	StDev	SE Mean

	N	Mean	StDev	SE Mean
5 Year_B	604	26.5	17.1	0.70
5 Year_A	80	37.9	22.7	2.5

95% CI for mu 5 Year_B - mu 5 Year_A: (-16.62, -6.2)
T-Test mu 5 Year_B = mu 5 Year_A (vs not =): T= -4.33 P=0.0000 DF= 91

Two Sample T-Test and Confidence Interval

Two sample T for 6 Year_B vs 6 Year_A

	N	Mean	StDev	SE Mean
6 Year_B	874	34.6	39.6	1.3
6 Year_A	29	86.6	96.2	18

95% CI for mu 6 Year_B - mu 6 Year_A: (-88.7, -15)
T-Test mu 6 Year_B = mu 6 Year_A (vs not =): T= -2.90 P=0.0072 DF= 28

Two Sample T-Test and Confidence Interval

Two sample T for 7 Year_B vs 7 Year_A

	N	Mean	StDev	SE Mean
7 Year_B	319	58.3	41.3	2.3
7 Year_A	39	60.3	27.2	4.3

95% CI for mu 7 Year_B - mu 7 Year_A: (-11.9, 7.8)

APPENDIX E

TWO SAMPLE T-TEST RESULTS FROM MINI-TAB USED TO EVALUATE THE RIDE QUALITY INDEX (RQI) PREVENTIVE MAINTENANCE (PM) GUIDELINE VALUES FOR THE FOLLOWING PM TREATMENTS BASED ON THE DISTRESS INDEX

Non-Structural Bituminous Overlay
Surface Milling with a Non-Structural Bituminous Overlay
Single Chip Seal
Multiple Course Micro-Surfacing
Bituminous Crack Seal

Non-Structural Bituminous Overlay

Two Sample T-Test and Confidence Interval

Two sample T for 1 Year_B vs 1 Year_A

	N	Mean	StDev	SE Mean
1 Year_B	232	4.92	5.03	0.33
1 Year_A	13	5.08	7.52	2.1

95% CI for mu 1 Year_B - mu 1 Year_A: (-4.76, 4.4)
T-Test mu 1 Year_B = mu 1 Year_A (vs not =): T= -0.08 P=0.94 DF= 12

Two Sample T-Test and Confidence Interval

Two sample T for 2 Year_B vs 2 Year_A

	N	Mean	StDev	SE Mean
2 Year_B	470	6.80	6.04	0.28
2 Year_A	46	8.16	5.34	0.79

95% CI for mu 2 Year_B - mu 2 Year_A: (-3.03, 0.32)
T-Test mu 2 Year_B = mu 2 Year_A (vs not =): T= -1.62 P=0.11 DF= 56

Two Sample T-Test and Confidence Interval

Two sample T for 3 Year_B vs 3 Year_A

	N	Mean	StDev	SE Mean
3 Year_B	233	8.79	8.67	0.57
3 Year_A	11	8.17	9.99	3.0

95% CI for mu 3 Year_B - mu 3 Year_A: (-6.20, 7.5)
T-Test mu 3 Year_B = mu 3 Year_A (vs not =): T= 0.20 P=0.84 DF= 10

Two Sample T-Test and Confidence Interval

Two sample T for 4 Year_B vs 4 Year_A

	N	Mean	StDev	SE Mean
4 Year_B	244	6.33	7.11	0.46
4 Year_A	41	25.2	19.4	3.0

95% CI for mu 4 Year_B - mu 4 Year_A: (-25.07, -12.7)
T-Test mu 4 Year_B = mu 4 Year_A (vs not =): T= -6.15 P=0.0000 DF= 41

Two Sample T-Test and Confidence Interval

Two sample T for 5 Year_B vs 5 Year_A

	N	Mean	StDev	SE Mean

5 Year_B	186	8.14	6.71	0.49
5 Year_A	11	13.0	10.7	3.2

95% CI for mu 5 Year_B - mu 5 Year_A: (-12.14, 2.4)
T-Test mu 5 Year_B = mu 5 Year_A (vs not =): T= -1.49 P=0.17 DF= 10

Two Sample T-Test and Confidence Interval

Two sample T for 6 Year_B vs 6 Year_A

	N	Mean	StDev	SE Mean
6 Year_B	213	14.92	7.81	0.53
6 Year_A	7	13.95	9.13	3.4

95% CI for mu 6 Year_B - mu 6 Year_A: (-7.57, 9.5)
T-Test mu 6 Year_B = mu 6 Year_A (vs not =): T= 0.28 P=0.79 DF= 6

Surfacing Milling with a Non-Structural Bituminous Overlay

Two Sample T-Test and Confidence Interval

Two sample T for 1 Year_B vs 1 Year_A

	N	Mean	StDev	SE Mean
1 Year_B	46	12.21	3.50	0.52
1 Year_A	26	12.47	3.25	0.64

95% CI for mu 1 Year_B - mu 1 Year_A: (-1.90, 1.38)
T-Test mu 1 Year_B = mu 1 Year_A (vs not =): T= -0.31 P=0.75 DF= 55

Two Sample T-Test and Confidence Interval

Two sample T for 2 Year_B vs 2 Year_A

	N	Mean	StDev	SE Mean
2 Year_B	115	8.77	8.79	0.82
2 Year_A	34	9.68	9.43	1.6

95% CI for mu 2 Year_B - mu 2 Year_A: (-4.56, 2.7)
T-Test mu 2 Year_B = mu 2 Year_A (vs not =): T= -0.51 P=0.61 DF= 51

Two Sample T-Test and Confidence Interval

Two sample T for 3 Year_B vs 3 Year_A

	N	Mean	StDev	SE Mean
3 Year_B	79	13.06	7.33	0.82
3 Year_A	39	14.48	9.39	1.5

95% CI for mu 3 Year_B - mu 3 Year_A: (-4.85, 2.0)
T-Test mu 3 Year_B = mu 3 Year_A (vs not =): T= -0.83 P=0.41 DF= 61

Two Sample T-Test and Confidence Interval

Two sample T for 4 Year_B vs 4 Year_A

	N	Mean	StDev	SE Mean
4 Year_B	73	12.49	7.81	0.91
4 Year_A	27	10.11	9.55	1.8

95% CI for mu 4 Year_B - mu 4 Year_A: (-1.77, 6.5)
T-Test mu 4 Year_B = mu 4 Year_A (vs not =): T= 1.16 P=0.25 DF= 39

Two Sample T-Test and Confidence Interval

Two sample T for 5 Year_B vs 5 Year_A

	N	Mean	StDev	SE Mean

	N	Mean	StDev	SE Mean
5 Year_B	46	29.89	9.95	1.5
5 Year_A	32	42.9	22.3	3.9

95% CI for mu 5 Year_B - mu 5 Year_A: (-21.6, -4.5)
T-Test mu 5 Year_B = mu 5 Year_A (vs not =): T= -3.10 P=0.0036 DF= 39

Two Sample T-Test and Confidence Interval

Two sample T for 6 Year_B vs 6 Year_A

	N	Mean	StDev	SE Mean
6 Year_B	8	18.89	5.43	1.9
6 Year_A	7	20.00	4.28	1.6

95% CI for mu 6 Year_B - mu 6 Year_A: (-6.6, 4.4)
T-Test mu 6 Year_B = mu 6 Year_A (vs not =): T= -0.44 P=0.66 DF= 12

Single Chip Seal

Two Sample T-Test and Confidence Interval

Two sample T for 1 Year_B vs 1 Year_A

	N	Mean	StDev	SE Mean
1 Year_B	621	19.9	20.7	0.83
1 Year_A	228	24.2	22.4	1.5

95% CI for mu 1 Year_B - mu 1 Year_A: (-7.60, -0.9)
T-Test mu 1 Year_B = mu 1 Year_A (vs not =): T= -2.50 P=0.013 DF= 378

Two Sample T-Test and Confidence Interval

Two sample T for 2 Year_B vs 2 Year_A

	N	Mean	StDev	SE Mean
2 Year_B	646	10.31	9.86	0.39
2 Year_A	160	11.5	12.0	0.95

95% CI for mu 2 Year_B - mu 2 Year_A: (-3.24, 0.79)
T-Test mu 2 Year_B = mu 2 Year_A (vs not =): T= -1.20 P=0.23 DF= 215

Two Sample T-Test and Confidence Interval

Two sample T for 3 Year_B vs 3 Year_A

	N	Mean	StDev	SE Mean
3 Year_B	571	37.9	29.4	1.2
3 Year_A	108	32.7	21.3	2.1

95% CI for mu 3 Year_B - mu 3 Year_A: (0.5, 9.9)
T-Test mu 3 Year_B = mu 3 Year_A (vs not =): T= 2.19 P=0.030 DF= 193

Two Sample T-Test and Confidence Interval

Two sample T for 4 Year_B vs 4 Year_A

	N	Mean	StDev	SE Mean
4 Year_B	373	9.6	10.2	0.53
4 Year_A	214	17.2	13.9	0.95

95% CI for mu 4 Year_B - mu 4 Year_A: (-9.72, -5.44)
T-Test mu 4 Year_B = mu 4 Year_A (vs not =): T= -6.96 P=0.0000 DF= 345

Two Sample T-Test and Confidence Interval

Two sample T for 5 Year_B vs 5 Year_A

	N	Mean	StDev	SE Mean

5 Year_B	600	30.4	53.8	2.2
5 Year_A	121	59.5	45.1	4.1

95% CI for mu 5 Year_B - mu 5 Year_A: (-38.2, -19.9)
T-Test mu 5 Year_B = mu 5 Year_A (vs not =): T= -6.24 P=0.0000 DF= 195

Two Sample T-Test and Confidence Interval

Two sample T for 6 Year_B vs 6 Year_A

	N	Mean	StDev	SE Mean
6 Year_B	324	61.9	62.7	3.5
6 Year_A	27	41.3	69.2	13

95% CI for mu 6 Year_B - mu 6 Year_A: (-7.5, 49)
T-Test mu 6 Year_B = mu 6 Year_A (vs not =): T= 1.50 P=0.14 DF= 29

Multiple Course Micro-Surfacing

Two Sample T-Test and Confidence Interval

Two sample T for 1 Year_B vs 1 Year_A

	N	Mean	StDev	SE Mean
1 Year_B	413	11.97	7.91	0.39
1 Year_A	58	10.8	11.0	1.4

95% CI for mu 1 Year_B - mu 1 Year_A: (-1.81, 4.2)
T-Test mu 1 Year_B = mu 1 Year_A (vs not =): T= 0.79 P=0.43 DF= 65

Two Sample T-Test and Confidence Interval

Two sample T for 2 Year_B vs 2 Year_A

	N	Mean	StDev	SE Mean
2 Year_B	413	10.01	9.82	0.48
2 Year_A	182	30.2	22.8	1.7

95% CI for mu 2 Year_B - mu 2 Year_A: (-23.63, -16.7)
T-Test mu 2 Year_B = mu 2 Year_A (vs not =): T= -11.48 P=0.0000 DF= 211

Two Sample T-Test and Confidence Interval

Two sample T for 3 Year_B vs 3 Year_A

	N	Mean	StDev	SE Mean
3 Year_B	405	8.47	7.63	0.38
3 Year_A	52	8.86	8.71	1.2

95% CI for mu 3 Year_B - mu 3 Year_A: (-2.93, 2.1)
T-Test mu 3 Year_B = mu 3 Year_A (vs not =): T= -0.31 P=0.76 DF= 61

Two Sample T-Test and Confidence Interval

Two sample T for 4 Year_B vs 4 Year_A

	N	Mean	StDev	SE Mean
4 Year_B	401	10.17	9.91	0.49
4 Year_A	159	35.6	44.5	3.5

95% CI for mu 4 Year_B - mu 4 Year_A: (-32.50, -18.4)
T-Test mu 4 Year_B = mu 4 Year_A (vs not =): T= -7.14 P=0.0000 DF= 164

Two Sample T-Test and Confidence Interval

Two sample T for 5 Year_B vs 5 Year_A

	N	Mean	StDev	SE Mean

	N	Mean	StDev	SE Mean
5 Year_B	355	17.3	22.6	1.2
5 Year_A	44	19.5	14.0	2.1

95% CI for mu 5 Year_B - mu 5 Year_A: (-7.1, 2.6)
T-Test mu 5 Year_B = mu 5 Year_A (vs not =): T= -0.92 P=0.36 DF= 74

Two Sample T-Test and Confidence Interval

Two sample T for 6 Year_B vs 6 Year_A

	N	Mean	StDev	SE Mean
6 Year_B	243	31.7	35.4	2.3
6 Year_A	116	60.9	53.9	5.0

95% CI for mu 6 Year_B - mu 6 Year_A: (-40.0, -18.3)
T-Test mu 6 Year_B = mu 6 Year_A (vs not =): T= -5.31 P=0.0000 DF= 163

Bituminous Crack Seal

Two Sample T-Test and Confidence Interval

Two sample T for 1 Year_B vs 1 Year_A

	N	Mean	StDev	SE Mean
1 Year_B	873	11.0	10.3	0.35
1 Year_A	186	15.0	10.1	0.74

95% CI for mu 1 Year_B - mu 1 Year_A: (-5.59, -2.37)
T-Test mu 1 Year_B = mu 1 Year_A (vs not =): T= -4.87 P=0.0000 DF= 272

Two Sample T-Test and Confidence Interval

Two sample T for 2 Year_B vs 2 Year_A

	N	Mean	StDev	SE Mean
2 Year_B	761	8.09	7.34	0.27
2 Year_A	36	13.14	7.31	1.2

95% CI for mu 2 Year_B - mu 2 Year_A: (-7.57, -2.5)
T-Test mu 2 Year_B = mu 2 Year_A (vs not =): T= -4.05 P=0.0002 DF= 38

Two Sample T-Test and Confidence Interval

Two sample T for 3 Year_B vs 3 Year_A

	N	Mean	StDev	SE Mean
3 Year_B	688	15.7	14.0	0.53
3 Year_A	159	20.58	8.52	0.68

95% CI for mu 3 Year_B - mu 3 Year_A: (-6.61, -3.22)
T-Test mu 3 Year_B = mu 3 Year_A (vs not =): T= -5.71 P=0.0000 DF= 383

Two Sample T-Test and Confidence Interval

Two sample T for 4 Year_B vs 4 Year_A

	N	Mean	StDev	SE Mean
4 Year_B	796	18.9	17.7	0.63
4 Year_A	35	15.4	10.6	1.8

95% CI for mu 4 Year_B - mu 4 Year_A: (-0.32, 7.4)
T-Test mu 4 Year_B = mu 4 Year_A (vs not =): T= 1.85 P=0.071 DF= 42

Two Sample T-Test and Confidence Interval

Two sample T for 5 Year_B vs 5 Year_A

	N	Mean	StDev	SE Mean

	N	Mean	StDev	SE Mean
5 Year_B	751	23.7	18.4	0.67
5 Year_A	155	26.0	13.2	1.1

95% CI for mu 5 Year_B - mu 5 Year_A: (-4.84, 0.1)
T-Test mu 5 Year_B = mu 5 Year_A (vs not =): T= -1.90 P=0.059 DF= 293

Two Sample T-Test and Confidence Interval

Two sample T for 6 Year_B vs 6 Year_A

	N	Mean	StDev	SE Mean
6 Year_B	335	16.2	12.0	0.66
6 Year_A	16	29.6	16.7	4.2

95% CI for mu 6 Year_B - mu 6 Year_A: (-22.43, -4.4)
T-Test mu 6 Year_B = mu 6 Year_A (vs not =): T= -3.17 P=0.0063 DF= 15

Two Sample T-Test and Confidence Interval

Two sample T for 7 Year_B vs 7 Year_A

	N	Mean	StDev	SE Mean
7 Year_B	189	49.9	31.5	2.3
7 Year_A	76	41.6	14.0	1.6

95% CI for mu 7 Year_B - mu 7 Year_A: (2.7, 13.8)

BIBLIOGRAPHY

LIST OF REFERENCES

1. Al-Mansour, Abdullah I., Kuczek, Thomas, and Sinha, Kumares C. "Effects of Routine Maintenance on Flexible Pavement Condition". *Journal of Transportation Engineering*, Vol 120 No. 1. 1994.

2. Batac, Gilbert and Ray, Michael. "French Strategy for Preventive Road Maintenance: Why and How?" *Transportation Research Record* 1183, TRB, National Research Council, Washington D.C., pp. 22-34.

3. Brown, E.R. "Preventive Maintenance of Asphalt Concrete Pavements," *Transportation Research Record* 1205, TRB, National Research Council, Washington D.C., pp. 6-10.

4. Brown, Ray E., Kandhal, Prithvi S., Kennedy, Thomas W., Lee, Dah-Yinn, and Roberts, Freddy L. Hot Mix Asphalt Materials, Mixture Design and Construction. Maryland: NAPA Education Foundation, 1996.

5. Butt, Abbas A., Carpenter, Samuel H., Feighan, Kieran J. and Shahin, Mohamed Y. "Pavement Performance Prediction Model Using Markov Process", *Transportation Research Record* 1123, TRB, National Research Council, Washington D.C., pp. 12-19.

6. Cation, Kathryn A, Lytton, Robert L., Scullion, Thomas and Shahin, Mohamed Y. "Development of a Preventive Maintenance Algorithm for Use in Pavement Management Systems," *Transportation Research Record* 1123, TRB, National Research Council, Washington D.C., pp. 1-11.

7. Chan, W.T., Fwa, T.F., Hoque, K.Z. and Nixon, E. "Benefits of Active Planning for Preventive Pavement Maintenance at Network Level", *TRB 1999 Annual Meeting CD-ROM*, TRB, National Research Council, Washington D.C.

8. Chong, G.G. and Phang, W.A. "Improved Preventive Maintenance: Sealing Cracks in Flexible Pavements in Cold Regions," *Transportation Research Record* 1205, TRB, National Research Council, Washington D.C., pp. 12-19.

9. Daleiden, Jerome F., Eltahan, Ahmed A., and Simpson, Amy L. "Effectiveness of Maintenance Treatments of Flexible Pavements," *Transportation Research Record* 1680, TRB, National Research Council, Washington D.C., pp. 18-25.

10. Daleiden, Jerry, Hicks, Gary R., and Moulthrop, James S. "Selecting a Preventive Maintenance Treatment for Flexible Pavements," *TRB 1999 Annual Meeting CD-ROM*, TRB, National Research Council, Washington D.C.

11. Hicks, Gary R., Dunn, Kimberly, and Moulthrop, James S. "Framework for Selecting Effective Preventive Maintenance Treatments for Flexible Pavements," *Transportation Research Record* 1597, TRB, National Research Council, Washington D.C., pp. 1-10.

12. National Highway Institute. Techniques for Pavement Rehabilitation Reference Manual 6th Ed. Arlington, VA: National Highway Institute, 1998.

13. Galehouse, Larry. "Innovative Concepts for Preventive Maintenance," *Transportation Research Record* 1627, TRB, National Research Council, Washington D.C., pp. 1-6.

14. Geoffroy, D.N. *Evaluation and Benefits of Preventive Maintenance Strategies.* NCHRP Synthesis of Highway Practice 153.

15. George, K.P. and Rajagopal, A.S. "Pavement Maintenance Effectiveness," *Transportation Research Record* 1276, TRB, National Research Council, Washington D.C., pp. 62-68.

16. George, K.P., Shekharan, Raja A. and Vepa, T.S. "Prediction of Pavement Remaining Life," *Transportation Research Record* 1524, TRB, National Research Council, Washington D.C., pp. 137-144.

17. Haas, Ralph, Li, Ningyuan, and Xie, Wei-Chau. "Investigation of Relationship Between Deterministic and Probabilistic Prediction Models in Pavement Management" *Transportation Research Record* 1592, TRB, National Research Council, Washington D.C., pp. 70-79.

18. Hand, Adam, Lani, Stephen, and Sebaaly, Peter E. "Performance Models for Flexible Pavement Maintenance Treatments," *Transportation Research Record* 1508, TRB, National Research Council, Washington D.C., pp. 9-21.

19. Huang, Yang H. Pavement Analysis and Design. New Jersey: Prentice Hall, 1993.

20. Hicks, Gary R. and Moulthrop, James S. "Pavement Maintenance: Preparing for the 21st Century". *Proceedings of the Ninth Maintenance Management Conference.*

21. Mamlouk, Michael and Zaniewski, John. "Pavement Preventive Maintenance: The Key to Quality Highways," *TRB 1999 Annual Meeting CD-ROM*, TRB, National Research Council, Washington D.C.

22. Michigan Department of Transportation (MDOT). Capital Preventive Maintenance Program Guidelines. Lansing, MI, March, 1998.

23. Metcalf, John B and Romanoschi, Stefan A. "Evaluation of Probability Distribution Function for the Life of Pavement Structures" *Transportation Research Record* 1730, TRB, National Research Council, Washington D.C., pp. 91-98.

24. Moulthrop, James S and Smith, Roger E. *State of the Art and State of the Practice in Pavement Maintenance.* A3C05: Committee on Pavement Maintenance.

25. Shahin, Mohamed Y., Sharaf, Essam A., and Sinha, Kumares C. "Analysis of the Effect of Deferring Pavement Maintenance," *Transportation Research Record* 1205, TRB, National Research Council, Washington D.C., pp. 29-35.

26. Ayyub, Bilal M., and McCuen, Richard H. Probability, Statistics, & Reliability for Engineers. New York: CRC Press. 1997.

27. McCabe, George P. and Moore, David S. Introduction to the Practice of Statistics. New York: W.H. Freeman and Company. 1999.

28. Baladi, Gilbert Y. The Role of Pavement Management System in Tracking the Performance of Preventive Maintenance Actions Case Studies. Michigan State University. 2001.

29. Lee, Doseung. *Development of Roughness Thresholds for the Preventive Maintenance of Pavements Based on Dynamic Loading Considerations and Damage Analysis.* Masters Thesis. Michigan State University. 2001.

30. Reigle, Jenifer A. *Development of an Integrated Project-Level Pavement Management Model Using Risk Analysis*. PhD Thesis. West Virginia University. 2000.

31. Hicks, Gary R, Seeds, Stephen B, and Peshkin, David G. Selecting a Preventive Maintenance Treatment for Flexible Pavements. FHWA-IF-00-027. Foundation for Pavement Preservation. 2000.

32. Smith, Roger E and Lytton, Robert L. "Evaluation of Effectiveness of Pavement Preventive Maintenance". *Proceedings of SHRP and Traffic Safety on Two Continents.* 1989.

33. Virtala, P. "Modeling the Effects of Maintenance and Rehabilitation Actions on Road Conditions at Network Level". *4^{th} International Conference on Managing Pavements*. 1998.

34. Reddy, B.B., Kumar, Sivath N, and Veeraragavan, A. "Development of Maintenance Intervention Criteria for Inservice Flexible Pavements". *4^{th} International Conference on Managing Pavements*. 1998.

35. Smith, R. B. and Cerecina B. "Development of Maintenance Strategies for a National Highway System". *4th International Conference on Managing Pavements*. 1998.

36. Sharaf, Essam A. "A Procedure to Determine Critical Preventive Maintenance Timing". *4th International Conference on Managing Pavements*. 1998.

37. Mamlouk, Michael S. and Zaniewski, John P. "Optimizing Pavement Preservation: An Urgent Demand for Every Highway Agency," *The International Journal of Pavement Engineering*. Volume 2. Number 2. 2001.

38. Morian, Dennis, Gibson, Scott, and Epps, Jon. "Study of Maintenance Treatments for Asphalt Pavements". *8th International Conference on Asphalt Pavements*. 1997.

39. Li, Ningyuan, Xie, Wei-Chau, and Haas Ralph. "Reliability-based Processing of Markov Chains for Modeling Pavement Network Deterioration," *TRB 1996 Annual Meeting CD-ROM*, TRB, National Research Council, Washington D.C.

40. Pedigo, Daryl R., Hudson, Ronald W., and Roberts, Freddy L. "Pavement Performance Modeling for Pavement Management," *Transportation Research Record* 814, TRB, National Research Council, Washington D.C., pp. 8-21.

41. Gharaibeth, Nasir, LaTorre, Francesca, Darter, Michael, and Lippert, David. " Use of Pavement Management System Data for Pavement Engineering Applications," *Transportation Research Record* 1592, TRB, National Research Council, Washington D.C., pp. 35-45.

42. Sebaaly, Peter E., Hand, Adam, Epps, John and Bosch, Chuck. "Nevada's Approach to Pavement Management," *Transportation Research Record* 1524, TRB, National Research Council, Washington D.C., pp. 109-117.

43. Colucci-Rios, Benjamin and Sinha, Kumares C. "Optimal Pavement Management Approach Using Roughness Measurements," *Transportation Research Record* 1048, TRB, National Research Council, Washington D.C., pp. 14-22.

44. Shober, Steve F. and Friedrichs, David A. "Pavement Preservation Strategy," *Transportation Research Record* 1643, TRB, National Research Council, Washington D.C., pp. 44-53.

45. Galehouse, Larry. A Pavement Preventive Maintenance Program. Moving Roadway Maintenance into the 21st Century. APWA Satellite Videoconference. 1999.

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

47. Correa, Carlos E., Hall, Kathleen T., and Simpson, Amy L. "Performance of Flexible Pavement Maintenance Treatments in the LTPP SPS-3 Experiment," *TRB 2003 Annual Meeting CD-ROM*, TRB, National Research Council, Washington D.C.

48. Chen, Dar-Hao, Lin, Deng-Fong, and Luo, Huan-Lin. "Effectiveness of Preventive Maintenance Treatments Using SPS-3 Data," *TRB 2003 Annual Meeting CD-ROM*, TRB, National Research Council, Washington D.C.

49. National Strategic Highway Research Program. LTTP Data Analysis: Effectiveness of Maintenance and Rehabilitation Options, National Research Council, June 2002.

50. B.T. Bellner & Associates. Effectiveness of the Capital Preventive Maintenance Program, November 2001.

51. Epps, J.A., Gibson, S.D., and Morian, D.A. Maintaining Flexible Pavements – The Long Term Pavement Performance Experiment SPS-3 5 Year Data Analysis, FHWA-RD-97-102, Federal Highway Administration, Washington D.C. 1998.

52. Freeman, Thomas, Pendleton, Olga, and Smith, Roger. Pavement Maintenance Effectiveness, SHRP-H-358, National Research Council, Washington D.C. 1993.

53. Pendleton, Olga. "Reliability in Pavement Design: Issues, Concepts, and Significance," *Transportation Research Record* 1449, TRB, National Research Council, Washington D.C., pp. 8-12.

54. *AASHTO Guide for Design of Pavement Structures*. AASHTO, Washington, D.C., 1986.

55. *@ Risk User's Manual,* 1997, Palisade Corporation, Newfield, NY.

56. Kuo, Shiou-San, Mahgoub, Hesham, Hoffman, Lorrie. "Development of Flexible Pavement Performance Prediction Model Based on Pavement Data". *TRB 2003 Annual Meeting CD-ROM*, TRB, National Research Council, Washington D.C.

57. Baladi, G.Y., and Snyder, M.B. Highway Pavements, Volumes 1 and 2. The National Highway Institute, Washington D.C., September 1989.