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Performance Evaluation of Arizona's LTPP SPS-3 Project: Strategic Study of Maintenance Procedure Effectiveness for Flexible Pavements

Arizona Department of Transportation Research Center

ADOT

Performance Evaluation of Arizona's LTPP SPS-3 Project: Strategic Study of Maintenance Procedure Effectiveness for Flexible Pavements

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16. Abstract

As part of the Long Term Pavement Performance (LTPP) Program, the Arizona Department of Transportation (ADOT) constructed 36 Specific Pavement Study-3 (SPS-3) test sections across four test sites in Arizona. The purpose of the SPS-3 experiment was to study various maintenance strategies for asphalt concrete (AC) pavements. Using surface distress and profile data collected throughout the life of the test sections, investigators evaluated the performance of four AC pavement maintenance strategies: thin overlay, slurry seal, crack seal, and chip seal. This report documents the analyses conducted as well as practical findings and lessons learned that will be of interest to ADOT.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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List of Acronyms and Abbreviations

AB	aggregate base
AC	asphalt concrete
ADOT	Arizona Department of Transportation
ADS	automated distress survey
EDI	environmental damage index
ESAL	equivalent single-axle load
FHWA	Federal Highway Administration
GPS	General Pavement Study
HMAC	hot-mix asphalt concrete
HRI	Half-car Roughness Index
ID	identification
IRI	International Roughness Index
LTPP	Long Term Pavement Performance
MDS	manual distress survey
MRI	Mean Roughness Index
N/A	not available, not applicable
PSD	power spectral density
RN	Ride Number
SDI	structural damage index
SHRP	Strategic Highway Research Program
SPS	Specific Pavement Study

EXECUTIVE SUMMARY

As part of the Long Term Pavement Performance (LTPP) Program, the Arizona Department of Transportation (ADOT) constructed 36 Specific Pavement Study-3 (SPS-3) test sections over four project sites located in four areas of Arizona. The SPS-3 experiment was designed to study a variety of preventive maintenance strategies for asphalt concrete (AC) pavements. Construction of the sections, which was staggered, began in June 1990 and ended in November 1990. All sections had been removed from study by 1998.

In accordance with the national SPS-3 experiment design, investigators tested four core preventive maintenance strategies: thin overlays, slurry seals, crack seals, and chip seals. These four treatments were applied at every SPS-3 project site, regardless of existing pavement condition. (A total of 14 supplemental sections were also constructed, but this report does not cover their performance as construction documentation and data availability were highly variable.) The treatments were not intended to repair the existing pavement distress, and the condition of the test sections prior to treatment application varied considerably. Therefore, in determining the effectiveness of each treatment strategy, investigators evaluated the progression of pavement distress rather than the overall condition of the pavement.

This report provides general information about the project locations—including climate, traffic, and subgrade conditions—as well as details on the layer configurations of each test section. Of the 36 test sections constructed, 22 were core sections (testing the four core maintenance strategies) and 14 were supplemental sections added by ADOT. While all SPS-3 sections were constructed within the same year, they were constructed in different months and therefore under what may have been slightly different climate conditions. Likewise, the locations were spread across Arizona, introducing further differences in climate conditions. The project sites also had different traffic-loading conditions. Therefore, these varying factors must be considered when analyzing the data, and direct comparisons must be made carefully.

Distress analysis revealed that all the sections receiving a maintenance treatment improved in some respect, whether measured by structural damage, environmental damage, or rutting. The data were limited due to the short lifespan of the test sections, and that made it difficult for investigators to draw strong conclusions about the performance of the test strategies. However, they found that across four different methods of analyzing the data (time-series analysis of distress, single-time-point analysis of distress, life-extension calculation, and treatment effectiveness), the thin-overlay sections generally exhibited the best performance while the crack-seal sections exhibited the worst performance.

Profile analysis of the 22 core test sections indicated that the rank order of roughness progression was different for each of the four sites. It is likely that the sites' original condition and traffic loading overshadowed the influence of surface treatment. The analyses confirmed that some long-wavelength features, but no medium- or short-wavelength features, were preserved after mill and overlay. Finally, although use of a "machine premix patch" may have helped reduce structural deterioration, the patches were often evident in the profile and produced additional roughness by causing the surface elevation to differ from that of the surrounding pavement.

It should be noted that some sections received additional maintenance work during the study to maintain safe driving conditions. As was deemed necessary to meet roadway safety standards, pothole patching, crack sealing, and sand sealing were permitted in the test sections. These maintenance events may have masked the extent and severity of actual distresses in the pavement in the short term.

CHAPTER 1. INTRODUCTION

Understanding the contribution of maintenance and rehabilitation procedures to long-term pavement performance can be extremely valuable to pavement managers who are looking to optimize resources and improve overall performance. The objectives of this research were to document the overall performance trends revealed by the Specific Pavement Study-3 (SPS-3) project, to identify key differences in performance by timing and type of maintenance technique used, and to document key findings that would be useful to the Arizona Department of Transportation (ADOT).

This report provides the results of surface distress and profile analyses for the four Arizona sites at which the Long Term Pavement Performance (LTPP) Program SPS-3 project was conducted. The SPS-3 experiment studied the effect of specific preventive maintenance treatments on the performance of asphalt concrete (AC) pavement. The project consisted of 36 test sections. Of these, 22 were core sections, representing the standard experimental matrix that the Strategic Highway Research Program (SHRP) required, and 14 were state supplemental sections added by ADOT. In this report, the test sections are referred to by their six-digit SHRP project identification (ID) numbers (for example, 04A310). The four Arizona sites are labeled A through D (see the alpha indicator in the third position):

- 04A300, located near Kingman on U.S. Route 93 (U.S. 93)
- 04B300, located near Kingman on Interstate 40 (I-40)
- 04C300, located near Green Valley on Interstate 19 (I-19)
- 04D300, located near Nogales on I-19

Each site contained five sections: a control section where no preventive maintenance measures were taken, and four test sections that each received a different preventive maintenance treatment. (One site had an extra control section and one had an extra test section, bringing the total to 22 core sections.) The four preventive maintenance methods (and their section ID numbers) were as follows:

- Thin overlay (310) of approximately 1.25-inch thickness
- Slurry seal (320)
- Crack seal (330)
- Chip seal (350) of approximately 0.25-inch thickness

Treatment application occurred between June and November 1990 for all sections. The construction documentation and data availability for the supplemental sections were insufficient to provide meaningful results. Therefore, the supplemental sections were not fully evaluated in this study. Some information on the roughness of supplemental sections is provided in the Roughness Analysis chapter of this report (Chapter 3).

All four of the Arizona SPS-3 test sites were located in a dry, no-freeze climate. The location of the four SPS-3 sites across Arizona is shown in Figure 1 below.

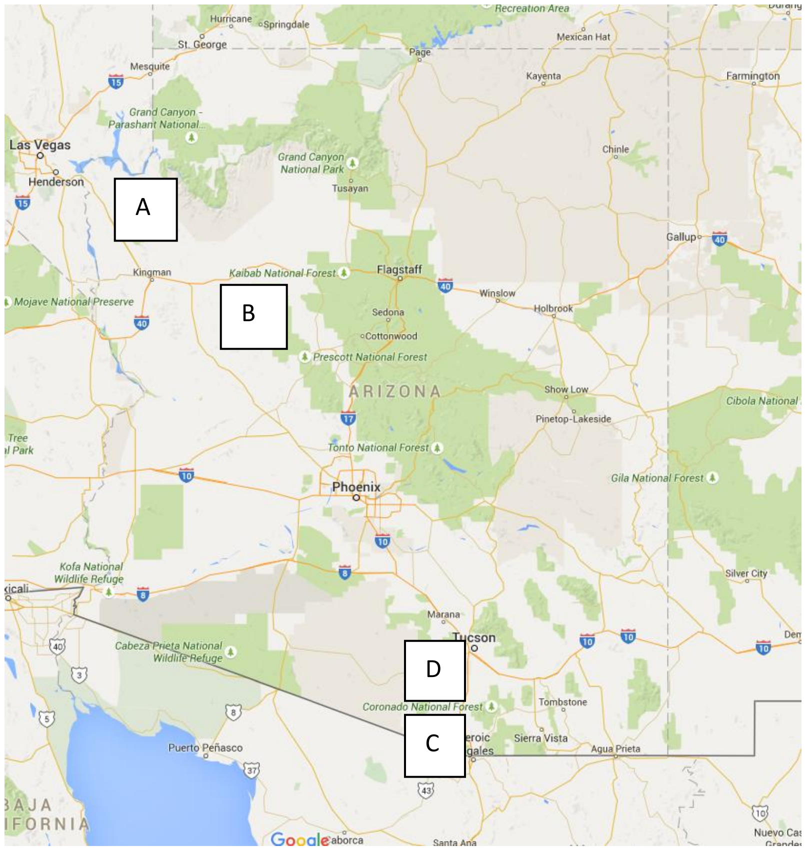

Figure 1. Location of the Arizona SPS-3 Sites
(map courtesy of Google Maps)

As Figure 1 shows, the project sites are clustered in two different parts of the state, which means that the sites have slightly different climates. The relevant climatic information for all four sites is shown in Table 1. As the table shows, sites C and D have very similar climate variables, while there is slight variation between sites A and B and between the two pairs of sites.

Table 1. Climatic Profiles Across Four Arizona SPS-3 Sites

	SPS-3 Project Site											
	04A300			04B300			04C300			04D300		
	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
Annual average daily mean temperature (°F)	70	74	65	65	69	62	66	69	62	65	69	62
Annual average daily max temperature (°F)	83	87	77	80	84	76	82	84	80	82	84	79
Annual average daily min temperature (°F)	58	61	53	51	57	48	50	56	44	48	56	42
Absolute maximum annual temperature (°F)	115	121	109	110	117	103	108	111	104	108	112	103
Absolute minimum annual temperature (°F)	26	35	15	20	26	8	20	32	8	18	32	4
Number of days per year above 90° F	147	174	109	125	161	88	127	162	96	120	153	81
Number of days per year below 32° F	7	23	0	36	65	4	39	84	0	50	97	0
Annual average freezing index (°F-days)	1	12	0	2	19	0	1	12	0	1	13	0
Annual average precipitation (inches)	6	11	1	8	18	3	14	28	7	15	29	7
Annual average daily maximum relative humidity (%)	45	57	35	52	62	41	58	66	49	58	66	49
Annual average daily minimum relative humidity (%)	19	24	13	2	24	17	19	22	15	19	22	15

The existing pavements used as test sections in the Arizona SPS-3 study were constructed between 1976 and 1983, as is shown in Table 2. The sections exhibited varying amounts of distress when the study began. Each of the four sites included as a control a General Pavement Study (GPS) section that was still in study. Table 2 also shows the pavement condition of the control section at each project site as of 1989. (The project sites were selected for inclusion in the study regardless of existing pavement condition, in accordance with the national SPS-3 experimental design.)

Table 2. Site Age and Condition at the Start of the Arizona SPS-3 Study

Project Site	Existing Pavement Age	Existing Pavement Condition (based on distress surveys of the control test sections in 1989)
A	7 years (constructed 06/01/1983)	The site had low- to moderate-severity fatigue cracking and low-severity longitudinal and transverse cracking.
B	12 years (constructed 07/01/1978)	The site had low-severity longitudinal cracking (which was mostly not in the wheelpath) and some transverse cracking.
C	14 years (constructed 08/01/1976)	The site had some low-severity fatigue cracking, a significant amount of low-severity non-wheelpath longitudinal cracking, and some low-severity wheelpath longitudinal and transverse cracking.
D	11 years (constructed 06/01/1979)	The site had a significant amount of low-severity longitudinal cracking (which was mostly not in the wheelpath) and low-severity transverse cracking.

All test sections were constructed between June and November 1990; Table 3 shows the exact date of construction for each section. During or after the treatment application, several anomalous events occurred that may have had an impact on the results:

- In section 04A350, the original chip seal wore away shortly after construction. This original chip seal section was relabeled as section 04A390 and a new section 04A350 was constructed to replace it.
- At the two-month follow-up of the new section 04A350, almost half of the chips had already worn away. It was determined that the emulsion probably had been applied too heavily during the construction of the chip seal.
- At the two-month follow-up of section 04B320, some potholing was seen, probably because traffic had been allowed on the section too soon after the slurry seal was applied. It was observed that vehicles suddenly braking once they reached the slurry seal were causing some distresses at the beginning of the section, including potholing.
- During construction of section 04C320, a car accidentally drove through the section before it was open to traffic, causing obvious damage to the slurry seal. The seal was able to be recompacted under normal traffic, but the damage was still noticeable.

Table 3. Location and Critical Dates for Arizona SPS-3 Sections

SHRP ID	Latitude, degrees	Longitude, degrees	Length (ft)	Preventive Maintenance	Date Constructed	Out of Study Date
04A310	35.72619	-114.48855	500	Thin overlay	11/19/1990	5/1/1998
04A320	35.71976	-114.48506	500	Slurry seal	8/24/1990	5/1/1998
04A330	35.72446	-114.48761	500	Crack seal	8/24/1990	5/1/1998
04A350	35.7277	-114.48936	500	Chip seal	8/24/1990	5/1/1998
04B310	35.1614	-113.67561	500	Thin overlay	11/28/1990	6/13/1996
04B320	35.16057	-113.68334	500	Slurry seal	8/27/1990	6/13/1996
04B330	35.16115	-113.67791	500	Crack seal	8/27/1990	6/13/1996
04B350	35.16028	-113.68600	500	Chip seal	8/27/1990	6/13/1996
04C310	31.77613	-111.03015	500	Thin overlay	6/05/1990	2/8/1997
04C320	31.76703	-111.03500	500	Slurry seal	9/04/1990	2/8/1997
04C330	31.76878	-111.03408	500	Crack seal	9/05/1990	2/8/1997
04C350	31.7739	-111.03141	500	Chip seal	9/06/1990	2/8/1997
04D310	31.63547	-111.05673	500	Thin overlay	6/05/1990	5/1/1998
04D320	31.63935	-111.05738	500	Slurry seal	9/06/1990	4/28/1998
04D330	31.63742	-111.05706	500	Crack seal	9/06/1990	5/1/1998

Sites 04C300 and 04D300 were located on the same roadway and were expected to have similar traffic loading, while section 04B300 was located on a major highway and received heavier traffic volumes. The monitored amount of equivalent single-axle loads (ESALs) for each section is shown in Table 4. As expected, sections 04C300 and 04D300 contain similar traffic levels while section 04B300 has a much higher level.

Table 4. Traffic Loading for Arizona SPS-3 Project

	Traffic Loading (ESALs)			
Year	**04A300**	**04B300**	**04C300**	**04D300**
1991	165,000	900,000	230,000	140,000
1992	175,000	950,000	240,000	150,000
1993	n/a	730,000	n/a	n/a
1994	200,000	900,000	150,000	n/a
1995	200,000	1,000,000	150,000	180,000
1996	220,000	1,000,000	150,000	180,000
1997	390,000	1,100,000	n/a	200,000
1998	n/a	1,200,000	190,000	220,000

n/a: No data available

Following the treatment application at each site, each pavement, base, and subgrade layer was categorized and measured. The results, along with the project-level stations, are shown in Table 5. The large variations seen in base type and thickness indicate that site-level comparisons will be much more effective than section-level comparisons. Additionally, Table 5 shows that sections 04B320 and 04B350 are generally overbuilt, with different existing layer thicknesses, while 04C320 is slightly underbuilt. These layer thickness discrepancies should be considered during the project-level and section-level analyses later in this report.

Table 5. Thickness and Layer Characteristics of Each Site

SHRP ID	Location		Asphalt Concrete		Base		Subgrade
	Begin	End	Thickness (inches)	Type	Thickness (inches)	Type	Type
041036 (control)	0+00	5+00	3.8	Original surface layer	18.6	Soil-aggregate mixture (predominantly coarse-grained)	Coarse-grained soil: clayey sand with gravel
			0.6	Friction course			
04A310	55+50	60+50	1.2	Thin overlay			
			4.3	Original surface layer			
			0.4	Friction course			
04A320	29+50	34+50	3.6	Original surface layer			
			0.5	Friction course			
04A330	48+50	53+50	3.5	Original surface layer			
			0.6	Friction course			
04A350	66+50	71+50	3.7	Original surface layer			
			0.5	Friction course			
041021 (control)	44+78	49+78	4.7	Original surface layer	8.4	Soil-aggregate mixture (predominantly coarse-grained)	Coarse-grained soil: silty sand with gravel
			0.5	Friction course			
04B310	29+61	34+61	1.4	Thin overlay			
			4.5	Original surface layer			
			0.2	Friction course			
04B320	52+28	57+28	5.5	Original surface layer			
			0.4	Friction course			
04B330	36+61	41+61	4.7	Original surface layer			
			0.5	Friction course			
04B350	60+61	65+61	5.6	Original surface layer			
			0.4	Friction course			

Table 5. Thickness and Layer Characteristics of Each Project Site (Continued)

SHRP ID	Begin	End	Asphalt Concrete Thickness (inches)	Asphalt Concrete Type	Base Thickness (inches)	Base Type	Subgrade Type
041017 (control)	0+00	5+00	8.2	Original surface layer	11.2	Crushed gravel	Coarse-grained soil: clayey gravel with sand
			0.7	Friction course			
04C310	43+40	48+40	1.6	Thin overlay			
			7.8	Original surface layer			
			0.8	Friction course			
04C320	7+00	12+00	7.4	Original surface layer			
			0.6	Friction course			
04C330	14+00	19+00	8.4	Original surface layer			
			0.5	Friction course			
04C350	34+40	39+40	7.9	Original surface layer			
			0.6	Friction course			
041016 (control)	0+00	5+00	9.5	Original surface layer	6.7	Crushed gravel	Coarse-grained soil: clayey gravel with sand
			0.5	Friction course			
04D310	29+23	34+23	1.7	Thin overlay			
			9.9	Original surface layer			
			0.5	Friction course			
04D320	14+23	19+23	9.5	Original surface layer			
			0.6	Friction course			
04D330	21+23	26+23	9.7	Original surface layer			
			0.4	Friction course			
04D350	45+23	50+23	9.4	Original surface layer			
			0.2	Friction course			

Analysis of the SPS-3 project involved two primary methodologies for evaluating pavement performance: distress analysis and profile (roughness) analysis. Chapter 2 covers the distress analysis, and Chapter 3, the profile analysis. Each chapter provides a description of the research approach along with performance comparisons between test sections, overall trends, a summary of the results, and key findings.

CHAPTER 2. DISTRESS ANALYSIS

This chapter describes the methodology for and results from evaluating surface distress data collected in the Arizona SPS-3 project using LTPP manual survey techniques (Miller and Bellinger 2003). Surface distress provides powerful information on the nature and extent of pavement deterioration, which can be used to quantify performance trends as well as to investigate the contribution of design features to service life.

The 36 flexible SPS-3 test sections were constructed at varying times within the same year, but mostly in the summer months, as was shown in Table 1. As discussed in Chapter 1, the traffic, climate, and subgrade conditions varied across the sections, so care must be taken when drawing conclusions across different test sections. The varying conditions may have introduced confounding effects that complicate comparisons between layer configurations and design features.

Finally, it should be noted that some sections received additional maintenance work during the study to maintain safe driving conditions. As was deemed necessary to meet roadway safety standards, pothole patching, crack sealing, and sand sealing were permitted in the test sections. These maintenance events may have masked the extent and severity of actual distresses in the pavement in the short term.

ASPHALT CONCRETE DISTRESS TYPES

Surface deterioration is composed of multiple distress types. Definitions of each type are as follows (Huang 1993):

- **Fatigue cracking:** A series of interconnecting cracks caused by repeated traffic loading. Cracking starts at the bottom of the asphalt layer, where tensile stress is the highest under the wheel load. With repeating loading, the cracks propagate to the surface.

- **Longitudinal wheelpath cracking:** Cracking parallel to the centerline occurring in the wheelpath. This cracking can be the early stages of fatigue cracking or can start from construction-related issues such as paving seams and segregation of the mix during paving. In the latter case, cracking is typically very straight (no meandering).

- **Longitudinal non-wheelpath cracking:** Cracking parallel to the centerline occurring outside the wheelpath. This cracking is not load-related and can come from paving seams or areas where segregation issues occurred during paving. Cracking can also be caused by tensile forces experienced during temperature changes. Pavements with oxidized/hardened asphalt are more prone to this type of cracking.

- **Transverse cracking:** Cracking that is predominantly perpendicular to the pavement centerline. This distress type starts from tensile forces experienced during temperature changes. Pavements with oxidized/hardened asphalt are more prone to this type of cracking.

- **Block cracking:** Cracking that forms a block pattern and divides the surface into approximately rectangular pieces. This distress type starts from tensile forces experienced during temperature changes. It indicates that the asphalt concrete has significantly oxidized/hardened.
- **Raveling:** Wearing away of the surface caused by dislodging of aggregate particles and loss of asphalt binder. Raveling is caused by moisture stripping and asphalt hardening.
- **Bleeding:** A defect of excessive bituminous binder on the surface that can lead to loss of surface texture or a shiny, glass-like, reflective surface. Bleeding is a result of high asphalt content or low air void content in the mix.
- **Rutting:** A surface depression in the wheelpaths that can result from consolidation or lateral movement of material due to traffic loads. Rutting can also signify plastic movement of the asphalt mix because of inadequate compaction, excessive asphalt, or a binder that is too soft given the climatic conditions.

The distress types defined above can be grouped into two general categories based on cause or failure mechanism. Table 6 summarizes flexible pavement distress types and their associated failure mechanisms.

Table 6. Flexible Pavement Distress Types and Associated Failure Mechanisms

Distress Type	Failure Mechanism	
	Traffic load–related	Climate/materials–related
Fatigue cracking	X	
Longitudinal wheelpath cracking	X	
Longitudinal non-wheelpath cracking		X
Transverse cracking		X
Block cracking		X
Raveling		X
Bleeding		X
Rutting	X	X

RESEARCH APPROACH

The research began with a cursory review of all distress data collected at each test section to identify suspect or inconsistent information. The analysis team used photos and distress maps to verify quantities reported in the database. Variation is expected in distress data due to the subjective nature of the data collection technique (i.e., raters must select distress type and severity based on a set of rules). The SPS-3 data set was well within the acceptable range of variability.

Distress data collected for LTPP purposes are reported at three severity levels: low, moderate, and high. It has been well-documented that inconsistent determinations of severity levels (within one distress type) are one of the largest sources of variability in distress data (Rada et al. 1999). In addition, conducting analyses on three separate severity levels for each distress type becomes an increasingly complex process with results that are difficult to interpret. To reduce variability and to consolidate the information for analysis, the quantities from the three severity levels have been summed into one composite value in this report.

As noted above and as shown in Table 6, pavement distress (when not directly attributable to mix problems or construction deficiencies) can be caused by structural factors or environmental factors. Structural factors are the result of traffic loading relative to the structural capacity of the pavement section. Environmental factors represent the influence of climate on pavement deterioration. Therefore, structural and environmental indices were developed to focus the analyses on overall structural and environmental damage, which are more consistent and provide a better avenue for comparison, rather than on individual types of distress, which vary from section to section and year to year. These indices were developed and used for distress analysis in multiple previous LTPP studies of SPS projects in Arizona (Puccinelli et al. 2016; Puccinelli et al. 2015; Puccinelli et al. 2013; Puccinelli et al. 2012). They are not the standard pavement condition indices used in the pavement industry and are entirely based on visually observable distresses surveyed during the monitoring period of the LTPP program. The effect of aging is not accounted for in these indices.

The structural damage index (SDI) is a composite of distresses affecting the portion of the pavement that experiences loading (i.e., wheelpaths). Therefore, the structural damage index is presented as the percentage of wheelpath damage and includes fatigue and longitudinal wheelpath cracking. To normalize fatigue and longitudinal cracking, the structural damage index is calculated using the following equation:

$$S = \frac{F + 1ft * C_{lwp}}{2 * W_{wp} * L_s} \qquad \text{(Eq. 1)}$$

Where S = structural damage index
F = area of fatigue (ft^2)
C_{lwp} = length of longitudinal wheelpath cracking (ft)
W_{wp} = width of wheelpath = 1.0 (ft)
L_s = length of test section (ft)

The environmental damage index (EDI)is a composite of distresses that generally result from climatic effects. The entire pavement surface is subject to environmental distress; therefore, the environmental damage index is characterized as the percentage of total pavement area damaged. Typically, transverse cracking, longitudinal cracking outside of the wheelpaths, and block cracking are specific to environmental damage. To normalize the environmental distress for the total area, the environmental damage index is calculated using the following equation:

$$E = \frac{B}{A_{tot}} + \frac{C_{nwp}}{L_s} + \frac{C_t}{L_s} \qquad \text{(Eq. 2)}$$

Where
E = environmental damage index
B = area of block cracking (ft^2)
C_{nwp} = length of non-wheelpath cracking (ft)
C_t = length of transverse cracking (ft)
A_{tot} = total area of test section (ft^2)
L_s = length of test section (ft)

Although the structural and environmental distress factors clearly had a significant impact on the SPS-3 project's structural and functional service life, the analyses also incorporated rutting, patching, and other surface defects (such as potholes, bleeding, and raveling). Rutting data reported in this study were generated using a 6-ft straightedge reference (Simpson 2001).

The experimental design of the SPS-3 project was such that replicate data were not collected. Therefore, standard statistical comparisons (i.e., *t*-tests) to determine the significance of findings could not be conducted. Instead, the evaluation consisted of graphical comparisons between test sections. Additionally, despite the presence of state supplemental test sections, only data from the core test sections were considered in the distress analysis. This was due to the short performance lives of the test sections and the inconsistencies across the sites.

The discussion that follows will first describe trends observed across the entire project life. Then, comparisons will be made across the data as of a single date (the latest date for which there are complete data for all sections within a single site). Next, life extension values (expressing the amount of time until the section returned to its pretreatment condition) will be compared for each preventive maintenance method. Finally, the effectiveness of the treatment methods (calculated by taking the difference between the distress levels before and after the treatment) will be examined.

Some data were not collected until shortly before the out-of-study date, and this should also be considered when drawing comparisons across sections. The test section construction dates, out-of-study dates, and final data collection dates are shown in Table 7. While many sections have consistent data collection across all sites, several data collection periods are quite short, most notably for sections 04B310, 04D320, and 04D350.

Table 7. Critical Dates for Arizona SPS-3 Test Sections

SHRP ID	Preventive Maintenance	Date Constructed	Out-of-Study Date	Date of Last Data Collection
04A310	Thin overlay	11/19/1990	5/1/1998	1/14/1998
04A320	Slurry seal	8/24/1990	5/1/1998	1/13/1998
04A330	Crack seal	8/24/1990	5/1/1998	1/14/1998
04A350	Chip seal	8/24/1990	5/1/1998	1/14/1998
04B310	Thin overlay	11/28/1990	6/13/1996	9/4/1991
04B320	Slurry seal	8/27/1990	6/13/1996	2/10/1994
04B30	Crack seal	8/27/1990	6/13/1996	2/11/1994
04B350	Chip seal	8/27/1990	6/13/1996	2/10/1994
04C310	Thin overlay	6/05/1990	2/8/1997	9/26/1996
04C320	Slurry seal	9/04/1990	2/8/1997	1/25/1994
04C330	Crack seal	9/05/1990	2/8/1997	9/26/1996
04C350	Chip seal	9/06/1990	2/8/1997	9/26/1996
04D310	Thin overlay	6/05/1990	5/1/1998	9/19/1996
04D320	Slurry seal	9/06/1990	4/28/1998	9/17/1992
04D330	Crack seal	9/06/1990	5/1/1998	9/19/1996
04D350	Chip seal	9/06/1990	4/28/1998	9/17/1992

OVERALL PERFORMANCE OBSERVATIONS

While gathering pavement distress data, researchers became aware of a few significant trends impacting the overall pavement performance. These observations were clearly driving issues for this project and were intrinsically important pieces of the distress performance.

Both the structural damage index and the environmental damage index were calculated for all sections that contained more than one data point in the data series. Once the indices were calculated, it became clear that all distress values should be normalized to the first complete set of survey data following construction. This was due to varying initial conditions of the roadways prior to treatment, and the normalization provided more meaningful comparisons. Therefore, the distress value measured for the first distress survey following construction was used as the normalized base value and all subsequent measurements were compared against it. All subsequent plots were also normalized in this way, as were all rutting data. It should be noted that the first distress survey for each section was conducted using automated distress survey (ADS) equipment. All other data used for comparisons were taken from manual distress data, which introduces potential problems into the normalization procedure due to inconsistencies between the two types of data collection. For example, the ADS may consider some distress to be block cracking while the manual distress survey (MDS) categorizes the same cracking as fatigue cracking. The ADS data are not typically used for analysis; however, as no other data immediately following construction were collected for any of the sections, it was necessary to utilize ADS data. Therefore, some inconsistencies within the first set of normalized data presented here could be attributed to differences between the ADS and MDS data.

To better observe trends, the structural damage index, environmental damage index, and average rutting value for each section were plotted individually as functions of time. The resulting three plots per section were supplemented by information from a site tour conducted in October 1992 (hereafter referred to as the "site tour"). All of these pieces of data were then combined to create a synopsis for each project section. These synopses are presented below.

04A300 Sections

Figures 2 through 4 show the three plots of the trends in the SDI, the EDI, and the average rutting depth for the 04A300 control and test sections.

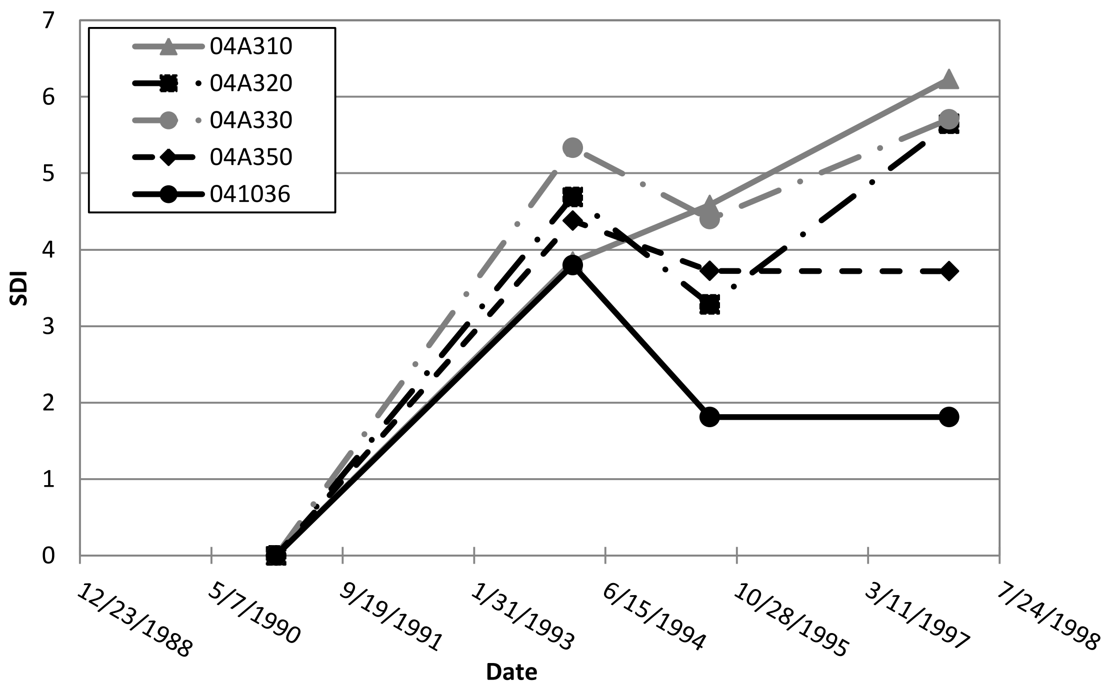

Figure 2. Structural Damage Index Trends for 04A300 Sections

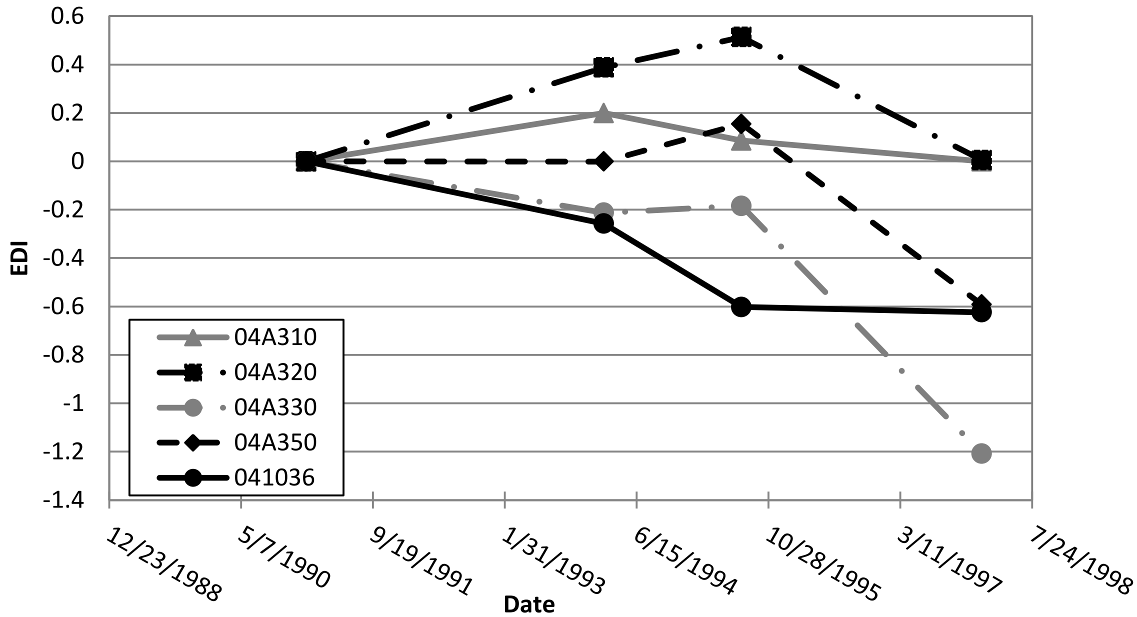

Figure 3. Environmental Damage Index Trends for 04A300 Sections

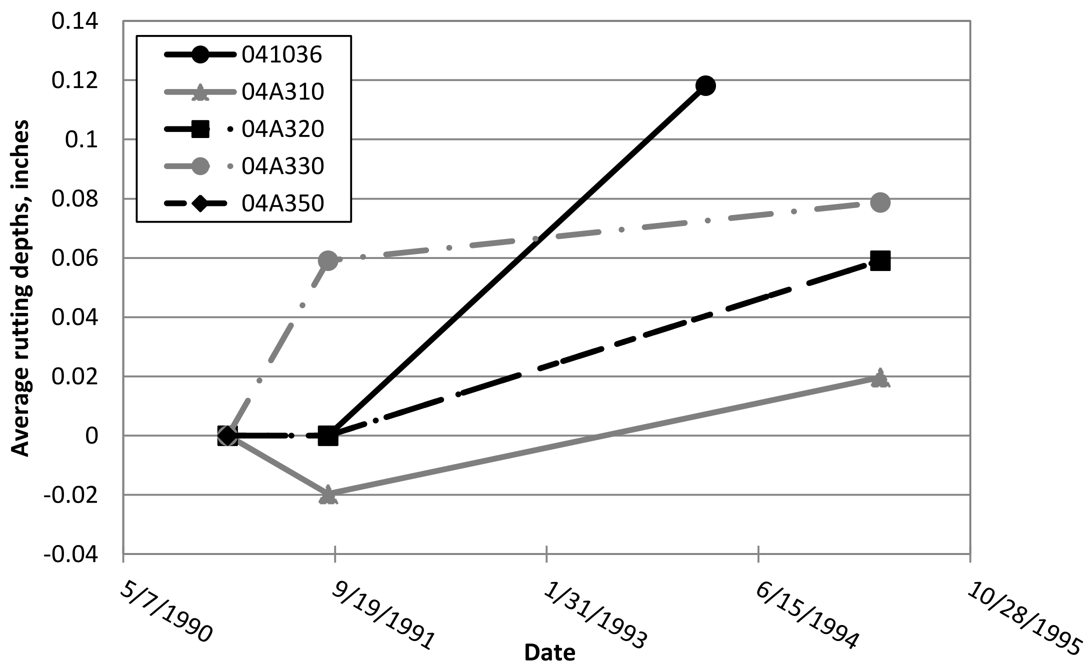

Figure 4. Rutting Trends for 04A300 Sections

It can be seen from Figure 2

Figure 4 that the distresses on the control section appear to decrease; this is expected considering that this section received a sand seal in 1993. Trends and comparisons for the control section do not consider distress measurements on the control section after the sand seal was placed. Despite strong initial performance, the thin overlay exhibited high levels of deterioration after 1995. It is important to note that all three measures of performance—SDI, EDI, and rutting—should be considered together. For example, the EDI distresses may appear to decrease while the SDI is simultaneously increasing, indicating that distresses originally categorized as EDI, such as longitudinal cracking, may eventually be recategorized as fatigue cracking. The general trends observed from the three plots are summarized in Table 8 for SDI, EDI, and rutting. For Site A , the performance trends are inconsistent among the preventive maintenance methods; however, the thin overlay is seen to perform slightly better than the rest.

Table 8. Performance Summary for 04A300 Sections

Ranking	SDI	EDI	Rutting
1 (Best performance)	Thin overlay	Control	Thin overlay
2	Control	Crack seal	Chip seal
3	Chip seal	Thin overlay	Slurry seal
4	Slurry seal	Chip seal	Crack seal
5 (Worst performance)	Crack seal	Slurry seal	Control

The October 1992 site tour yielded the following observations about the test sections:

- The control section (prior to the sand seal) had considerable fatigue cracking along with raveling in the existing pavement friction course.
- The thin overlay section was the best-performing one at the 04A300 site, with no rutting and no cracking observed.
- At the slurry seal section, the seal was in good condition, with only minor fatigue reflecting through and no rutting.
- The crack sealant of the crack seal section was still performing well, with only minor incompressibles. However, substantial fatigue cracking had formed since the sealant was originally placed.
- The chip seal section had performed more poorly than the other sections on the site. The first construction attempt had resulted in a failed placement, likely due to a number of factors including a light spray application, a long period of time before traffic was permitted, and higher traffic speeds. A replacement chip seal section was then placed in September 1990; however, it was noted that the new section had considerable heavy cracking in the wheelpaths and

noticeable rutting. A second review was done in November 1990, and that examination suggested that both seals had failed, with the first seal retaining only 40 percent of the rock, and the second seal, only 60 percent.

While it appeared that the asphalt had drained down into the existing open-graded friction course, the exact cause was unknown. The emulsion had been shot at a rate close to the upper limit of the quantity that was possible to place without causing a bleeding problem immediately following construction. Weather and the quality of construction techniques do not appear to have been the problem. Therefore, it can only be suggested that for open-graded surfaces, the placement of a heavy fog or sand seal some months prior to the placement of a chip seal could have remedied the drain-down issue. However, the chip seal was constructed per the experimental design for SPS-3 projects in the LTPP study. The site tour indicated that by October 1992, only 5 to 10 percent of the chips remained in the second seal.

04B300 Sections

Figures 5 through 7 show the three plots of the trends in the SDI, the EDI, and the average rutting depth for the 04B300 control and test sections.

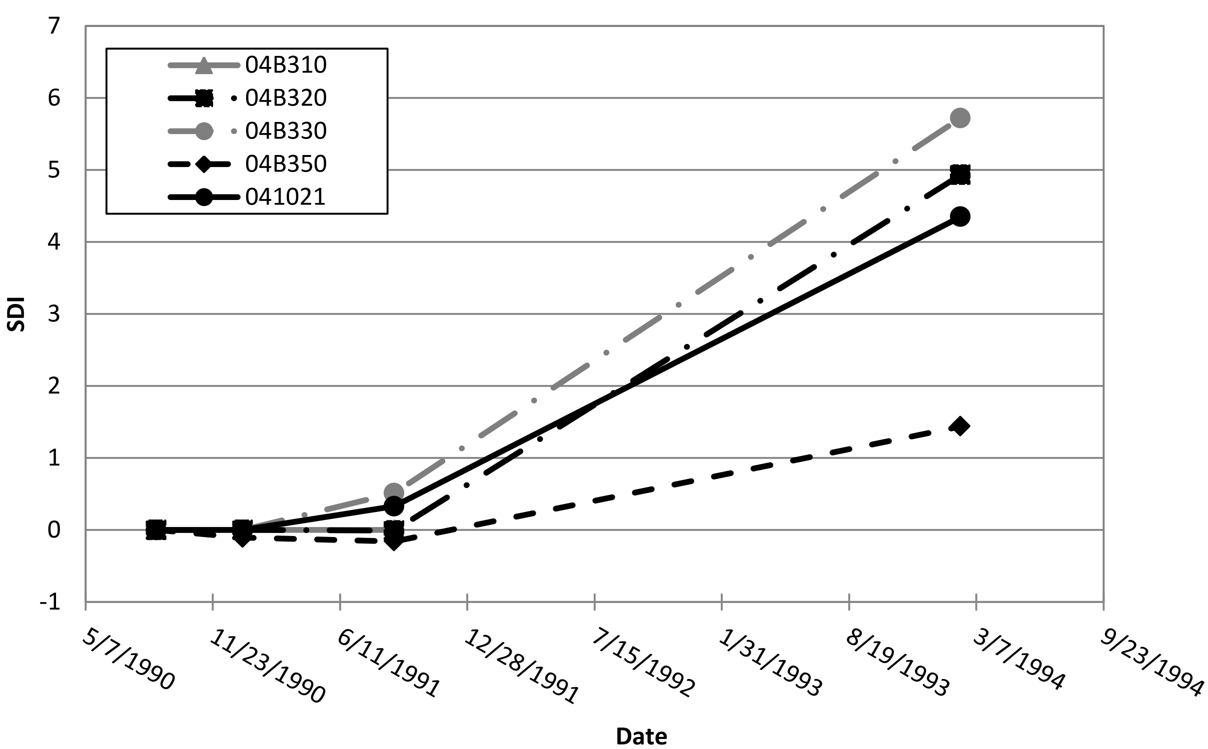

Figure 5. Structural Damage Index Trends for 04B300 Sections

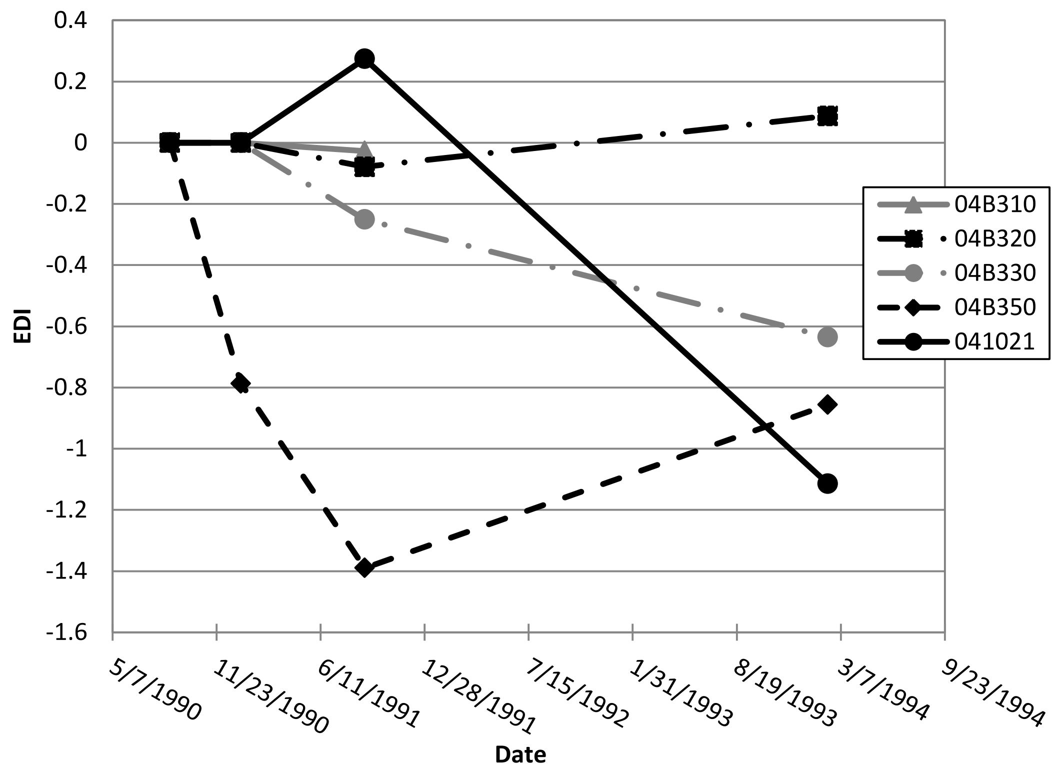

Figure 6. Environmental Damage Index Trends for 04B300 Sections

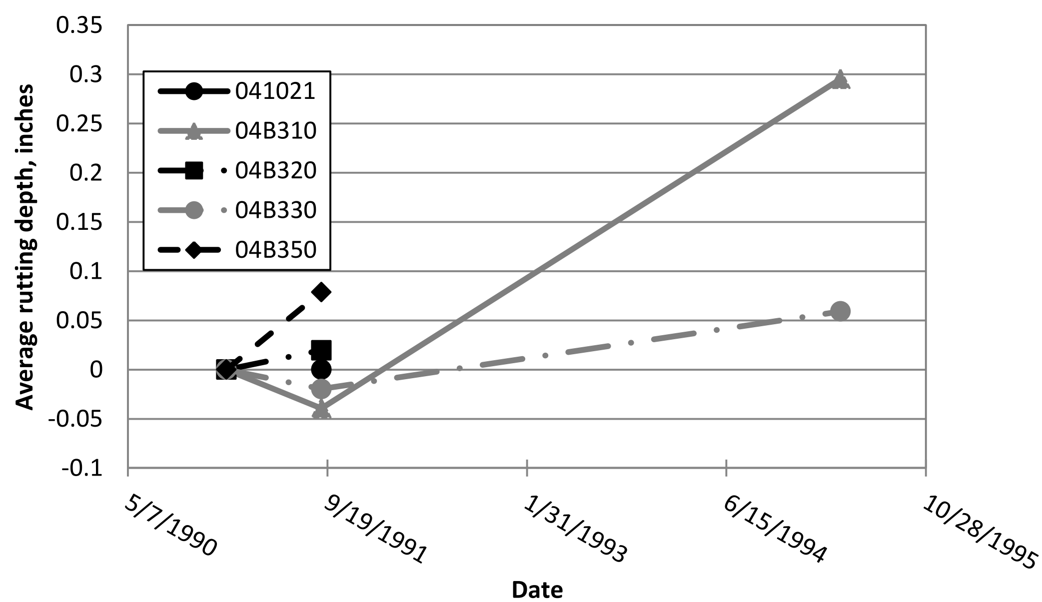

Figure 7. Rutting Trends for 04B300 Sections

It can be seen from Figure 5 that the thin overlay section did not exhibit any structural damage, but there were no distress measurements after 1991. Performance comparisons between this section and the other four are therefore based on the early measurements. The control section received pothole patching in 1991 and 1994, while the slurry seal and chip seal sections both received pothole patching in 1993. It is therefore important to note that the crack seal section, the worst performing of the five, was the only section to not receive pothole patching. From the three figures, it can be seen that environmental distress decreased over time for most sections, whereas structural distress and rutting both increased. At the B site, some environmental damage (i.e., longitudinal non-wheelpath cracking) was subsequently labeled as fatigue cracking as time and the distress progressed.

Table 9 shows the ranking of the 04B300 sections based on the trends in the above three plots. These comparisons are based on pre-1991 data so that all five treatment methods could be compared. (However, it should be noted that between 1991 and 1995, rutting increased drastically in the thin overlay section, whereas it increased much less in the crack seal section.) While some trends are scattered, generally the chip seal and thin overlay sections were performing better than the other options at one year after construction. The sealing effect of the chip seal over the open-graded friction course may have contributed to its good performance in the SDI and the EDI by inhibiting aging, but it may have contributed to its poor performance in rutting by trapping moisture.

Table 9. Performance Summary for 04B300 Sections

Ranking	SDI	EDI	Rutting
1 (Best performance)	Chip seal	Chip seal	Thin overlay[1]
2	Thin overlay[1]	Crack seal	Crack seal
3	Slurry seal	Slurry seal	Control
4	Control	Thin overlay[1]	Slurry seal
5 (Worst performance)	Crack seal	Control	Chip seal

[1] Data collection for the thin overlay section alone ended in 1991.

The 1992 site tour observations appeared to not follow the performance comparisons observed in the previous year. However, the 1992 observations are not quantifiable and do not consider the variability in the amount of distresses already in the sections prior to the placement of each preventive treatment. The site tour observed that the control section had less fatigue cracking than the thin overlay section, but the control section had slight rutting of under 0.5 inch and raveling characteristics in the friction course. The thin overlay was the most heavily distressed of all the sections. It showed considerable fatigue cracking reflected through the surface and also signs of pumping. The slurry seal was in better condition than the thin overlay. It had slight rutting and exhibited considerable fatigue cracking, but the cracks were very fine. The crack seal had pulled away from the edges by the time of the site tour. Finally, the chip seal had retained its chips surprisingly well, with some chip loss occurring between the travel and passing lanes. Fatigue cracking had reflected through the surface with a severity similar to that seen on the thin overlay section of the site. Significant bleeding on the outside edge of the outside wheelpath was also noted.

04C300 Sections

Figures 8 through 10 show the three plots of the trends in the SDI, the EDI, and the average rutting depth for the 04C300 control and test sections. It should be noted that at the 04C300 site, an additional control section, 04C340, was included. As mentioned previously, each of the four sites included as a control a General Pavement Study (GPS) section that was still in study. At the 04C300 site, the GPS control section (041017) is referred to as Control 1, while the additional control section (04C340) is referred to as Control 2.

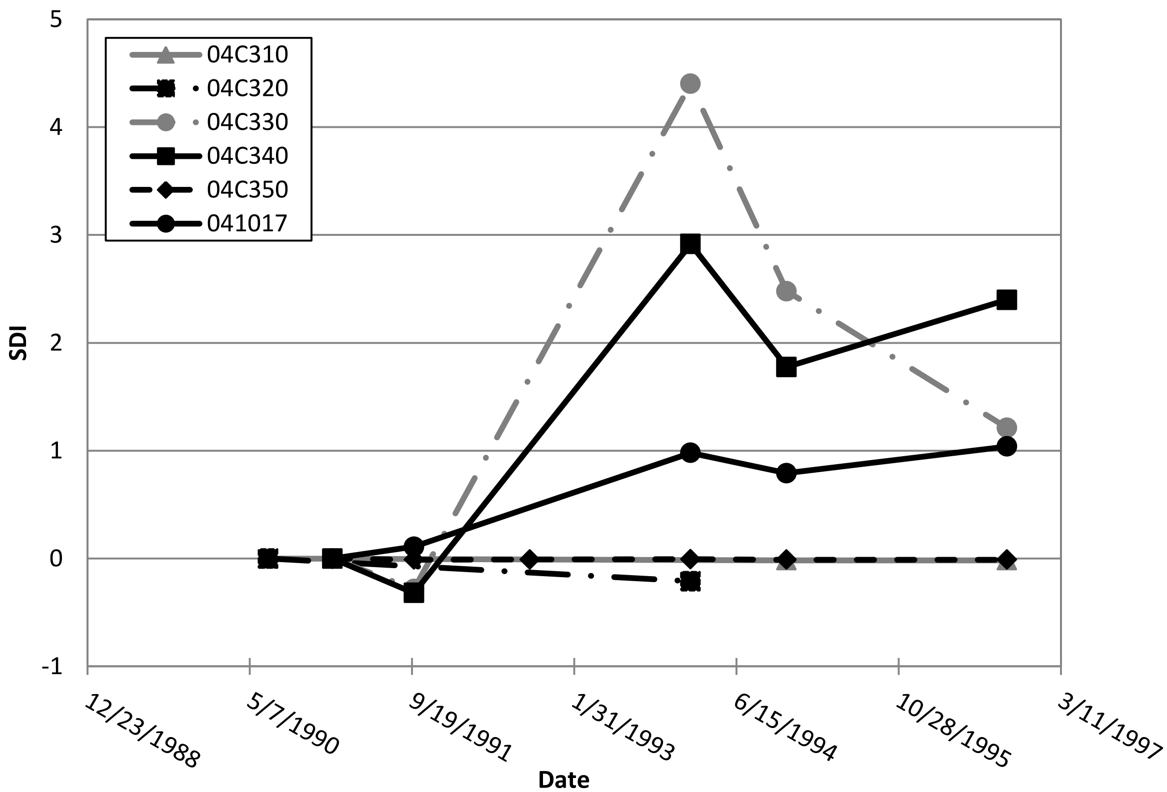

Figure 8. Structural Damage Index Trends for 04C300 Sections

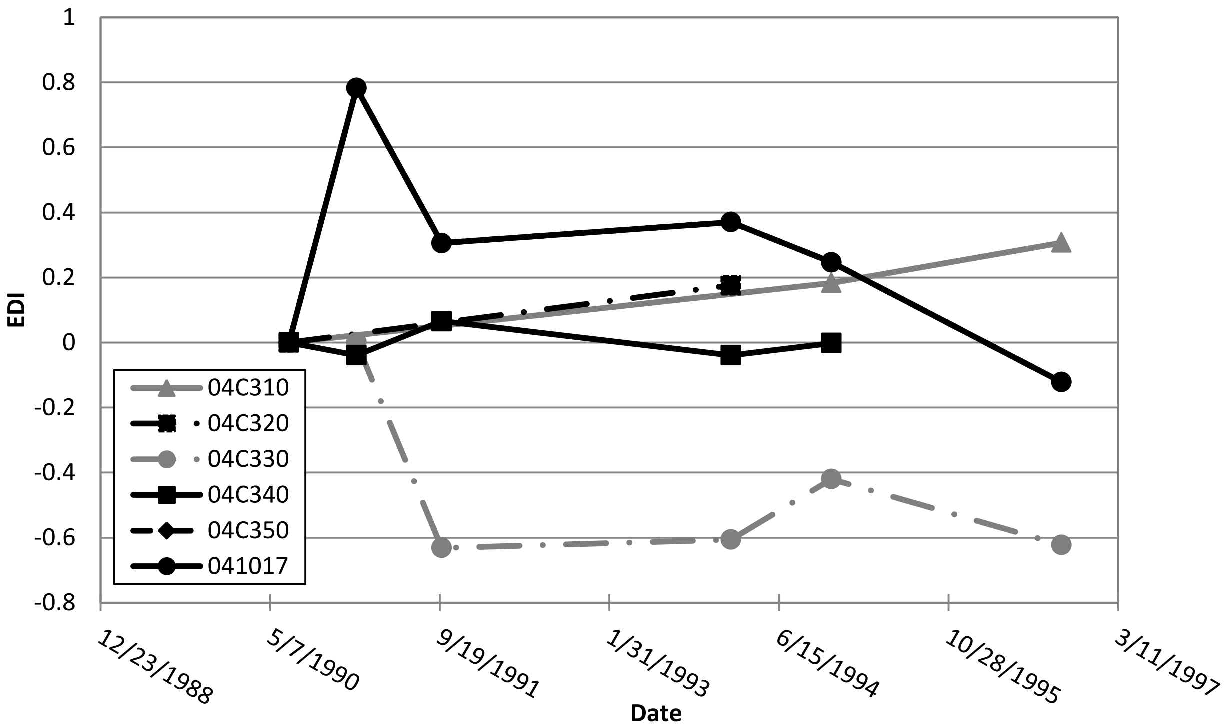

Figure 9. Environmental Damage Index Trends for 04C300 Sections

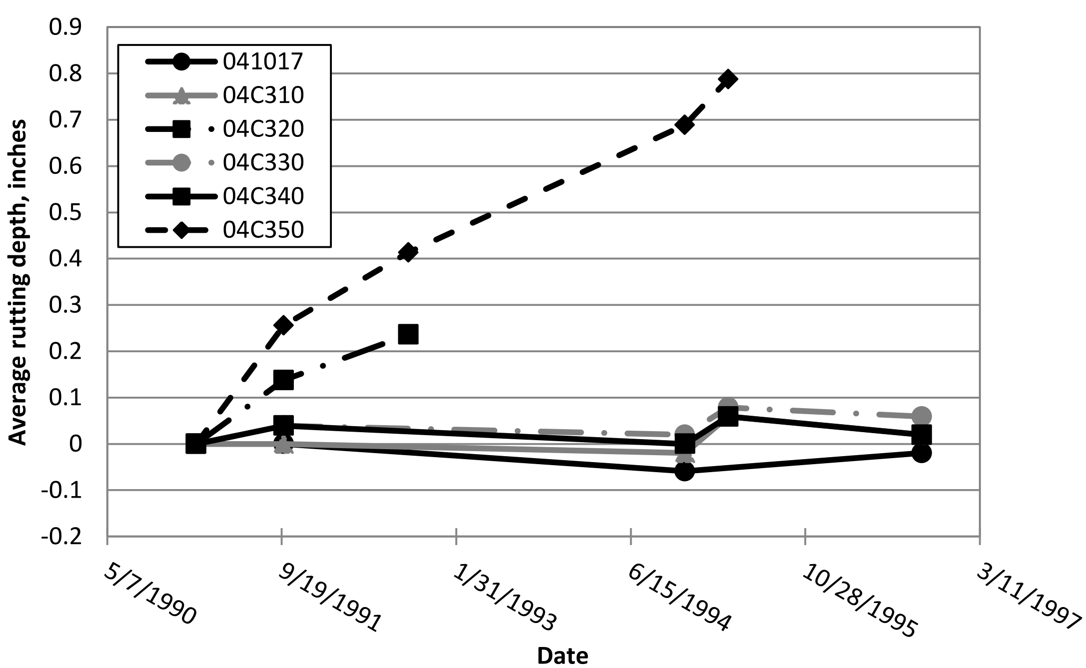

Figure 10. Rutting Trends for 04C300 Sections

The most unusual trend seen in Figures 8 to 10 is the improving performance of the crack seal treatment between 1994 and 1996. It was documented that the crack seal section received pothole patching in 1993; however, some preventive maintenance treatment also appears to have been applied at this time, since all the distress data (SDI, EDI, and rutting) for the crack seal section decrease from 1994 to 1996.

As Figure 8 shows, the crack seal section contained the highest level of structural damage for most of the observation period. A summary of all the trends appears in Table 10 below. Note that all sections except for the chip seal underwent pothole patching in 1993. The plot for average rutting depth reveals that the chip seal section exhibited by far the highest levels of rutting, followed by the slurry seal and crack seal sections. The thin overlay was the best performer, followed by the two controls.

Table 10. Performance Summary for 04C300 Sections

Ranking	SDI	EDI	Rutting
1 (Best performance)	Chip seal	Crack seal	Thin overlay
2	Slurry seal	Chip seal	Control 1 Control 2
3	Thin overlay	Control 2	Crack seal
4	Control 1 Control 2	Thin overlay	Slurry seal
5 (Worst performance)	Crack seal	Control 1	Chip seal

The site tour revealed that Control 1 exhibited raveling with minor rutting. The thin overlay was found to be the best-performing strategy on rutting at the 04C300 site, with only minimal rutting of approximately 0.12 inch to 0.25 inch. The slurry seal section showed rutting of between 0.75 and 1.5 inches. The crack sealant was in good condition, adhering to the edge of the routed area. The sealant was soft and pliable and did not exhibit incompressibles. The chip seal was observed to be badly rutted (2-3 inches) with extensive flushing in the wheelpaths.

04D300 Sections

Figures 11 through 13 show the three plots of the trends in the SDI, the EDI, and the average rutting depth for the 04D300 control and test sections.

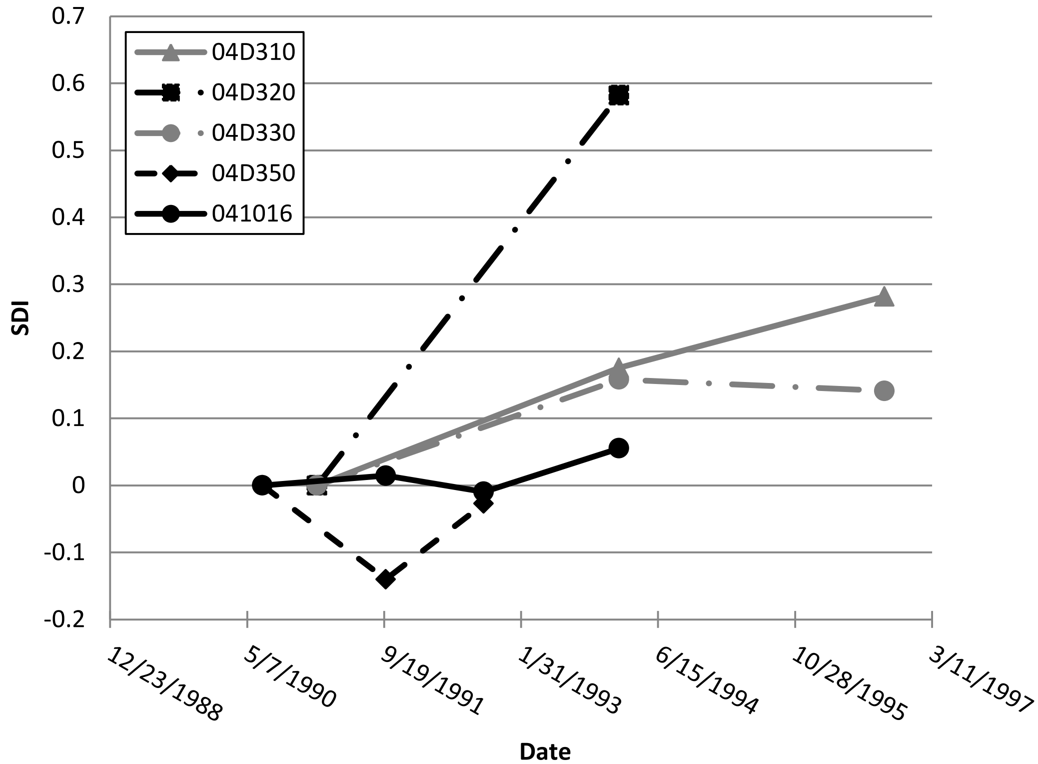

Figure 11. Structural Damage Index Trends for 04D300 Sections

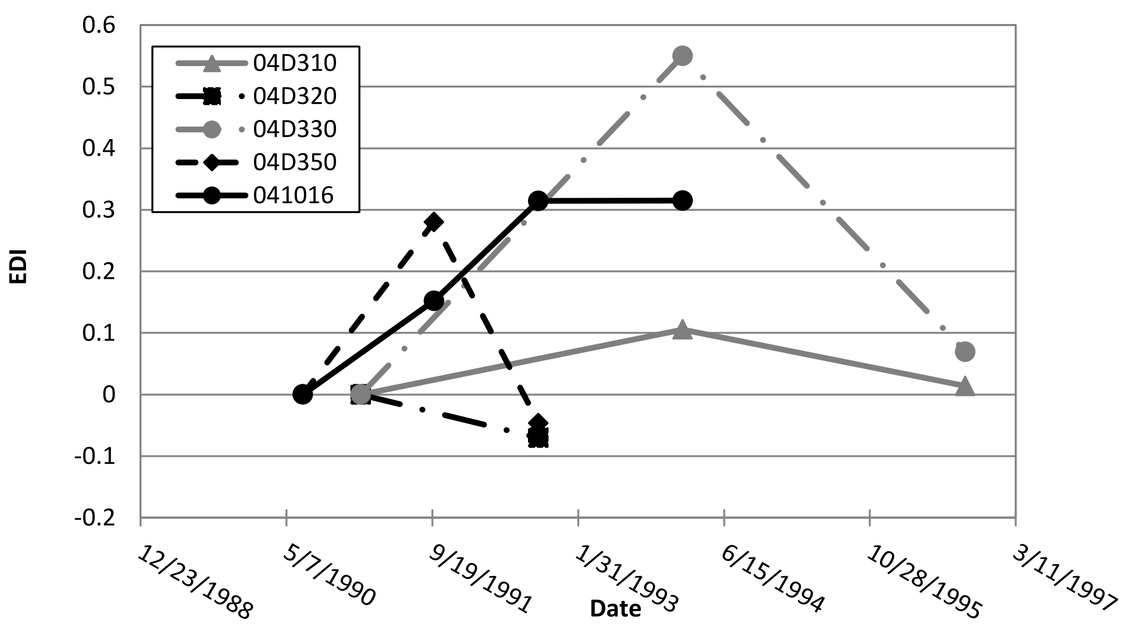

Figure 12. Environmental Damage Index Trends for 04D300 Sections

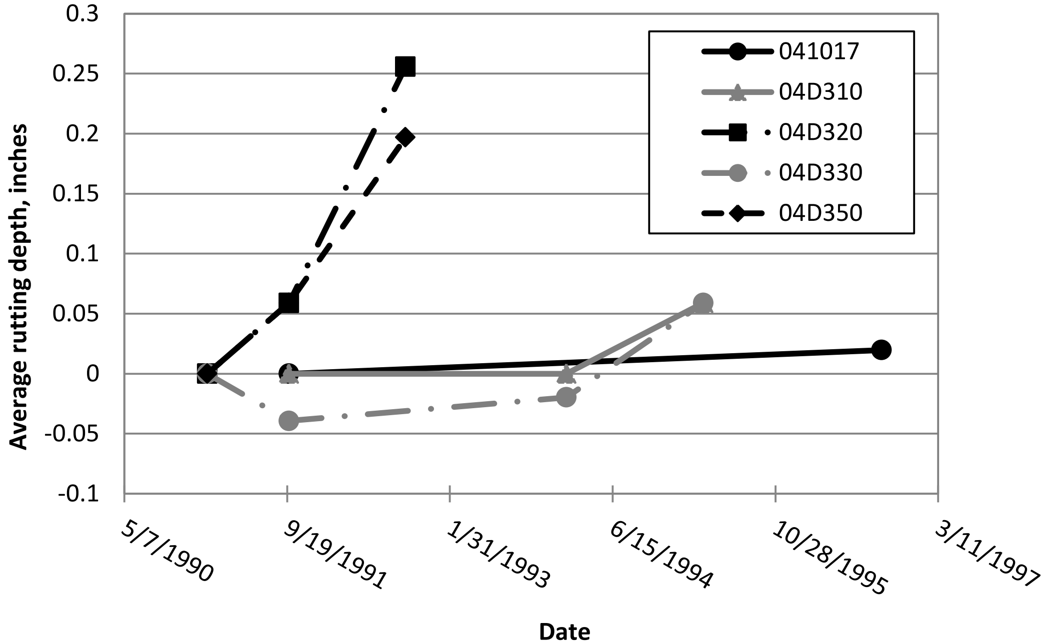

Figure 13. Rutting Trends for 04D300 Sections

The 04D300 sections furnished less time series data than the other three projects because fewer manual distress surveys were completed for them, and the data were extremely limited for the slurry seal and chip seal sections. However, several trends still emerged that are summarized in Table 11. It should be noted that the slurry seal section received pothole patching in 1993, while the crack seal section received additional crack sealing in 1995. While performance trends revealed by the three types of distress data are inconsistent, the slurry seal section appears to have been the worst performer of all the sections.

Table 11. Performance Summary for 04D300 Sections

Ranking	SDI	EDI	Rutting
1 (Best performance)	Chip seal	Slurry seal	Crack seal
2	Control	Thin overlay	Control
3	Crack seal	Chip seal	Thin overlay
4	Thin overlay	Control	Chip seal
5 (Worst performance)	Slurry seal	Crack seal	Slurry seal

The 1992 site tour observed fine fatigue cracking in the wheelpaths and raveling characteristics in the friction course of the control section. The thin overlay was the best-performing strategy of the project, with only minimal rutting of approximately 0.12 inch to 0.25 inch, and no reflective cracking. The slurry seal section showed deep rutting of 2 to 3 inches, and also flushing. The crack sealant was in good condition, adhering to the edge of the routed area. The sealant was soft and pliable and did not exhibit incompressibles. Finally, approximately 1 inch of rutting was observed throughout the chip seal. The wheelpaths were also noted to be bleeding.

SINGLE-POINT COMPARISONS

Additional comparisons were made using measurements from the SDI, EDI, and rutting data. A single point in time was selected for each of the four project sites based on the latest date at which data from all sections were available. However, the control sections, which were General Pavement Study (GPS) sections that were still in study, had all received significant maintenance improvements early in the lifetime of this project, which skewed comparisons between the control and the test sections. Therefore, the control sections were not included in the single-data-point comparisons, all of which occurred at a time following the control section maintenance activities. The single-point comparisons are presented below for each of the four sites.

04A300 Sections

The structural damage index (SDI), environmental damage index (EDI), and rutting measurements are shown in Figures 14 through 16, respectively.

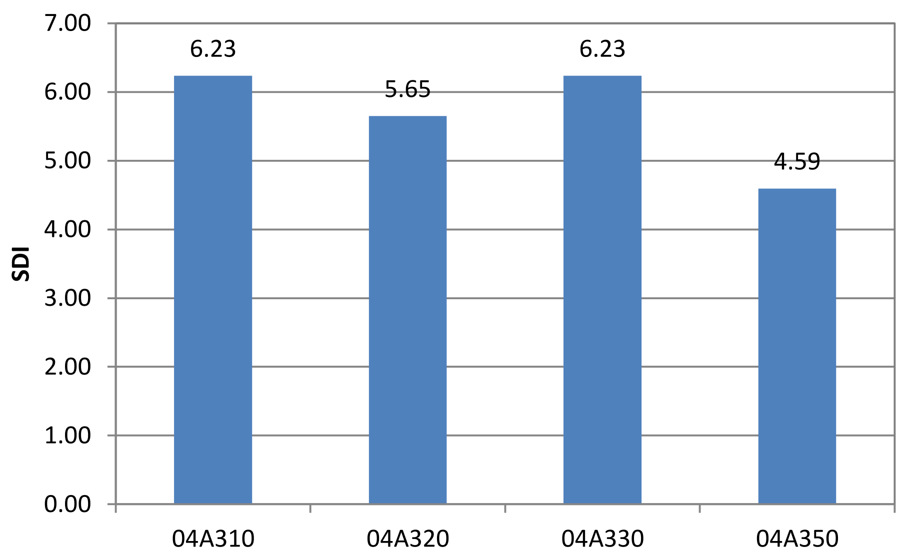

Figure 14. Structural Damage Index for 04A300 Sections

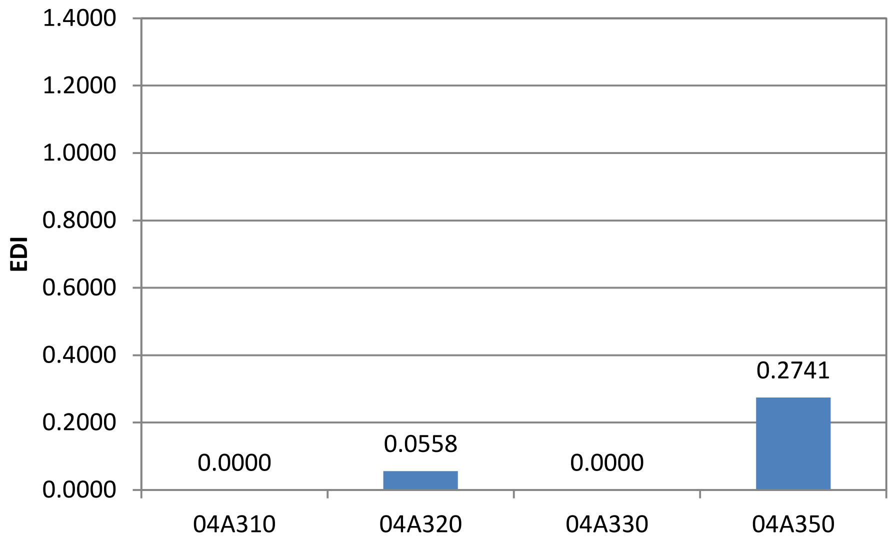

Figure 15. Environmental Damage Index for 04A300 Sections

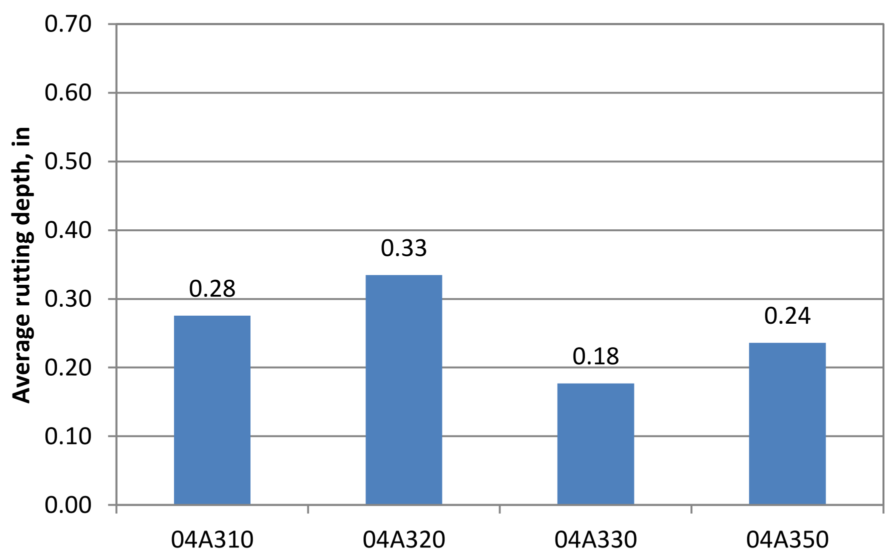

Figure 16. Average Rutting Depth for 04A300 Sections

January 1998, eight years following construction, was the final date at which data from all 04A300 sections were available. The ranking and comparison of performances from Figures 14 to 16 are shown in Table 12. It is difficult to draw immediate conclusions about treatment effectiveness from these three plots due to the inconsistencies between the three methods used to calculate effectiveness.

Table 12. Performance Summary of Single-Point Comparisons for 04A300 Sections

Ranking	SDI	EDI	Rutting
1 (Best performance)	Chip seal	Crack seal Thin overlay	Crack seal
2	Slurry seal	Slurry seal	Chip seal
3	Crack seal Thin overlay	Chip seal	Thin overlay
4 (Worst performance)			Slurry seal

04B300 Sections

For the 04B300 sections, the SDI, EDI, and rutting data were split into two analysis groups. The first group consists of data from 1991, the latest time point with distress values for all the test sections. However, 1991 was only one year after construction. The second analysis group consists of data from February 1994, when distress values were available for all test sections except the thin overlay. This second data set, when combined with the first set, provides a better overall time series perspective of distresses. Comparisons based on the 1991 data alone are shown in Figures 17 to 19 and Table 13. Comparisons based on the combined data sets (with thin overlay data excluded) are shown in Figures 20 and 21 and Table 14.

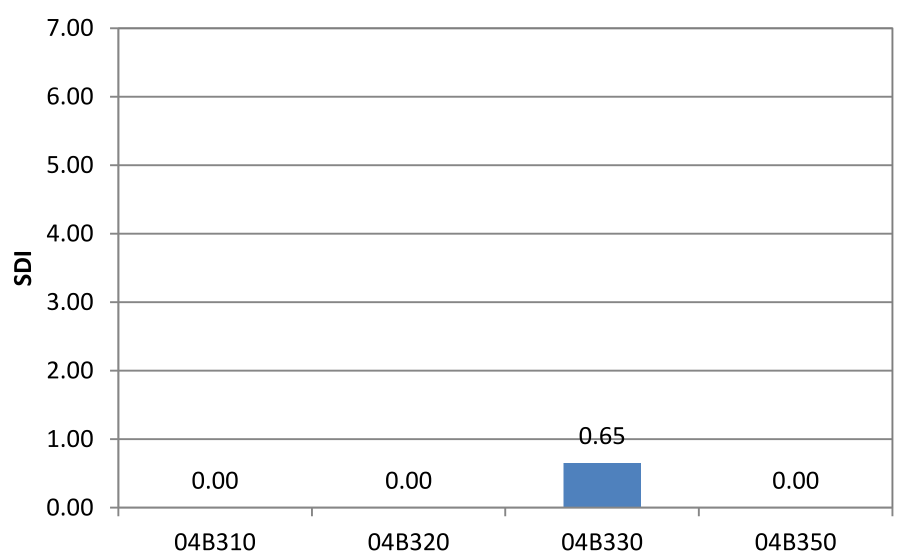

Figure 17. Structural Damage Index for 04B300 Sections

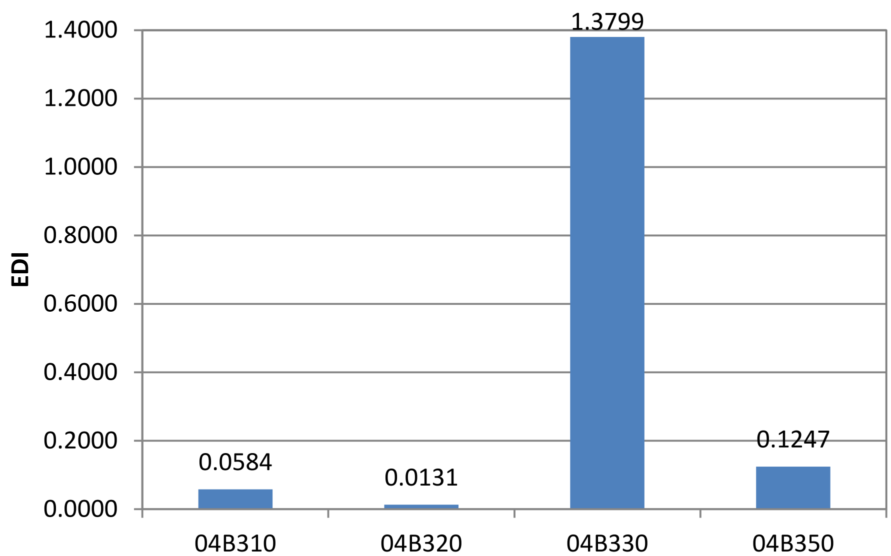

Figure 18. Environmental Damage Index for 04B300 Sections

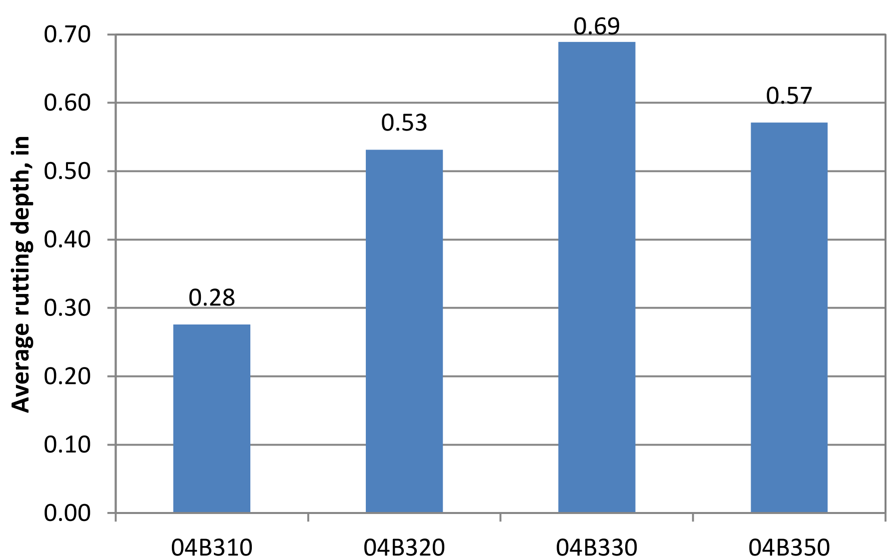

Figure 19. Average Rutting Depth for 04B300 Sections

Table 13. Performance Summary of Single-Point Comparisons for 04B300 Sections

Ranking	SDI	EDI	Rutting
1 (Best performance)	Chip seal Thin overlay Slurry seal	Slurry seal	Thin overlay
2	Crack seal	Thin overlay	Chip seal
3		Chip seal	Slurry seal
4 (Worst performance)		Crack seal	Crack seal

The data reveal clearer trends for the 04B300 sections than were seen for the 04A300 sections. It appears from the 1991 data that the crack seal consistently performed the worst (with higher damage indices and rutting values) of the four treatments, followed by the slurry seal and chip seal (which performed comparably) and finally by the thin overlay treatment, which appeared to perform best across all three measures.

Rutting measurements were not included in Figure 20, Figure 21, and Table 14 since the rutting data was incomplete at these later dates for comparison.

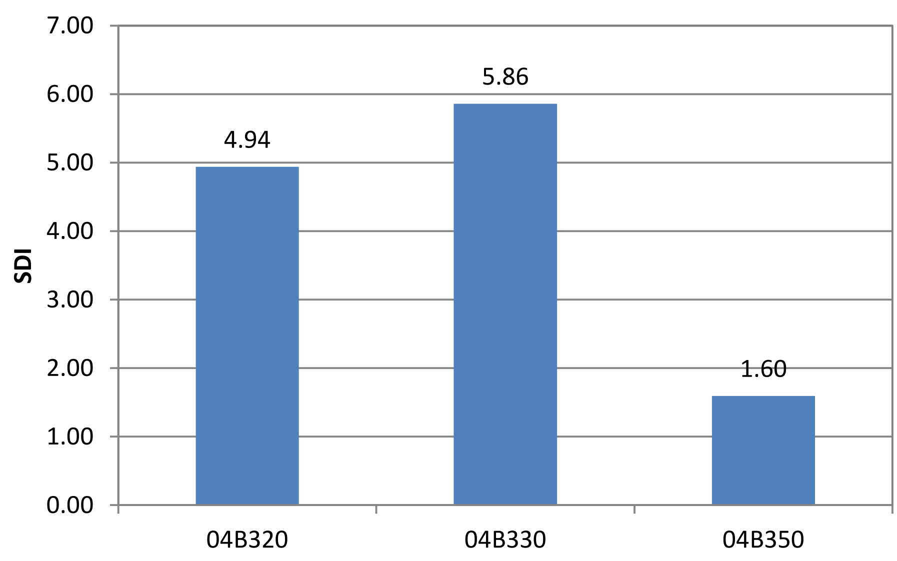

Figure 20. Structural Damage Index for 04B300 Sections

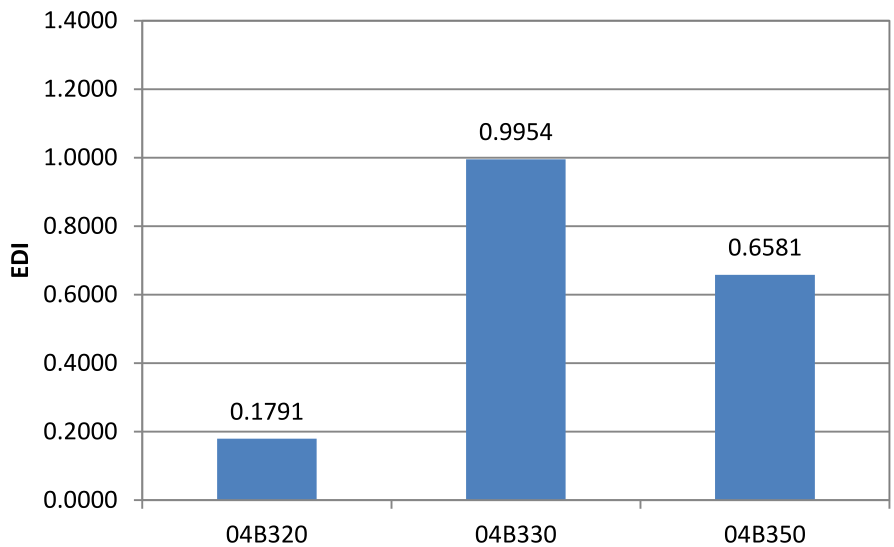

Figure 21. Environmental Damage Index for 04B300 Sections

Table 14. Performance Summary of Single-Point Comparisons for 04B300 Sections

Ranking	SDI	EDI
1 (Best performance)	Chip seal	Slurry seal
2	Slurry seal	Chip seal
3 (Worst performance)	Crack seal	Crack seal

The second 04B300 data set, with data from 1994, shows that after three years, the crack seal exhibited the worst structural and environmental distress. The slurry seal exhibited the second-worst structural distress followed by the chip seal, while the ranking of these two was reversed for environmental distress.

04C300 Sections

For project site 04C300, the SDI, EDI, and rutting measurements are shown in Figures 22 to 24.

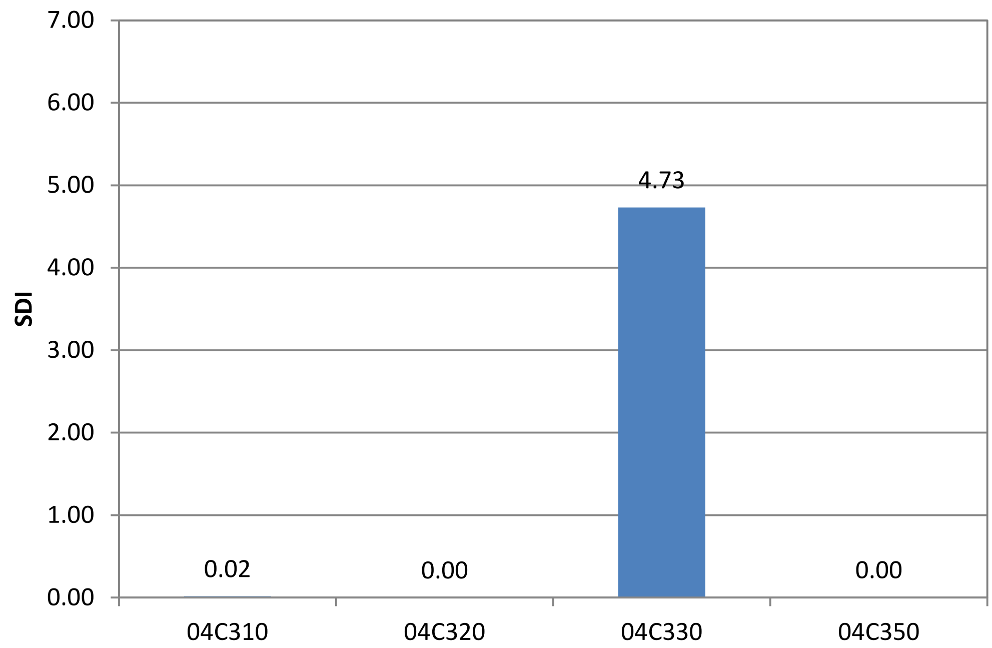

Figure 22. Structural Damage Index for 04C300 Sections

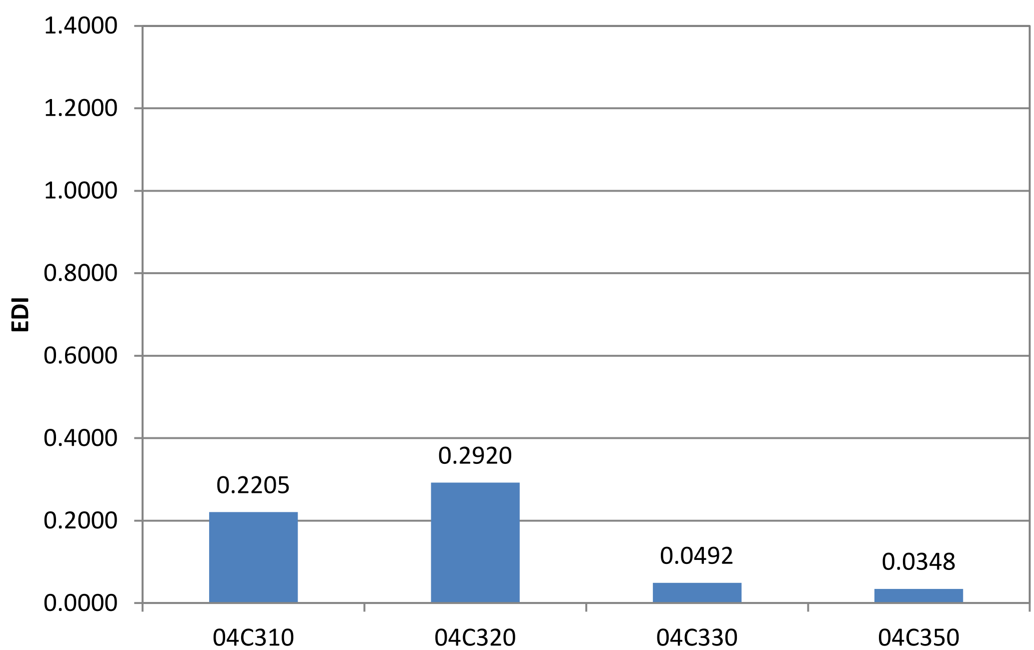

Figure 23. Environmental Damage Index for 04C300 Sections

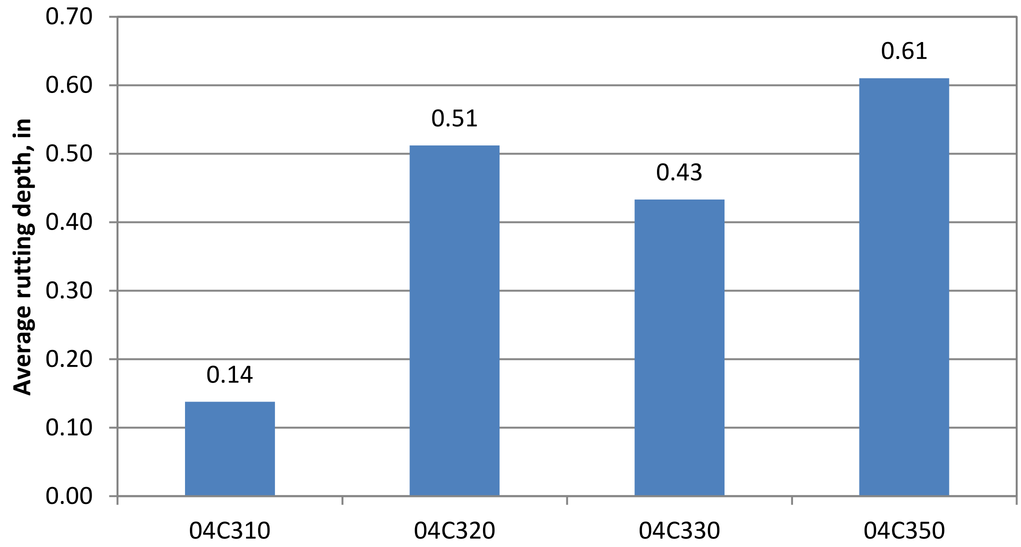

Figure 24. Average Rutting Depth for 04C300 Sections

The data set used for the 04C300 site was from January 1994. Like the 04B300 data, the 04C300 data reveal clearer trends than were seen with the 04A300 data. As of January 1994, the crack seal section exhibited the most structural distress, followed by the two control sections. The slurry seal section exhibited the most environmental distress, followed by the thin overlay, then the crack seal and then the chip seal. The chip seal section exhibited the most rutting, followed by the slurry seal, crack seal, and overlay sections. As indicated by Table 15, the crack seal consistently performed the worst, with the highest damage indices and the worst rutting, followed by the chip seal and then the slurry seal. Finally, the thin overlay section again consistently performed the best across the three methods of evaluation.

Table 15. Performance Summary of Single-Point Comparisons for 04C300 Sections

Ranking	SDI	EDI	Rutting
1 (Best performance)	Chip seal Slurry seal	Chip seal	Thin overlay
2	Thin overlay	Crack seal	Crack seal
3	Crack seal	Thin overlay	Slurry seal
4 (Worst performance)		Slurry seal	Chip seal

04D300 Sections

The SDI, EDI, and rutting measurements for project site 04D300 are shown in Figures 25 to 27.

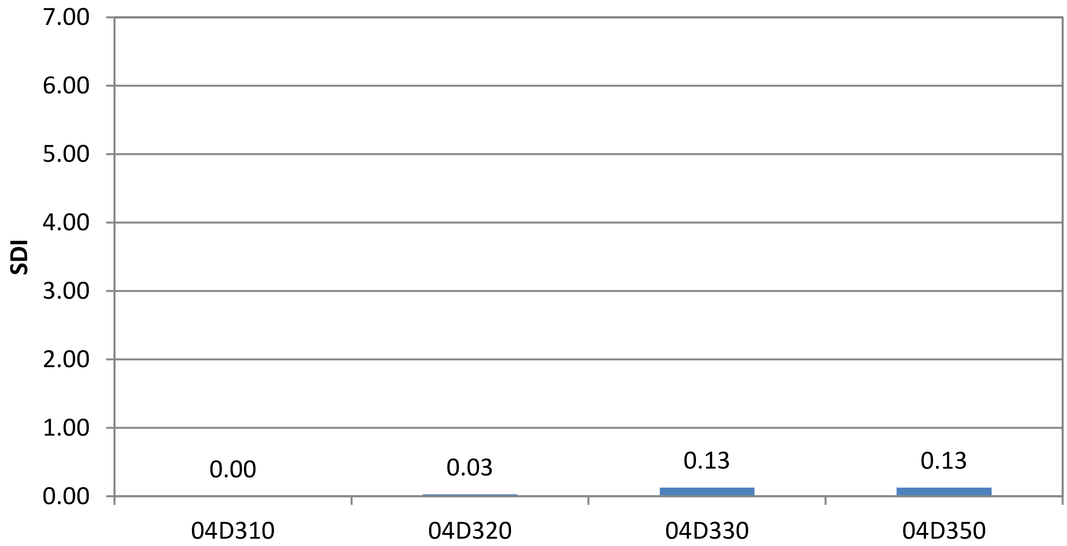

Figure 25. Structural Damage Index for 04D300 Sections

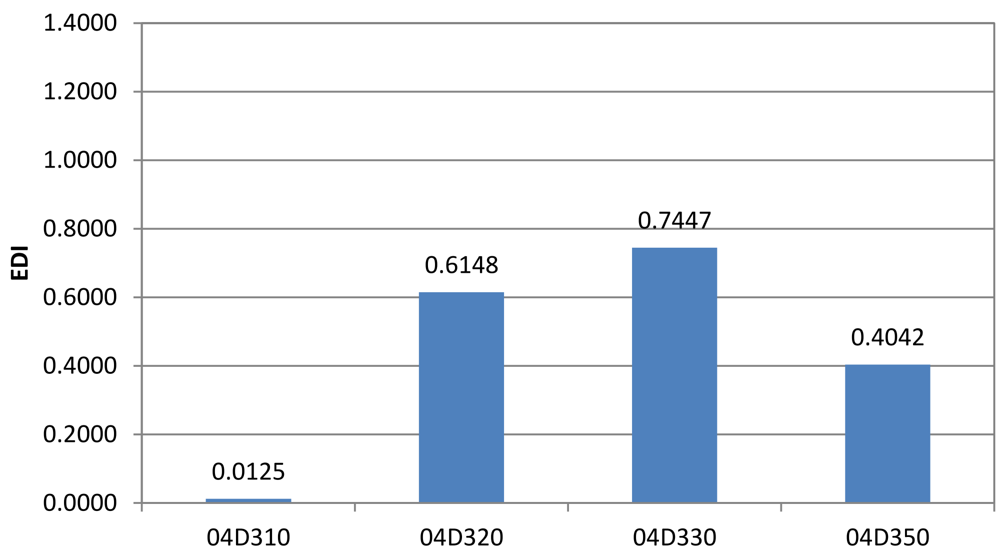

Figure 26. Environmental Damage Index for 04D300 Sections

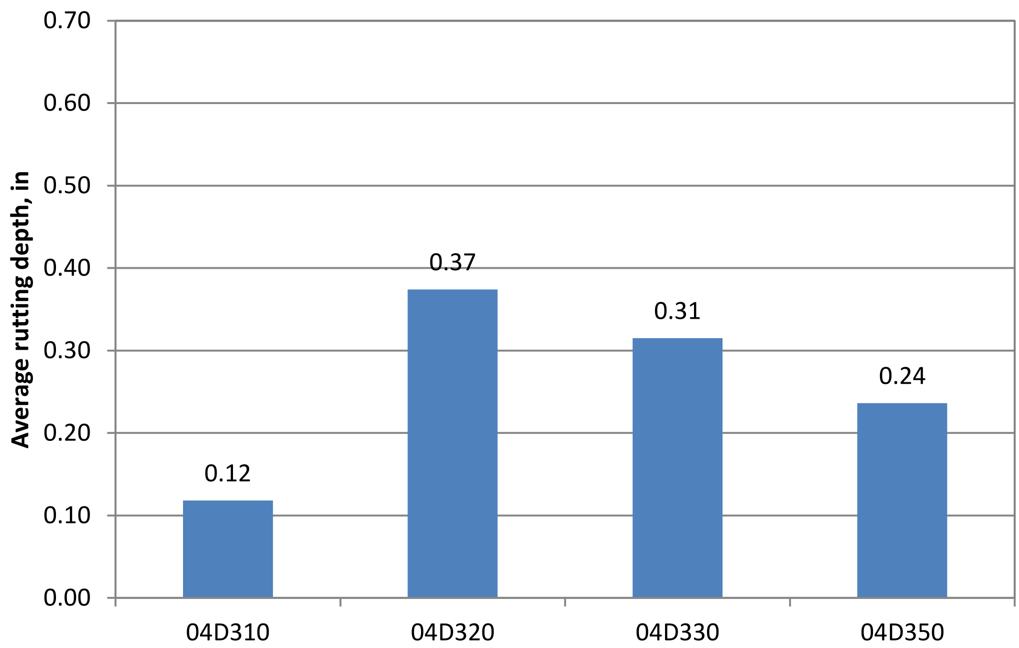

Figure 27. Average Rutting Depth for 04D300 Sections

The data set used for the 04D300 sections was from January 1992 (only limited data were collected from this project site). Results from the three plots are summarized in Table 16 below. Once again, the data reveal clear trends. The crack seal appeared to have the worst performance, followed by the slurry seal and then the chip seal, with the thin overlay performing the best across the three methods of measurement.

Table 16. Performance Summary of Single-Point Comparisons for 04D300 Sections

Ranking	SDI	EDI	Rutting
1 (Best performance)	Thin overlay	Thin overlay	Thin overlay
2	Slurry seal	Chip seal	Chip seal
3	Crack seal Chip seal	Slurry seal	Crack seal
4 (Worst performance)		Crack seal	Slurry seal

LIFE EXTENSION

Another method of comparing the calculated values was to use the plots of SDI, EDI, and rutting as a function of time and fit a trend line to the data points following treatment. This trend line was then used to extrapolate the number of years that would be required until the original amounts of distress (as revealed by the distress survey immediately preceding treatment) would occur. The plots of these durations are shown for each of the four project sites in the figures below. Because many of the trend lines were based on limited data, extrapolating beyond the scope of the lines might provide values that are seemingly unreasonable. However, the importance of this methodology comes from the comparison it allows between the performance measures rather than from the absolute values it provides. It should be noted that if the pavement distresses did not improve between the preconstruction survey and construction of the test section, the resulting value of the life extension would be negative. This will be discussed in further detail following the discussion of the plots. Additionally, the control sections were again not included in this analysis due to the early maintenance activities that were performed on them, which would skew this type of measurement; specifically, each had received either a sand seal or a pothole patching that improved its condition.

04A300 Sections

Figures 28 to 30 show the life extension results for project site 04A300 derived from the structural damage index, environmental damage index, and rutting measurements.

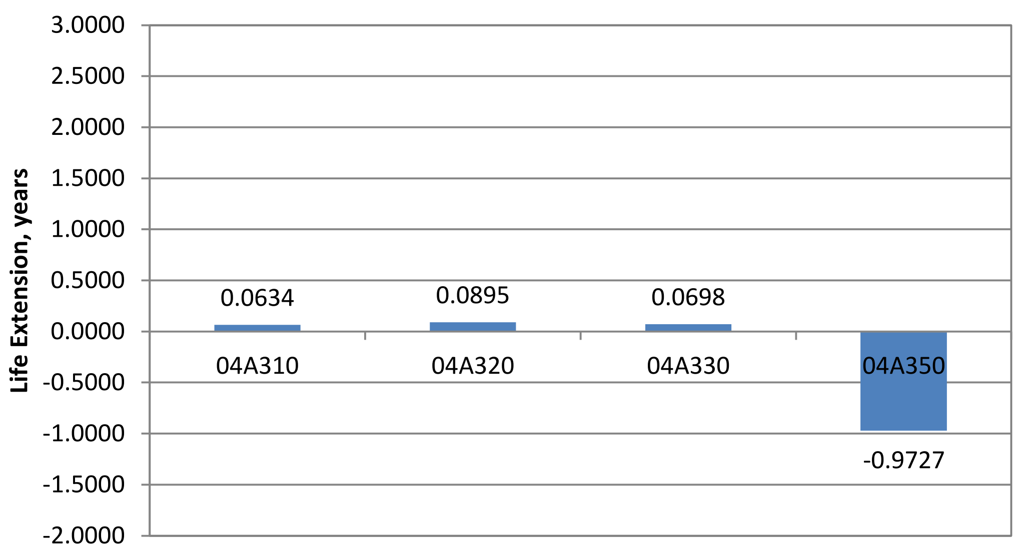

Figure 28. Life Extension Based on Structural Damage Index for 04A300 Sections

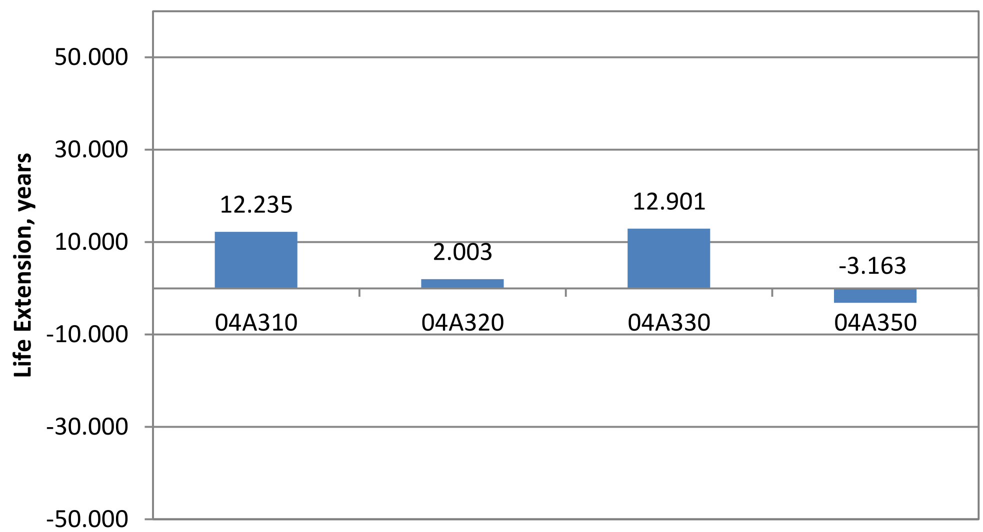

Figure 29. Life Extension Based on Environmental Damage Index for 04A300 Sections

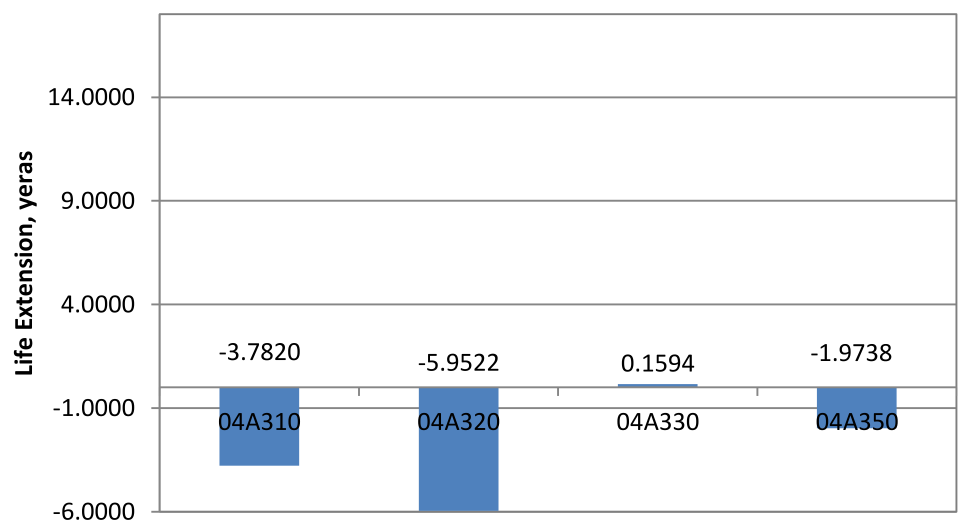

Figure 30. Life Extension Based on Rutting Measurements for 04A300 Sections

Table 17 summarizes the performance rankings from the figures above. The results appear to be quite inconsistent. The crack seal produced the longest life extension of the preventive maintenance treatments, and the chip seal performed the worst. This is logical because most of the chip seal wore away soon after it was placed.

Table 17. Life Extension Comparison of 04A300 Sections

Ranking	SDI	EDI	Rutting
1 (Longest life extension)	Slurry seal	Crack seal	Crack seal
2	Crack seal	Thin overlay	Chip seal
3	Thin overlay	Slurry seal	Thin overlay
4 (Shortest life extension)	Chip seal	Chip seal	Slurry seal

04B300 Sections

Figures 31 to 33 show the life extension results for project site 04B300 derived from the structural damage index, environmental damage index, and rutting measurements.

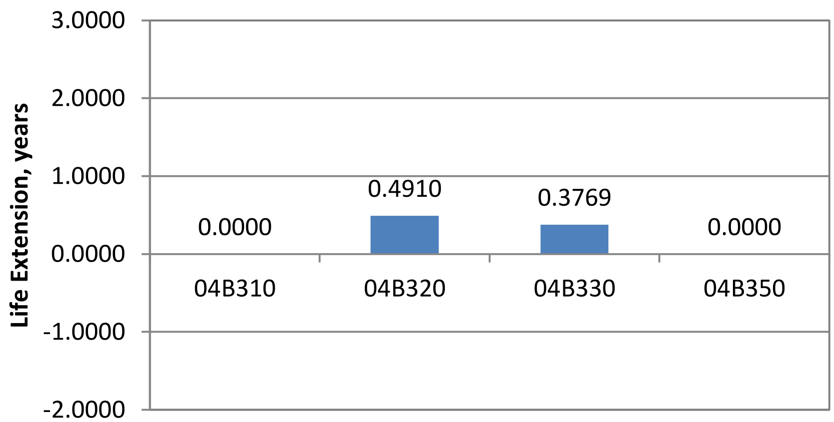

Figure 31. Life Extension Based on Structural Damage Index for 04B300 Sections

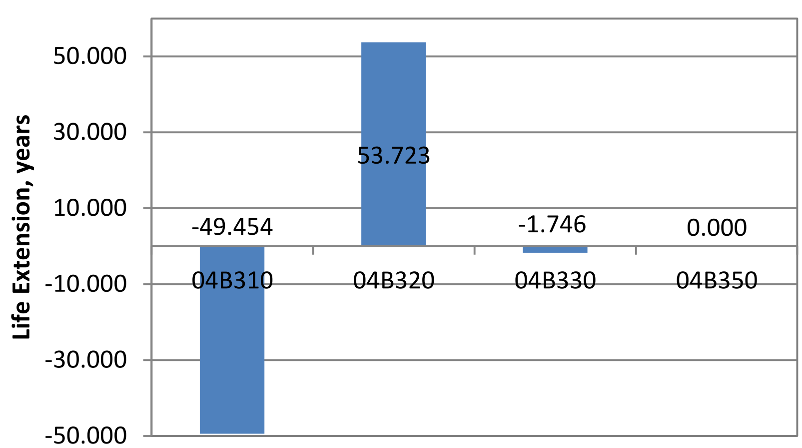

Figure 32. Life Extension Based on Environmental Damage Index for 04B300 Sections

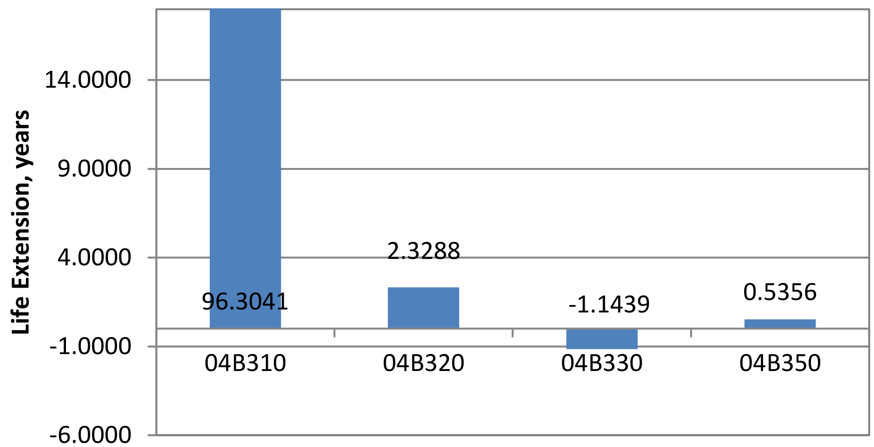

Figure 33. Life Extension Based on Rutting for 04B300 Sections

Table 18 summarizes the performance rankings of the sections. Some consistencies are found in these data, namely the consistently high performance of the slurry seal treatment.

Table 18. Life Extension Comparison of 04B300 Sections

Ranking	SDI	EDI	Rutting
1 (Longest life extension)	Slurry seal	Slurry seal	Thin overlay
2	Crack seal	Chip seal	Slurry seal
3	Thin overlay Chip seal	Crack seal	Chip seal
4 (Shortest life extension)		Thin overlay	Crack seal

04C300 Sections

Figures 34 to 36 show the life extension results for project site 04C300 derived from the structural damage index, environmental damage index, and rutting measurements.

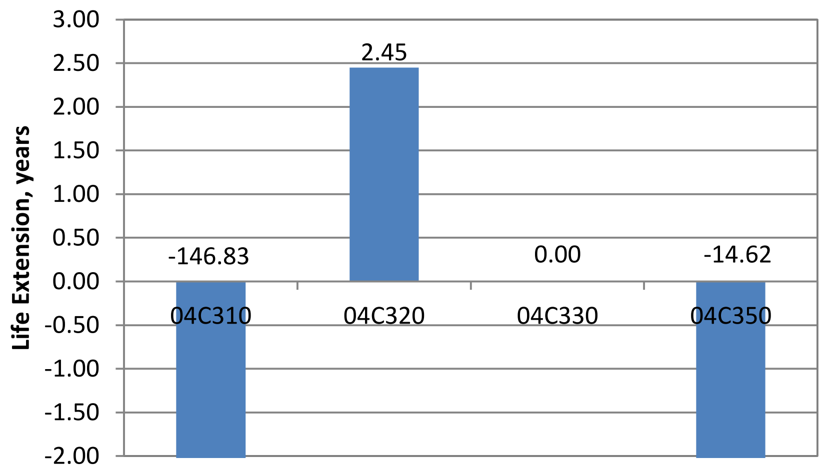

Figure 34. Life Extension Based on Structural Damage Index for 04C300 Sections

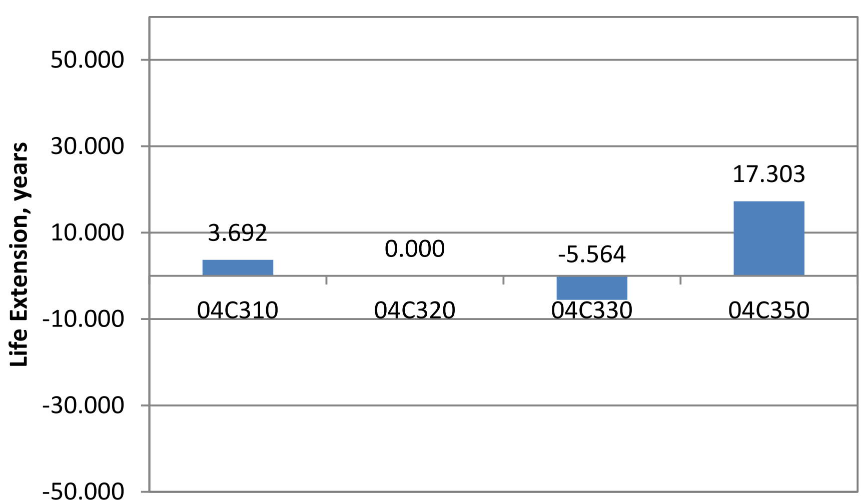

Figure 35. Life Extension Based on Environmental Damage Index for 04C300 Sections

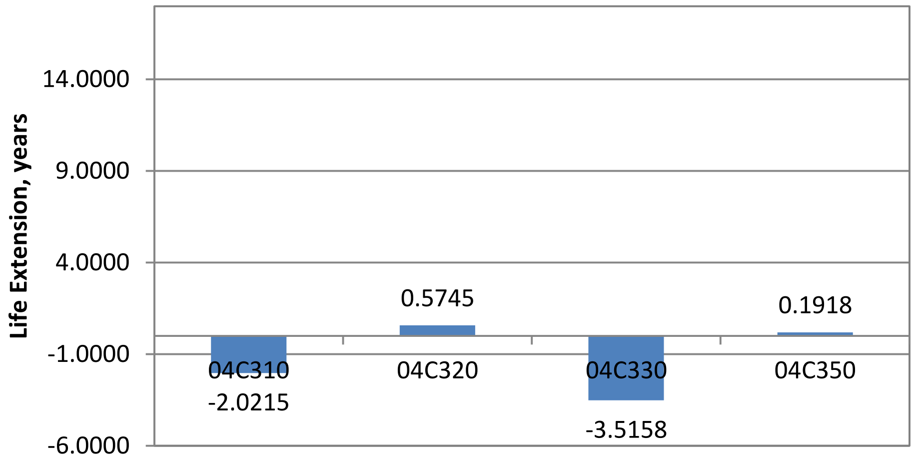

Figure 36. Life Extension Based on Rutting for 04C300 Sections

Table 19 summarizes the performance of the 04C300 sections. It can be seen that drawing conclusions between the three measurement methods is difficult; however, the crack seal generally exhibited the worst performance.

Table 19. Life Extension Comparison of 04C300 Sections

Ranking	SDI	EDI	Rutting
1 (Longest life extension)	Slurry seal	Chip seal	Slurry seal
2	Crack seal	Thin overlay	Chip seal
3	Chip seal	Slurry seal	Thin overlay
4 (Shortest life extension)	Thin overlay	Crack seal	Crack seal

04D300 Sections

Figures 37 to 39 show the life extension results for project site 04D300 derived from the structural damage index, environmental damage index, and rutting measurements.

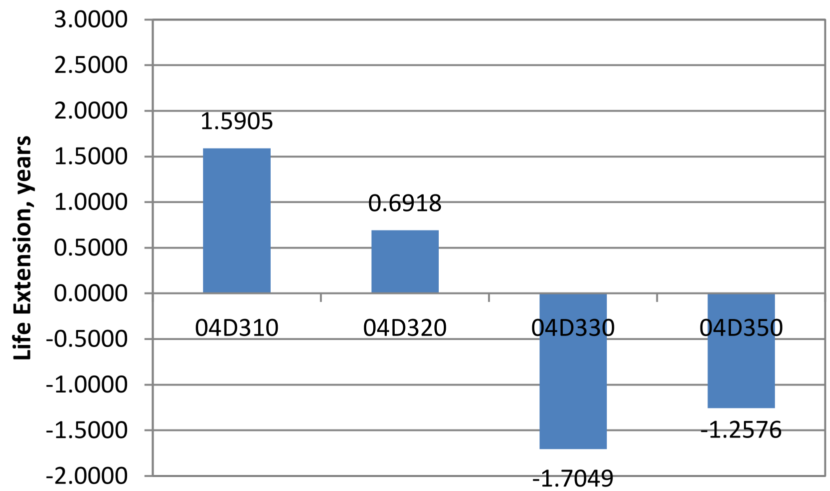

Figure 37. Life Extension Based on Structural Damage Index for 04D300 Sections

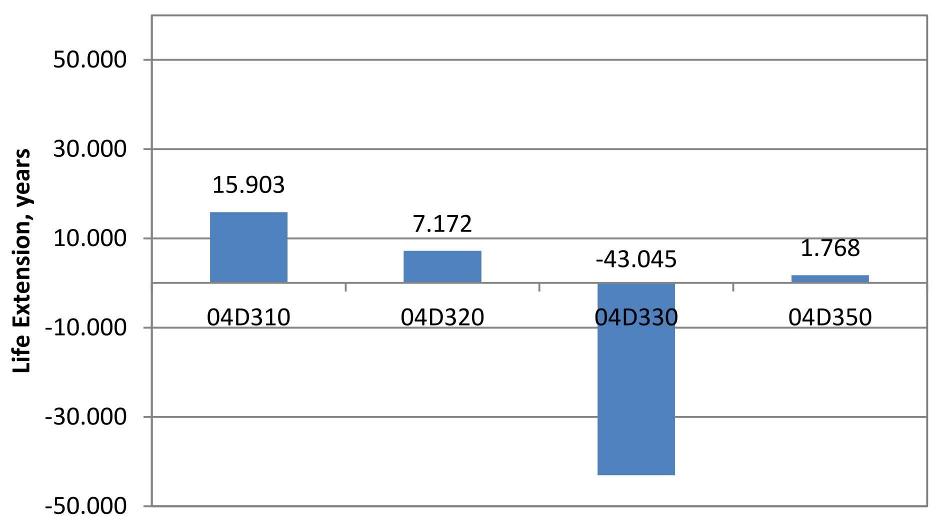

Figure 38. Life Extension Based on Environmental Damage Index for 04D300 Sections

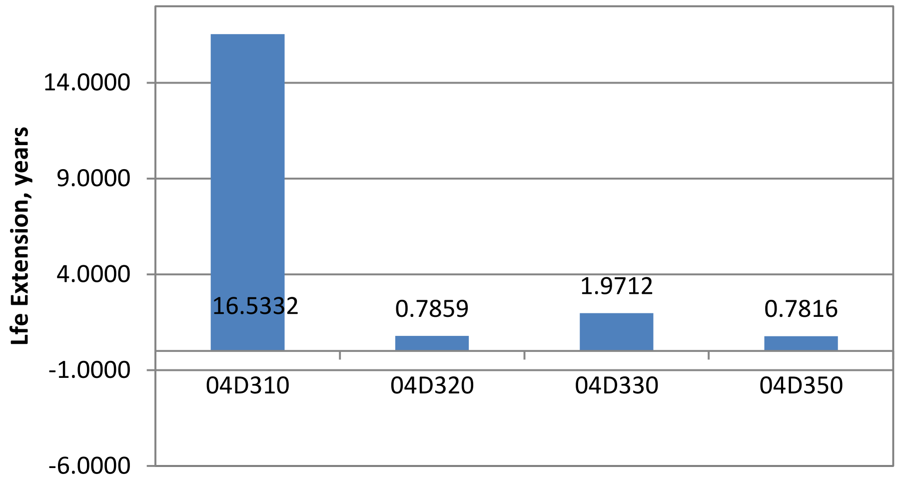

Figure 39. Life Extension Based on Rutting for 04D300 Sections

The plots from the 04D300 sections are summarized in Table 20. It can be seen that the trends are very consistent. Across all three measures, the thin overlay provided the longest life extension. Generally, the slurry seal contributed the second-longest life extension, followed by the chip seal. Finally, the crack seal section exhibited the shortest life extension of the 04D300 test sections.

Table 20. Life Extension Comparison of 04D300 Sections

Ranking	SDI	EDI	Rutting
1 (Longest life extension)	Thin overlay	Thin overlay	Thin overlay
2	Slurry seal	Slurry seal	Crack seal
3	Chip seal	Chip seal	Slurry seal
4 (Shortest life extension)	Crack seal	Crack seal	Chip seal

To better evaluate comparisons across sections, the three life extension values calculated from the three measures (structural damage index, environmental damage index, and rutting) for each section were averaged to create a single plot for each section. These plots are shown by site in the left column of

Figure 40 below. Then, all negative values were converted to zero, indicating that a "negative life extension" was meaningless and zero should be adopted as the absolute minimum for life extension calculations. With all negative values replaced by zero, the average of the three life extension values was recalculated. The recalculated plots are shown in the right column of

Figure 40.

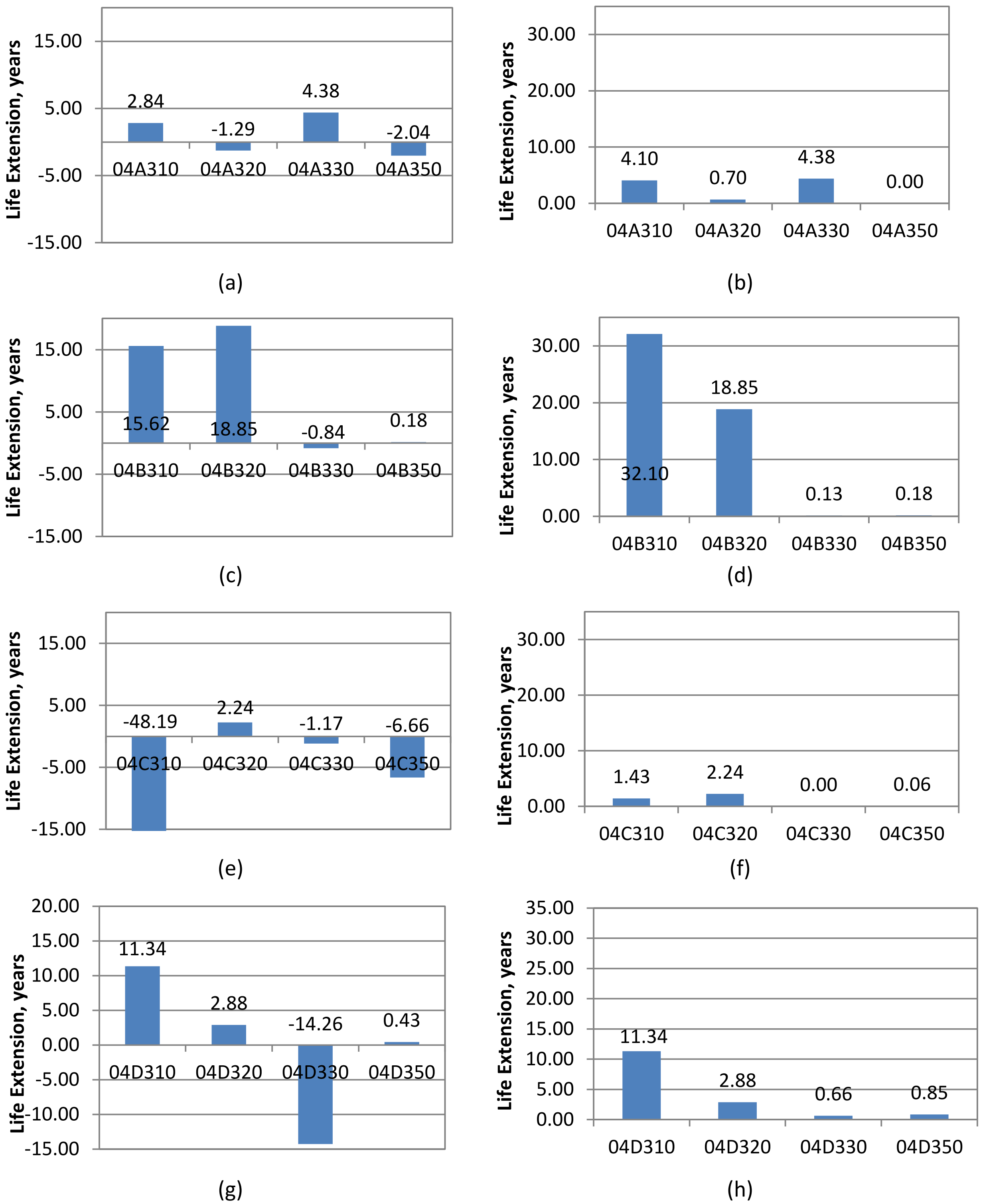

Figure 40. Average Life Extension for the Project Sections, With Negative Values Included (Plots a, c, e, g) and Excluded (Plots b, d, f, h)

The data from these plots are summarized in Table 21.

Table 21. Life Extension Comparison of All Sections

Project Site	Ranking	Average	
		Including Negative Values	**Excluding Negative Values**
04A300	1	Crack seal	Crack seal
	2	Thin overlay	Thin overlay
	3	Slurry seal	Slurry seal
	4	Chip seal	Chip seal
04B300	1	Slurry seal	Thin overlay
	2	Thin overlay	Slurry seal
	3	Chip seal	Chip seal
	4	Crack seal	Crack seal
04C300	1	Slurry seal	Slurry seal
	2	Crack seal	Thin overlay
	3	Chip seal	Chip seal
	4	Thin overlay	Crack seal
04D300	1	Thin overlay	Thin overlay
	2	Slurry seal	Slurry seal
	3	Chip seal	Chip seal
	4	Crack seal	Crack seal

Comparisons across sections can be made more easily from these plots, especially the plots with the negative life extension values omitted, shown on the right side of Figure 40. In general, the thin overlay increases section life extension the most, followed by the slurry seal, followed by the chip seal and then by the crack seal.

TREATMENT EFFECTIVENESS

Another way to compare the performance of the pavement treatments was to look at the effectiveness of the treatments. This involved normalizing the values used in the time series for each section to the initial distress value (before treatment). Treatment effectiveness was calculated for each section by taking the difference between the value at the latest date for which data were available (when a complete data set was present for each section) and the value from the distress survey taken immediately before the preventive maintenance treatment. Effectiveness in improving the SDI, EDI, and rutting measurements was calculated for each of the treatment sections. The treatment effectiveness subtracts the post-treatment distress from the initial amount of distress and normalizes it to this initial amount. Therefore, a negative percentage indicates a treatment that resulted in less distress than seen before treatment.

04A300 Sections

Figures 41 to 43 show the plots for treatment effectiveness with respect to SDI, EDI, and rutting for the 04A300 sections.

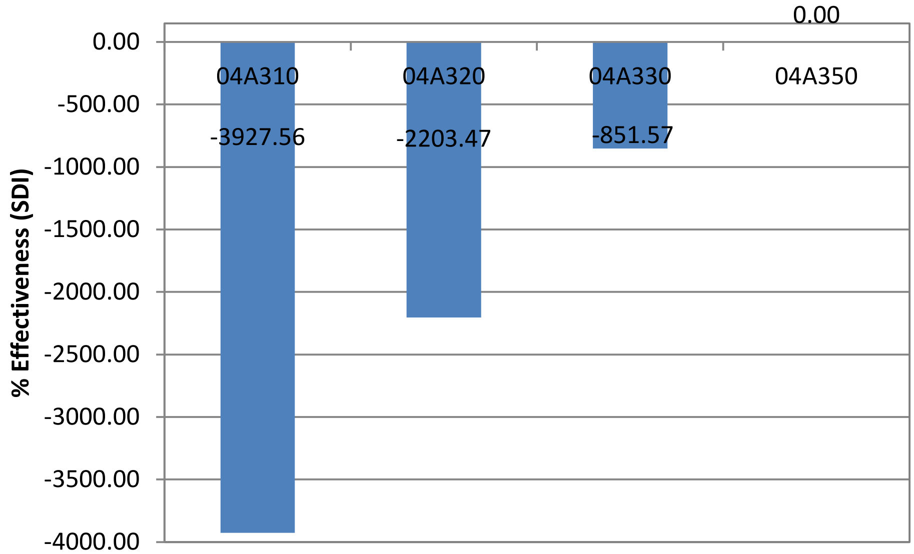

Figure 41. Treatment Effectiveness Based on SDI for 04A300 Sections

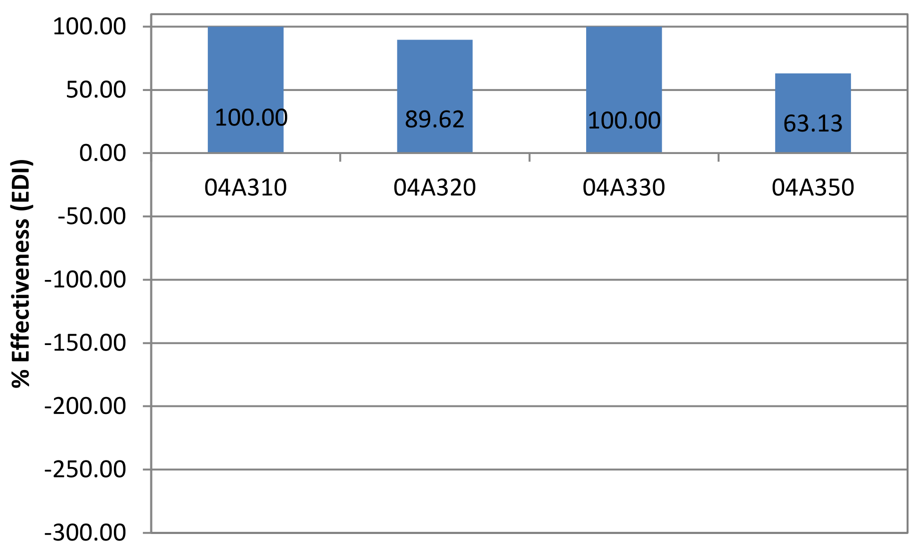

Figure 42. Treatment Effectiveness Based on EDI for 04A300 Sections

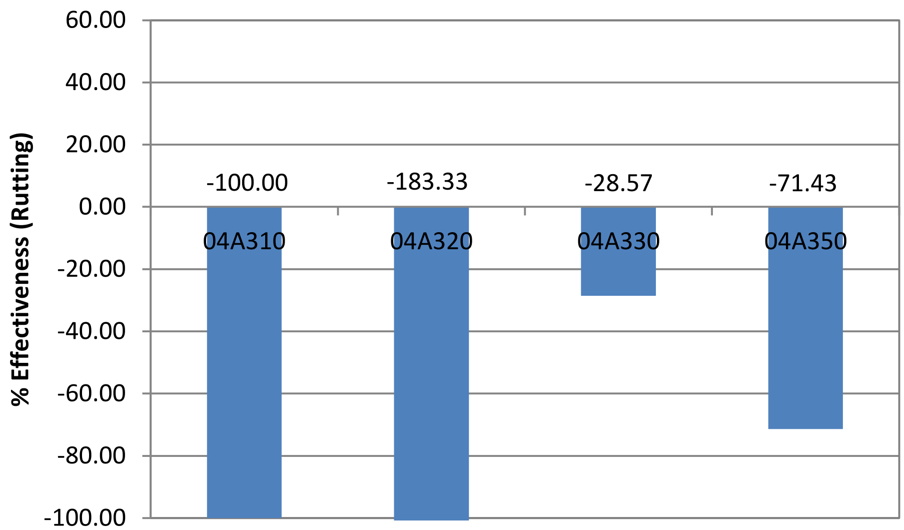

Figure 43. Treatment Effectiveness Based on Rutting for 04A300 Sections

The rankings of the 04A300 sections are shown in Table 22. Conclusions are difficult to draw across the four treatment types. Most consistently, the crack seal appeared to be the most effective treatment for this project, while the slurry seal tended to be the least effective treatment.

Table 22. Treatment Effectiveness Comparison for 04A300 Sections

Ranking	SDI	EDI	Rutting
1 (Most effective)	Chip seal	Thin overlay Crack seal	Crack seal
2	Crack seal	Slurry seal	Chip seal
3	Slurry seal	Chip seal	Thin overlay
4 (Least effective)	Thin overlay		Slurry seal

04B300 Sections

As noted previously, the 04B300 test sections were evaluated as of two different dates: 1991, when there were data for all the test sections, but only one year had elapsed since treatment; and 1994, when the data covered all sections except the thin overlay, but allowed for longer time comparisons of the other treatments. The plots for treatment effectiveness using the 1991 data for SDI, EDI, and rutting are shown in
Figure 44,
Figure 45, and

Figure 46, respectively.

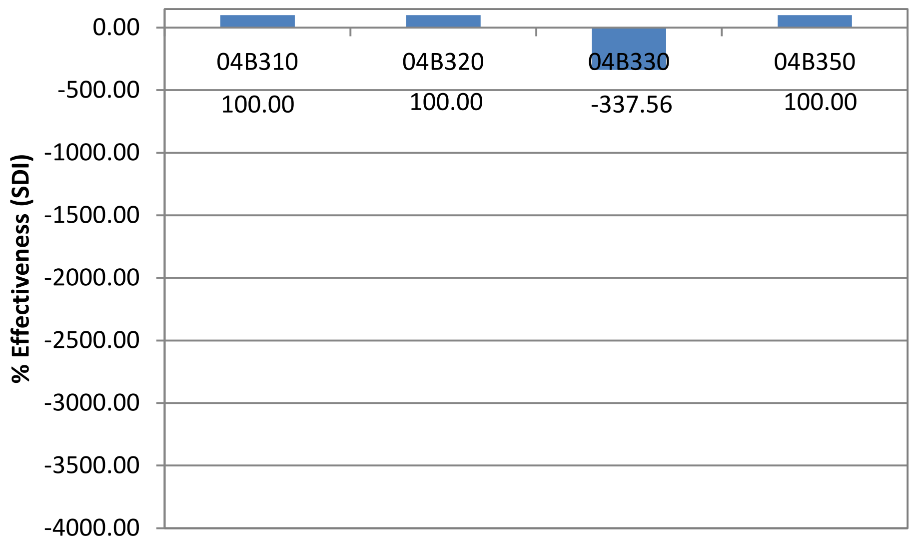

Figure 44. Treatment Effectiveness Based on SDI for 04B300 Sections, 1991

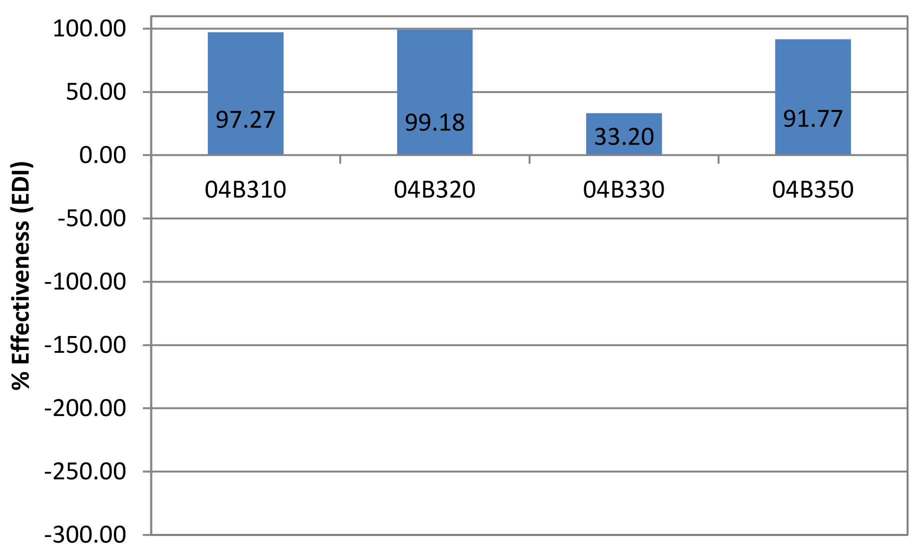

Figure 45. Treatment Effectiveness Based on EDI for 04B300 Sections, 1991

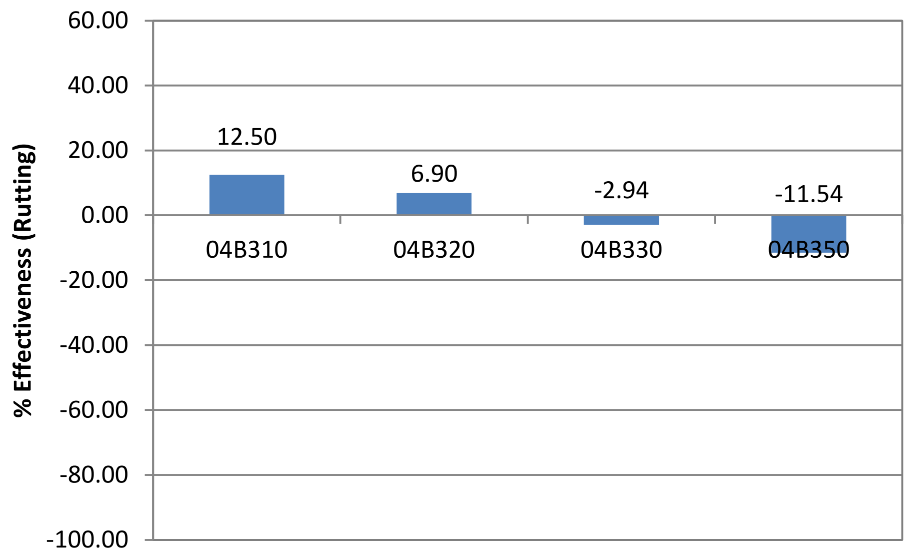

Figure 46. Treatment Effectiveness Based on Rutting for 04B300 Sections, 1991

The rankings of the 04B300 sections are summarized in Table 23 below. Some conclusions emerge from these data—specifically, that the crack seal was generally the least effective treatment method, and the slurry seal was generally the most effective treatment method.

Table 23. Treatment Effectiveness Comparison for 04B300 Sections, 1991

Ranking	SDI	EDI	Rutting
1 (Most effective)	Slurry seal Chip seal Thin overlay	Slurry seal	Thin overlay
2	Crack seal	Thin overlay	Slurry seal
3		Chip seal	Crack seal
4 (Least effective)		Crack seal	Chip seal

The plots for treatment effectiveness using the 1994 data for SDI, EDI, and rutting are shown in

Figure 47,

Figure 48, and

Figure 49.

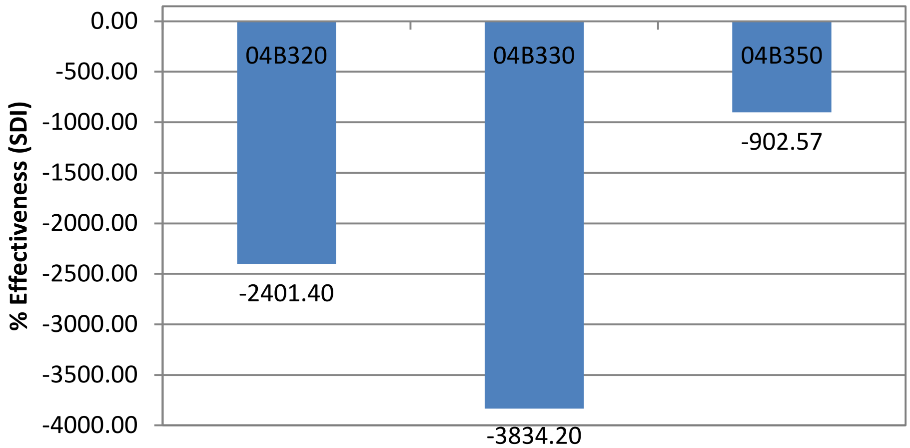

Figure 47. Treatment Effectiveness Based on SDI for 04B300 Sections, 1994

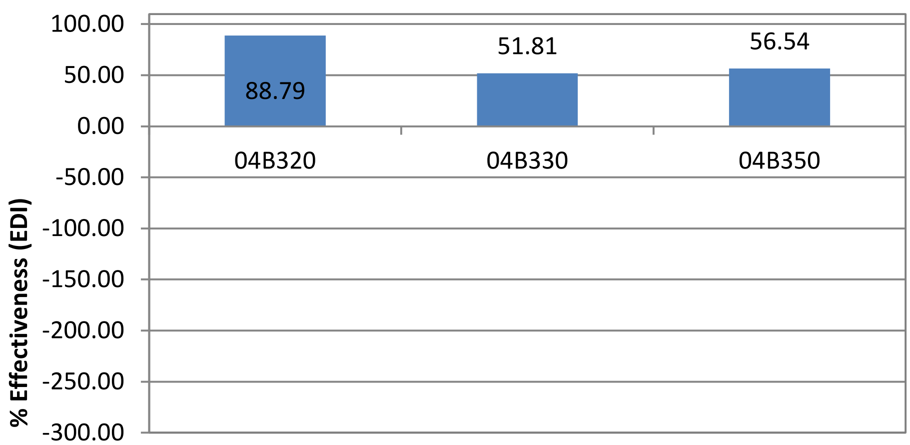

Figure 48. Treatment Effectiveness Based on EDI for 04B300 Sections, 1994

The section results for 04B300 from 1994 indicate that the slurry seal generally appeared to be the most effective while the chip seal was generally the least effective. The full summary can be seen in Table 24.

Table 24. Treatment Effectiveness Comparison for 04B300 Sections, 1994

Ranking	SDI	EDI
1 (Most effective)	Crack seal	Slurry seal
2	Slurry seal	Chip seal
3 (Least effective)	Chip seal	Crack seal

04C300 Sections

The plots for treatment effectiveness with respect to SDI, EDI, and rutting are shown in Figure 49,
Figure 50, and
Figure 51, respectively.

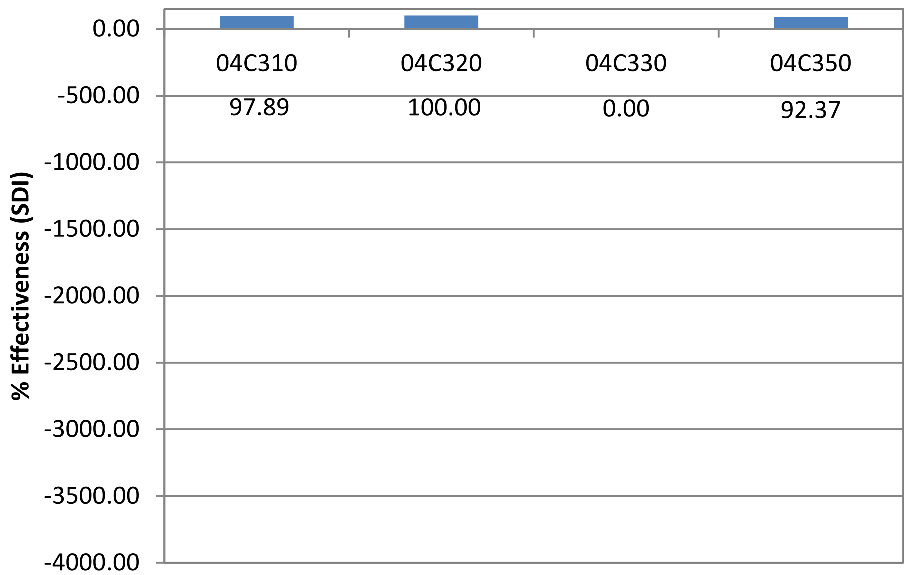

Figure 49. Treatment Effectiveness Based on SDI for 04C300 Sections

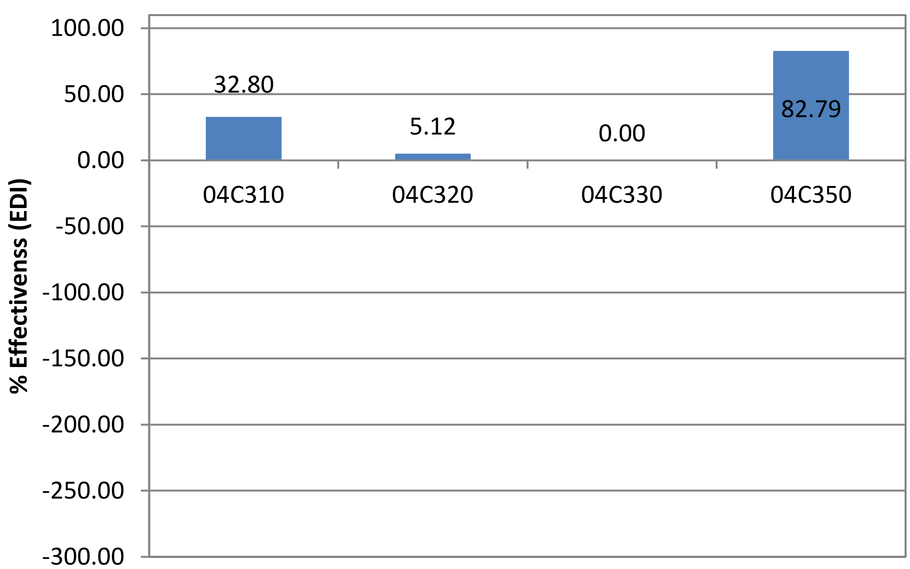

Figure 50. Treatment Effectiveness Based on EDI for 04C300 Sections

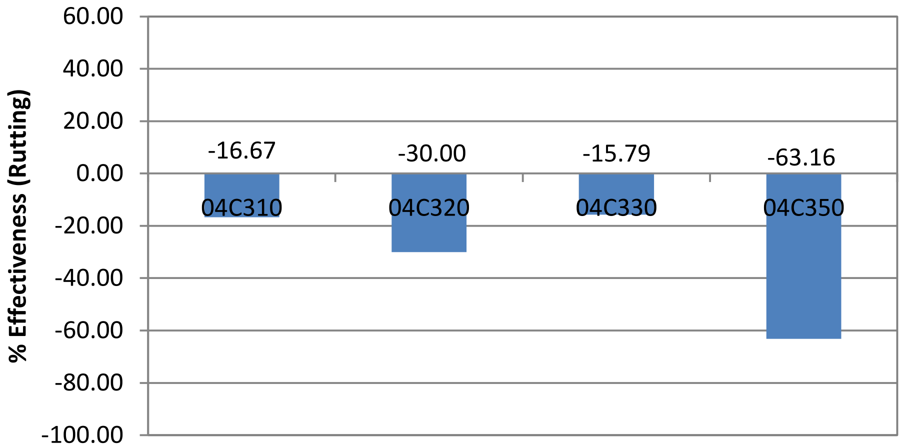

Figure 51. Treatment Effectiveness Based on Rutting for 04C300 Sections

The plots for the 04C300 sections are summarized in Table 25. Conclusions are difficult to draw from the variable rankings in these data.

Table 25. Treatment Effectiveness Comparison for 04C300 Sections

Ranking	SDI	EDI	Rutting
1 (Most effective)	Slurry seal	Chip seal	Crack seal
2	Thin overlay	Thin overlay	Thin overlay
3	Chip seal	Slurry seal	Slurry seal
4 (Least effective)	Crack seal	Crack seal	Chip seal

04D300 Sections

The plots for treatment effectiveness with respect to SDI, EDI, and rutting are shown in

Figure 52,

Figure 53, and

Figure 54, respectively.

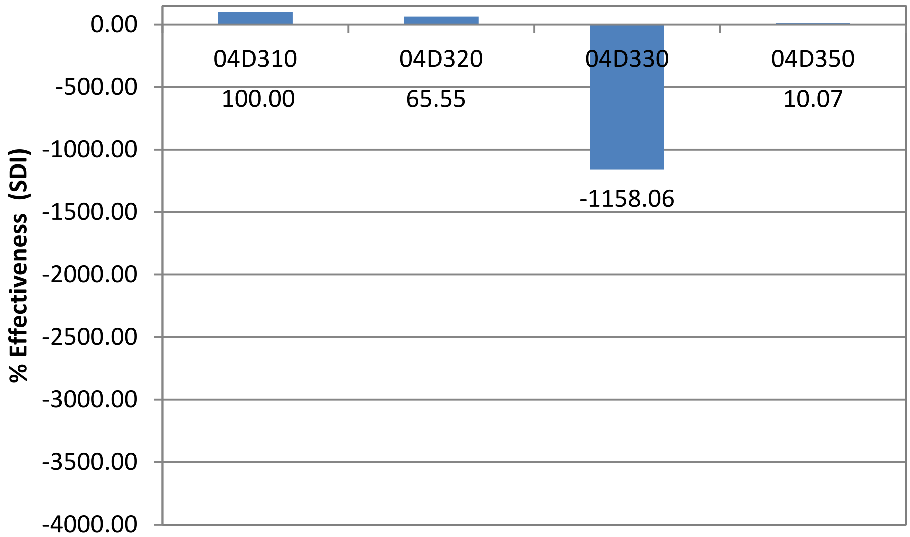

Figure 52. Treatment Effectiveness Based on SDI for 04D300 Sections

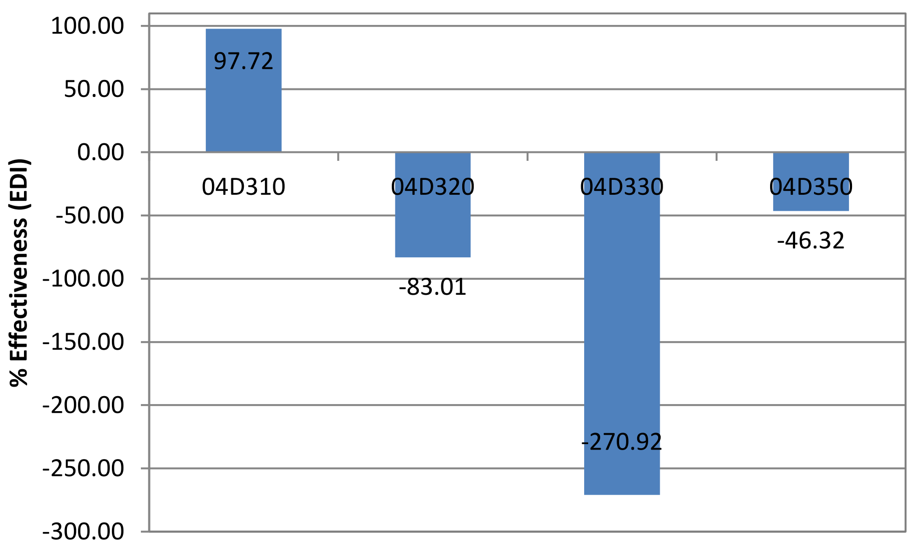

Figure 53. Treatment Effectiveness Based on EDI for 04D300 Sections

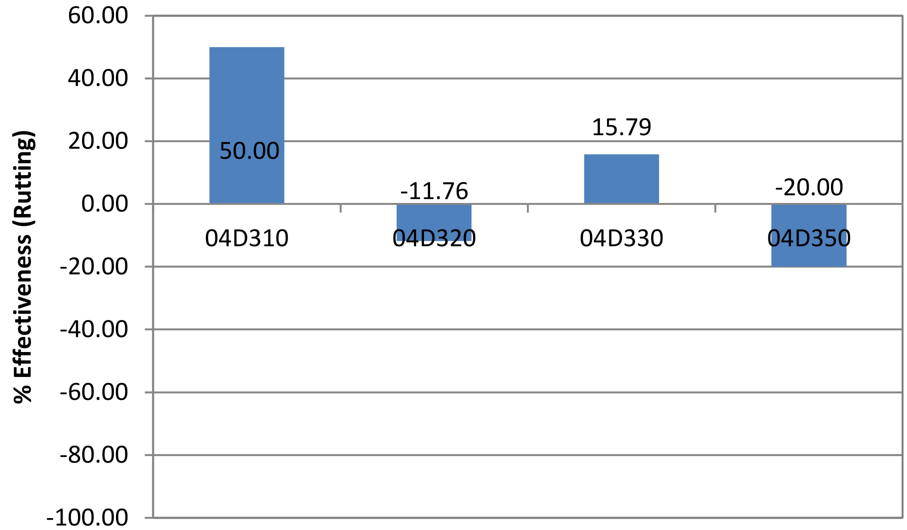

Figure 54. Treatment Effectiveness Based on Rutting for 04D300 Sections

The data from the 04D300 sections are summarized in Table 26. Consistently, the thin overlay was the most effective treatment, generally followed by the slurry seal and the chip seal and finally by the crack seal.

Table 26. Treatment Effectiveness Comparison for 04D300 Sections

Ranking	SDI	EDI	Rutting
1 (Most effective)	Thin overlay	Thin overlay	Thin overlay
2	Slurry seal	Chip seal	Crack seal
3	Chip seal	Slurry seal	Slurry seal
4 (Least effective)	Crack seal	Crack seal	Chip seal

DISTRESS KEY FINDINGS

The distress data captured for the SPS-3 experiment provide valuable insight into AC pavement maintenance. However, caution should be exercised when drawing conclusions from the data due to the inherent difficulty of combining manual and automatic distress survey data. This difficulty contributed to the inconsistencies seen in the plots. Despite such inconsistencies, several trends could still be observed. Following are the key findings from the distress analysis.

- Every section exhibited some level of improvement after the maintenance treatment, whether in the structural damage index, environmental damage index, or rutting.

- Comparison of the treatment sections based on the structural and environmental damage indices and amount of rutting indicated that, generally, the crack seal sections showed the highest levels of distress, followed by the slurry seal sections, and then the chip seal sections. The thin overlay treatment was associated with the least amount of structural and environmental damage and the lowest rutting levels.

- Analysis of the time series distress data revealed that, in general, the thin overlay performed the best among the preventive maintenance treatments, while the slurry seal generally performed the worst. The chip seal performed slightly worse than the thin overlay, followed by the crack seal.

- The distress data from a single point in time indicated that the thin overlay produced the best performance, followed by the chip seal, followed by the slurry seal, and then by the crack seal.

- Analysis of life extension data revealed that the thin overlay performed the best at protecting against environmental distress and rutting, and the crack seal performed the worst. The life extension data did not yield consistent results for structural distress.

- Treatment effectiveness measurements showed that the thin overlay was best at protecting against rutting, followed by the crack seal, then the slurry seal, and then the chip seal. The thin overlay protected against environmental distresses better than the crack seal, but other conclusions could not be drawn from the scattered data.

CHAPTER 3. ROUGHNESS ANALYSIS

This chapter provides the results of profile and roughness analyses performed for the LTPP SPS-3 project. The analyses follow the same approach applied in previous studies of SPS sites in Arizona (Karamihas 2007a; Karamihas 2007b; Karamihas 2007c; Karamihas and Senn 2009; Karamihas and Senn 2010; Karamihas and Senn 2012).

The analyses include (1) profile data synchronization, (2) selection of five repeat measurements for further analysis, (3) data-quality screening, (4) roughness calculations presented mainly in the form of International Roughness Index (IRI) values, and (5) observations from inspection of profiles needed to explain roughness trends. For many of the pavement sections, inspection of profiles did not provide much insight, since the overall monitoring period was short. This was not unexpected given the existing pavement condition and the maintenance treatments included in the experimental design.

PROFILE DATA SYNCHRONIZATION

Table 27 through Table 30 list the profile measurement dates for each section. State supplemental sections were only covered in some of the early visits, as LTPP data collection protocols assigned different monitoring frequencies to core sections and to supplemental sections. All of the SPS-3 sections were taken out of the study by mid-1998; however, the monitoring history of the control sections (which were sections from the GPS-1 study) was often much longer.

Table 27. Profile Measurement Visits to the 04A300 Site

Visit	Date	Repeats	Sections			
			Control (GPS-1)	Core		State
			041036	04A310, 04A320, 04A330, 04A350	04A390	04A360, 04A361, 04A362, 04A363
01	8/8/1989	9				
02	3/28/1990	5				
03	2/19/1992	7				
04	2/5/1993	9				
05	1/28/1994	9				
06	2/28/1995	7				
07	1/22/1997	9				
08	4/7/1998	7				

Table 28. Profile Measurement Visits to the 04B300 Site

Visit	Date	Repeats	Sections		
			Control (GPS-1)	Core	State
			041021	04B310, 04B320, 04B330, 04B350	04B360, 04B361
01	3/30/1990	5			
02	3/31/1990	5			
03	2/19/1992	9			
04	2/23/1992	9			
05	2/9/1993	9			
06	2/9/1993	9			
07	3/21/1995	9			
08	2/21/1997	9			
09	4/16/1998	7			
10	3/3/1999	7			
11	3/15/2000	7			
12	2/19/2002	7			
13	3/12/2004	9			
14	11/29/2011	9			

Table 29. Profile Measurement Visits to the 04C300 Site

Visit	Date	Repeats	Sections		
			Control (GPS-1)	Core	State
			041017	04C310, 04C320, 04C330, 04C350	04C360, 04C361, 04C362, 04C363
01	3/19/1990	5			
02	1/12/1992	9			
03	1/14/1992	7			
04	2/24/1993	9			
05	2/25/1993	9			
06	11/17/1994	9			
07	2/5/1997	9			
08	12/17/1997	5			
09	12/10/1998	7			
10	11/12/1999	7			
11	11/14/2001	9			
12	11/7/2002	9			
13	12/9/2004	9			
14	3/23/2006	9			
15	1/15/2010	9			
16	12/6/2011	9			

Table 30. Profile Measurement Visits to the 04D300 Site

Visit	Date	Repeats	Sections			
			Control (GPS-1)	Core		State
			041016	04D310, 04D330	04D320, 04D350	04D360, 04D361, 04D362
01	3/18/1990	5				
02	2/12/1992	9				
03	2/13/1992	7				
04	2/26/1993	9				
05	2/4/1997	9				
06	12/17/1997	7				
07	12/10/1998	7				
08	11/12/1999	7				
09	11/14/2001	9				
10	11/6/2002	9				
11	12/9/2004	9				
12	3/22/2006	9				
13	12/6/2011	9				

Data Extraction

Profiles of individual test sections were extracted directly from the raw measurements. This was done to ensure that test section starting and ending locations were consistent throughout the monitoring period. The raw data were used to synchronize all of the profiles to each other through their entire history. Three clues were available for this purpose: (1) the site layout from the construction report, (2) event markers in the raw profiles from the start and end of each section, and (3) the longitudinal offset between repeat measurements (identified through automated searching).

Cross-Correlation

A helpful way to refine the synchronization of repeat profile measurements is to search for the longitudinal offset that provides the best agreement between them. This can be done by inspecting filtered profile plots, but it is very time-consuming. Visual assessment, however, is somewhat subjective when two profiles do not agree well, which is often the case when measurements are made several years apart. Therefore, an automated procedure, rather than visual inspection, was used for finding the longitudinal offset between measurements.

The automated procedure is based on a customized version of cross-correlation (Karamihas 2004). In this procedure, a "basis" measurement is designated that is considered to have the correct longitudinal positioning. A "candidate" profile is then searched for the longitudinal offset that provides the highest cross- correlation with the basis measurement. A high level of cross-correlation requires a good match of profile shape, location of isolated rough spots, and overall roughness level. Therefore, the correlation level is often only high when the basis and candidate measurements are synchronized. When the optimal offset is found, a profile is extracted from the candidate measurement with the proper overall length and endpoint positions. For the rest of this discussion, this process will be referred to as *automated synchronization*.

For this application, cross-correlation was performed only after the International Roughness Index (IRI) filter had been applied to the profiles. This helped assign the proper weighting to relevant profile features. In particular, it increased the weighting of short-wavelength roughness that may be linked to pavement distress. This enhanced the effectiveness of the automated synchronization procedure. The long-wavelength content within the IRI output helped ensure that the longitudinal positioning was nearly correct, and the short-wavelength content was used to fine-tune the positioning by leveraging profile features at isolated rough spots.

Synchronization

Profiles of individual test sections were extracted from the raw measurements using the following steps:

1. Establish a basis measurement for each section from data collected at the first available visit. (For the SPS-3 project, the basis measurement was established using the event markers from a raw measurement. The first repeat measurement of each section was used for this purpose. All of the sections were assumed to begin at the appropriate event marker, and continue for 500 ft.)
2. Automatically synchronize the other repeats from the same visit to the basis set.
3. Automatically synchronize the measurements from the next visit to the current basis set.
4. Designate the next visit as the current visit.
5. Replace the basis set with a new set of synchronized measurements from the first repeat of the current visit.
6. Repeat steps 3 through 5 until all visits are synchronized.

The following difficulties were experienced:

- The layout for site 04A300 shows 1200 ft between the end of section 04A350 and the start of section 04A360. Event markers appeared 1400 ft apart. The event markers were used to establish the section locations.
- In visit 03 to the 04A300 site, the longitudinal distance was not consistent with the distance recorded in other visits. The event markers showed a total length of 11,700 ft, which is the length indicated in the test section layout. The actual length was 11,500 ft. (The operator may have used the site boundaries to calibrate the distance measurement instrument.) For visit 03, test section profiles were extracted using the event markers rather than automated

synchronization. In turn, visit 04 profiles were extracted using the basis measurements from visits 01 and 02.

- Visit 01 repeat 5 at the 04B300 site did not cover the test sections.
- In visit 04 to the 04B300 site, the distance measurement instrument produced a result that was not consistent with the results from other visits. Visit 04 profiles were extracted using the event markers. In turn, visit 05 and 06 profiles were extracted using the basis measurements from visit 02.
- Visit 08 to section 041021 was sufficiently different from visit 07 to confound the automated synchronization process. (Mill and overlay was performed between these two visits.) A new basis profile was established in visit 08 using event markers.
- In visits 02 and 03 to the 04C300 site, the distance measurement instrument produced a result that was not consistent with the results from other visits. Visits 02 and 03 profiles were synchronized to basis profiles from visit 01 that were adjusted to account for the difference. In turn, visit 04 profiles were extracted using the unmodified basis measurements from visit 01.
- Visit 08 to section 041017 was sufficiently different from visit 07 to confound the automated synchronization process. (Mill and overlay was performed between these two visits.) A new basis profile was established in visit 08 using event markers.
- Event markers for the state supplemental sections at the 04C300 site did not appear with the arrangement specified in the test section layout. The event markers were used to establish the section locations.
- In visit 02 to the 04D300 site, the distance measurement instrument produced a result that was not consistent with the result from other visits.
- Visit 07 to section 041016 was sufficiently different from visit 06 to confound the automated synchronization process. (Mill and overlay had been performed between visits 05 and 06.) A new basis profile was established in visit 07 using event markers.

DATA-QUALITY SCREENING

As shown in Table 27 through Table 30, the number of repeat measurements made during each visit to each section ranged from five to nine. Data-quality screening was performed to select five repeat profile measurements from each visit to each section. The five measurements selected from the group of available runs were those that exhibited the best agreement with each other. Agreement between any pair of profile measurements was judged by cross-correlating them after applying the IRI filter. The details of the cross-correlation method are described elsewhere (Karamihas 2007a). In this method, the IRI filter is applied to the profiles, and then the output signals are compared rather than the overall index. High correlation by this method requires that the overall roughness be in agreement, as well as the details of the profile shape that affect the IRI. The IRI filter was applied before correlation in this case for several reasons:

- Direct correlation of unfiltered profiles places a premium on very-long-wavelength content, but ignores much of the contribution of short-wavelength content.
- Correlation of filtered profiles emphasizes profile features in (approximate) proportion to their effect on overall roughness.
- Correlation of filtered profiles provides a good trade-off between emphasizing localized rough features at distressed pavement areas and placing too much weight on the very-short-duration, narrow features (spikes) that are not likely to agree between measurements. This is because the IRI filter amplifies short-wavelength content, but attenuates macrotexture, megatexture, and spikes.
- A relationship has been demonstrated between the cross-correlation level of filtered profiles and the expected agreement in the overall IRI (Karamihas 2004).

Each comparison between profiles produced a single value that summarized their level of agreement. When nine repeat profile measurements were available for a section, they produced a total of 36 correlation values. Averaging the relevant 10 correlation values yielded a value summarizing the consistency within any subgroup of five measurements. For a subgroup of five measurements, 10 distinct pairs can be correlated. The average of the 10 correlation values summarizes the consistency within the subgroup. The subgroup that produced the highest average was selected, and the other repeats were excluded from most of the analyses discussed in the rest of this report. Since the number of available profiles per section ranged from five to nine, the number of measurements that were excluded ranged from zero to four. Table 31 through Table 34 list the selected repeats for each visit to each section, and the composite correlation level produced by them.

Table 31. Selected Repeats, Site 04A300

Section	Visit	Repeat Numbers					Composite Correlation
041036	1	1	2	3	7	9	0.844
041036	3	1	2	4	5	6	0.722
041036	4	4	5	6	8	9	0.763
041036	6	1	4	5	6	7	0.788
041036	7	1	3	5	7	8	0.911
041036	8	1	2	3	4	5	0.784
04A310	2	1	2	3	4	5	0.786
04A310	3	1	3	5	6	7	0.833
04A310	4	1	3	4	7	9	0.808
04A310	5	1	3	4	5	8	0.808
04A310	6	2	3	5	6	7	0.819
04A310	7	3	4	6	7	8	0.795
04A310	8	1	2	5	6	7	0.535
04A320	2	1	2	3	4	5	0.843
04A320	3	1	2	4	6	7	0.802
04A320	4	2	3	6	7	9	0.852
04A320	5	2	3	5	6	8	0.819
04A320	6	1	2	4	5	6	0.799
04A320	7	1	2	5	6	7	0.783
04A320	8	2	3	4	5	7	0.699
04A330	2	1	2	3	4	5	0.924
04A330	3	1	2	3	4	5	0.817
04A330	4	2	4	5	6	7	0.864
04A330	5	1	2	4	7	9	0.837
04A330	6	1	3	4	6	7	0.808
04A330	7	1	3	5	7	8	0.698
04A330	8	1	2	3	5	7	0.662
04A350	2	1	2	3	4	5	0.875
04A350	3	2	3	4	5	6	0.568
04A350	4	2	3	5	6	7	0.686
04A350	5	3	6	7	8	9	0.784
04A350	6	2	4	5	6	7	0.657
04A350	7	1	5	6	7	8	0.711
04A350	8	2	4	5	6	7	0.353
04A360	2	1	2	3	4	5	0.894
04A360	3	1	4	5	6	7	0.814
04A361	2	1	2	3	4	5	0.889
04A361	3	1	2	4	5	6	0.823
04A362	2	1	2	3	4	5	0.866
04A362	3	1	2	3	5	7	0.766
04A363	2	1	2	3	4	5	0.828
04A363	3	2	3	4	5	7	0.673
04A390	2	1	2	3	4	5	0.906
04A390	3	1	2	3	5	7	0.646

Table 32. Selected Repeats, Site 04B300

Section	Visit	Repeat Numbers					Composite Correlation
041021	2	1	2	3	4	5	0.778
041021	3	2	3	6	7	9	0.799
041021	4	1	3	7	8	9	0.834
041021	5	1	3	6	7	9	0.865
041021	6	3	4	6	7	9	0.861
041021	7	1	3	4	5	9	0.870
041021	8	2	3	5	7	8	0.935
041021	9	1	3	4	6	7	0.898
041021	10	2	3	4	5	7	0.905
041021	11	1	2	3	5	7	0.915
041021	12	1	2	3	5	7	0.957
041021	13	1	2	3	6	7	0.958
041021	14	1	2	3	4	5	0.960
04B310	2	1	2	3	4	5	0.864
04B310	4	2	3	5	6	7	0.872
04B310	6	2	4	6	7	8	0.835
04B310	7	2	3	7	8	9	0.850
04B320	2	1	2	3	4	5	0.823
04B320	4	4	5	6	7	8	0.852
04B320	6	2	4	6	7	8	0.892
04B320	7	1	4	5	6	7	0.877
04B330	2	1	2	3	4	5	0.832
04B330	4	1	3	5	7	9	0.873
04B330	6	2	3	5	6	7	0.847
04B330	7	3	5	6	8	9	0.798
04B350	2	1	2	3	4	5	0.750
04B350	4	1	2	3	4	7	0.787
04B350	6	2	4	6	7	9	0.803
04B350	7	1	5	6	7	8	0.799
04B360	2	1	2	3	4	5	0.710
04B360	4	1	2	4	7	9	0.735
04B361	2	1	2	3	4	5	0.795
04B361	4	2	3	4	6	8	0.697

Table 33. Selected Repeats, Site 04C300

Section	Visit	Repeat Numbers					Composite Correlation
041017	1	1	2	3	4	5	0.614
041017	2	1	2	3	6	8	0.871
041017	3	1	2	4	5	7	0.731
041017	4	2	3	6	8	9	0.924
041017	5	1	2	3	6	8	0.820
041017	6	3	4	5	6	8	0.841
041017	7	1	2	3	7	9	0.941
041017	8	1	2	3	4	5	0.790
041017	9	2	3	4	6	7	0.900
041017	10	1	2	3	4	7	0.917
041017	11	1	2	3	6	8	0.916
041017	12	1	2	3	4	9	0.869
041017	13	2	4	6	7	8	0.847
041017	14	1	4	5	6	8	0.840
041017	15	1	2	3	4	9	0.816
041017	16	1	2	3	5	7	0.813
04C310	1	1	2	3	4	5	0.852
04C310	3	2	3	4	6	7	0.837
04C310	5	1	3	4	6	7	0.878
04C310	6	2	3	4	5	6	0.892
04C310	7	1	2	4	5	6	0.950
04C320	1	1	2	3	4	5	0.874
04C320	3	2	3	5	6	7	0.854
04C320	5	1	5	6	8	9	0.908
04C320	6	1	2	3	4	7	0.958
04C330	1	1	2	3	4	5	0.885
04C330	3	1	3	4	5	7	0.813
04C330	5	2	3	4	5	6	0.880
04C330	6	1	2	3	5	6	0.845
04C330	7	3	5	7	8	9	0.909
04C340	1	1	2	3	4	5	0.894
04C340	3	1	4	5	6	7	0.808
04C340	5	1	3	4	6	7	0.842
04C340	6	2	3	4	6	7	0.888
04C340	7	2	3	5	6	7	0.870
04C350	1	1	2	3	4	5	0.744
04C350	3	1	2	3	4	5	0.883
04C350	5	1	3	5	6	9	0.894
04C350	6	1	3	4	6	7	0.760
04C360	1	1	2	3	4	5	0.859
04C360	3	1	2	3	4	6	0.818
04C361	1	1	2	3	4	5	0.782
04C361	3	1	2	3	5	7	0.714
04C362	1	1	2	3	4	5	0.826
04C362	3	1	3	4	5	7	0.782
04C363	1	1	2	3	4	5	0.928
04C363	3	1	3	5	6	7	0.772

Table 34. Selected Repeats, Site 04D300

Section	Visit	Repeat Numbers					Composite Correlation
041016	1	1	2	3	4	5	0.714
041016	2	1	2	3	6	8	0.853
041016	3	1	2	4	5	7	0.884
041016	4	2	4	7	8	9	0.828
041016	5	1	4	7	8	9	0.866
041016	6	1	2	4	6	7	0.749
041016	7	2	3	5	6	7	0.822
041016	8	1	2	4	5	6	0.840
041016	9	2	3	7	8	9	0.924
041016	10	4	5	6	7	8	0.912
041016	11	1	2	3	7	9	0.791
041016	12	1	2	3	4	6	0.871
041016	13	1	5	6	7	9	0.774
04D310	1	1	2	3	4	5	0.903
04D310	3	1	2	3	6	7	0.930
04D310	5	1	3	4	7	9	0.958
04D320	1	1	2	3	4	5	0.920
04D320	3	1	2	4	5	6	0.927
04D330	1	1	2	3	4	5	0.923
04D330	3	1	3	4	6	7	0.940
04D330	5	1	2	3	4	9	0.872
04D350	1	1	2	3	4	5	0.715
04D350	3	1	2	3	6	7	0.794
04D360	1	1	2	3	4	5	0.889
04D360	3	3	4	5	6	7	0.887
04D361	1	1	2	3	4	5	0.931
04D361	3	1	2	3	6	7	0.870
04D362	1	1	2	3	4	5	0.702
04D362	3	1	2	3	5	7	0.890

The process described above for selecting five repeat measurements from a larger group is similar to the practice within the LTPP project, except that it is based on composite agreement in profile, rather than the overall index value. The correlation levels listed in Table 31 through Table 34 show the degree of agreement between profile measurements for each visit to each section. When two profiles produce a correlation level above 0.82, their IRI values are expected to agree within 10 percent most (95 percent) of the time. Above 0.82, the agreement between profiles is usually acceptable for studying the influence of distresses on profile. When two profiles produce a correlation level above 0.92, their IRI values are expected to agree within 5 percent most of the time. Above 0.92, the agreement between profiles is good. Correlation above 0.92 often depends on consistent lateral tracking by the profiler, and may be very difficult to achieve on highly distressed surfaces. Note that the IRI values provided in this report will be the average of five observations, which will tighten the tolerance even further.

SUMMARY OF ROUGHNESS VALUES

Figures 55 through 88 show the left and right IRI values for each pavement section over their monitoring period. The plots include up to 32 summary IRI values—two per visit with up to 16 visits. The figures show the IRI values plotted over time, with "years" referring to the number of years between the date the treatment was applied to each section and the date of measurement.

To supplement the plots, the appendix presents the IRI, Mean Roughness Index (MRI), Half-car Roughness Index (HRI), and Ride Number (RN) of each section for each visit. These roughness values are the averages derived from the five repeat measurements selected in the data-quality screening. The appendix also provides the standard deviation of the IRI over the five repeat measurements. This helps identify erratic roughness values that are the result of transverse variations in profile caused by surface distresses.

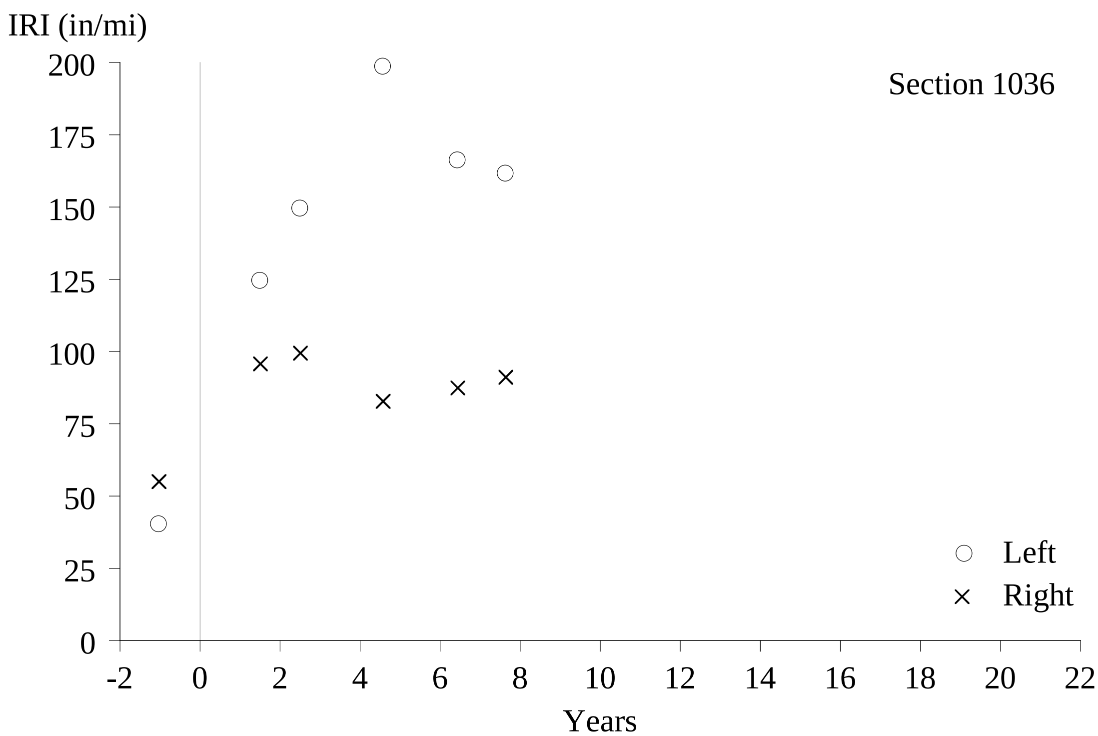

Figure 55. IRI Progression, Section 041036

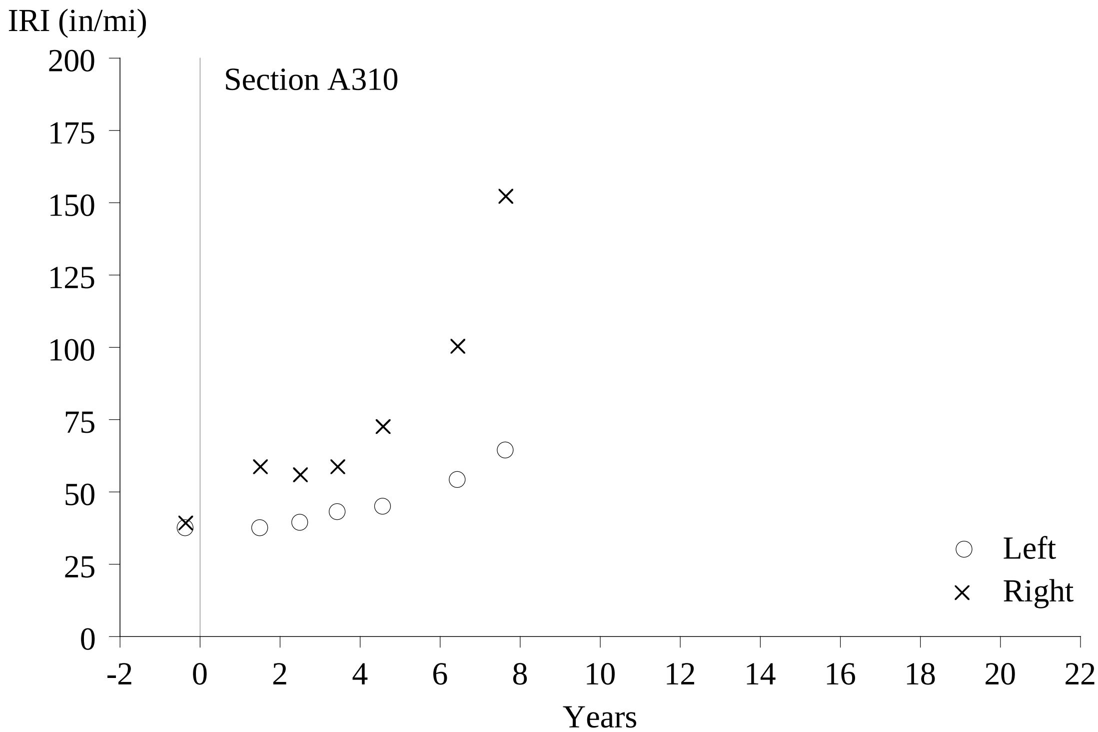

Figure 56. IRI Progression, Section 04A310

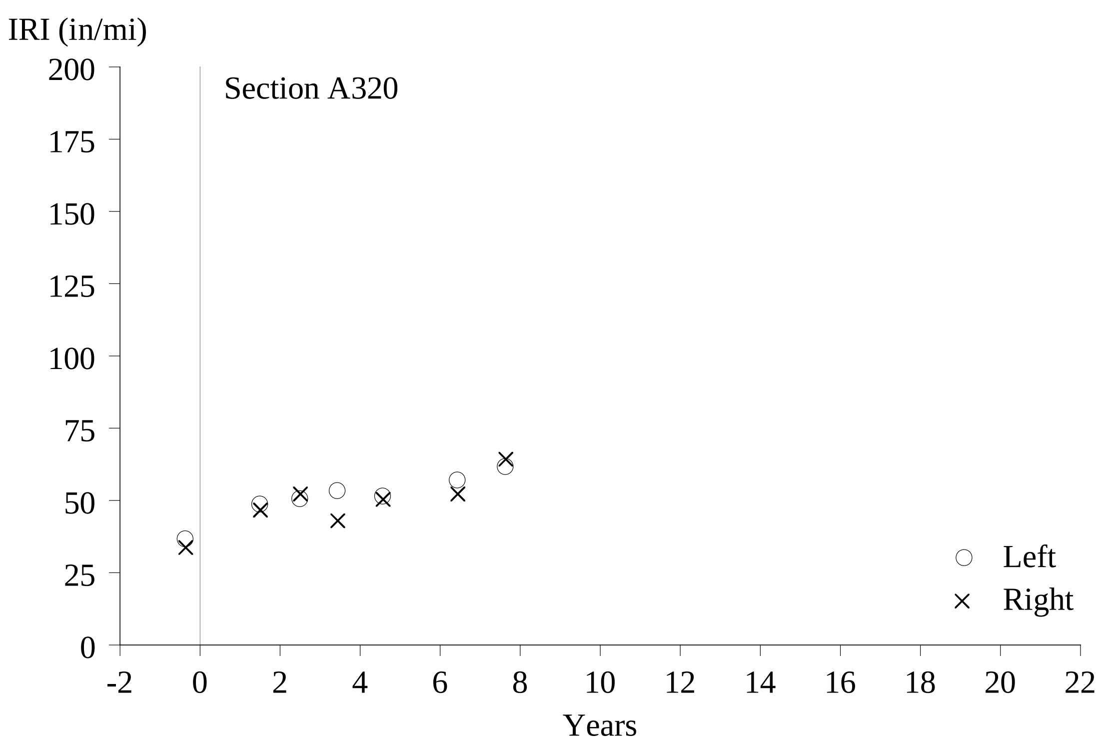

Figure 57. IRI Progression, Section 04A320

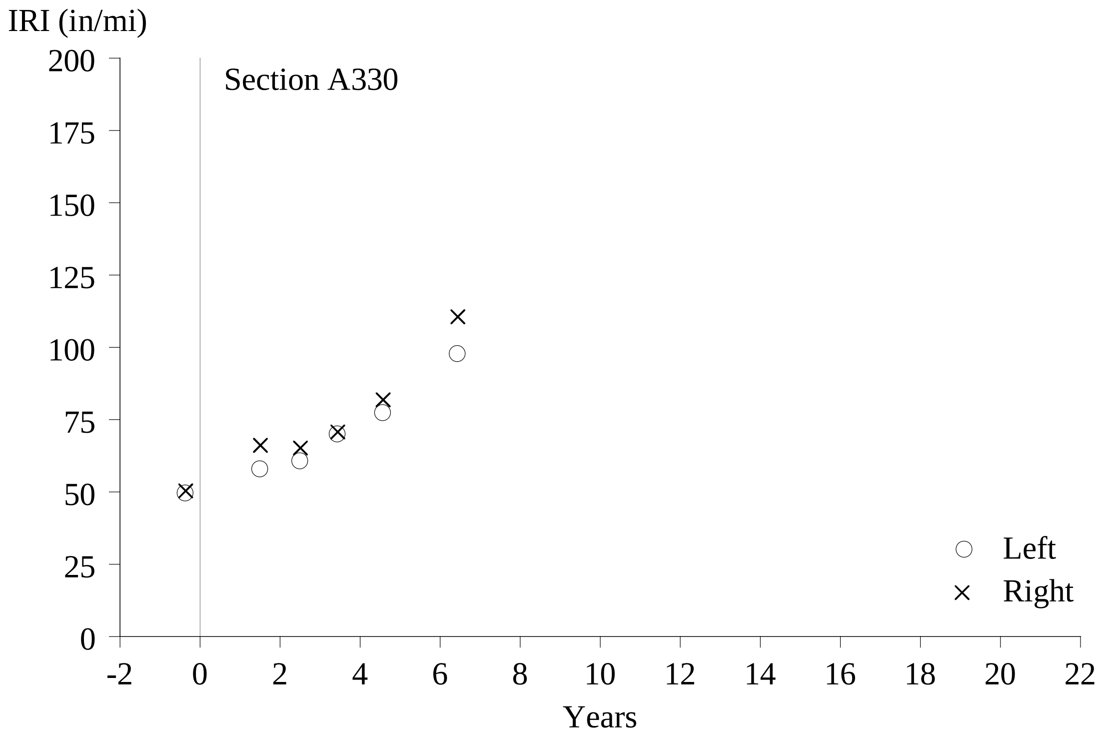

Figure 58. IRI Progression, Section 04A330

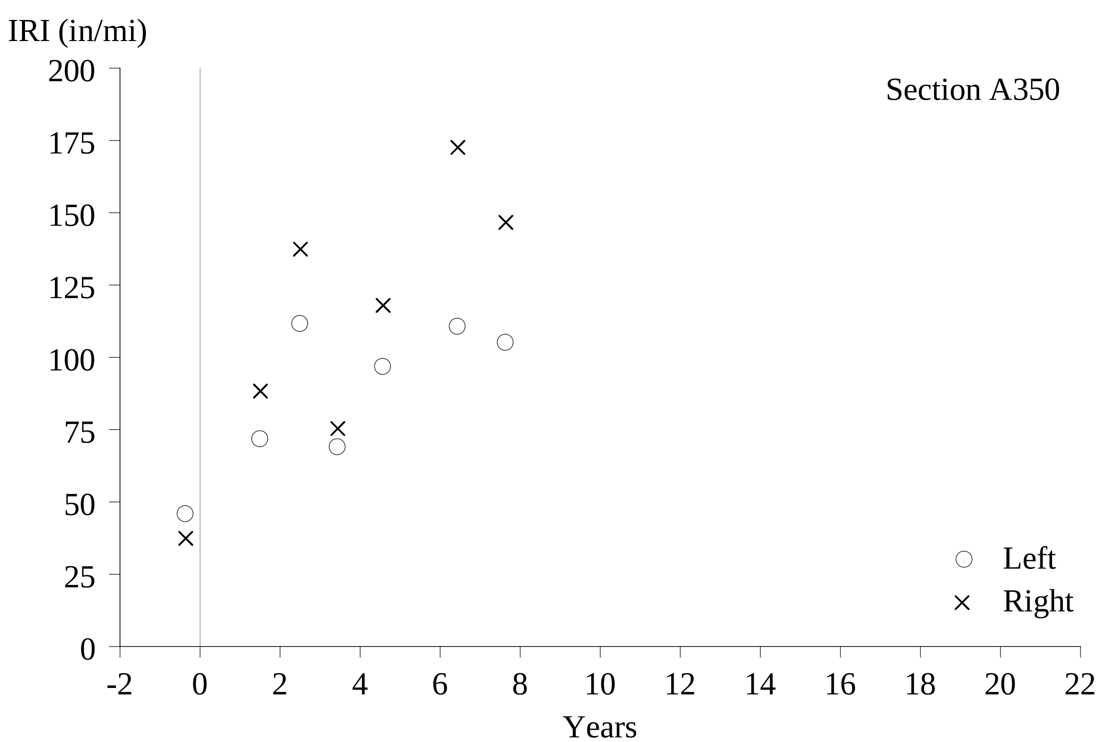

Figure 559. IRI Progression, Section 04A350

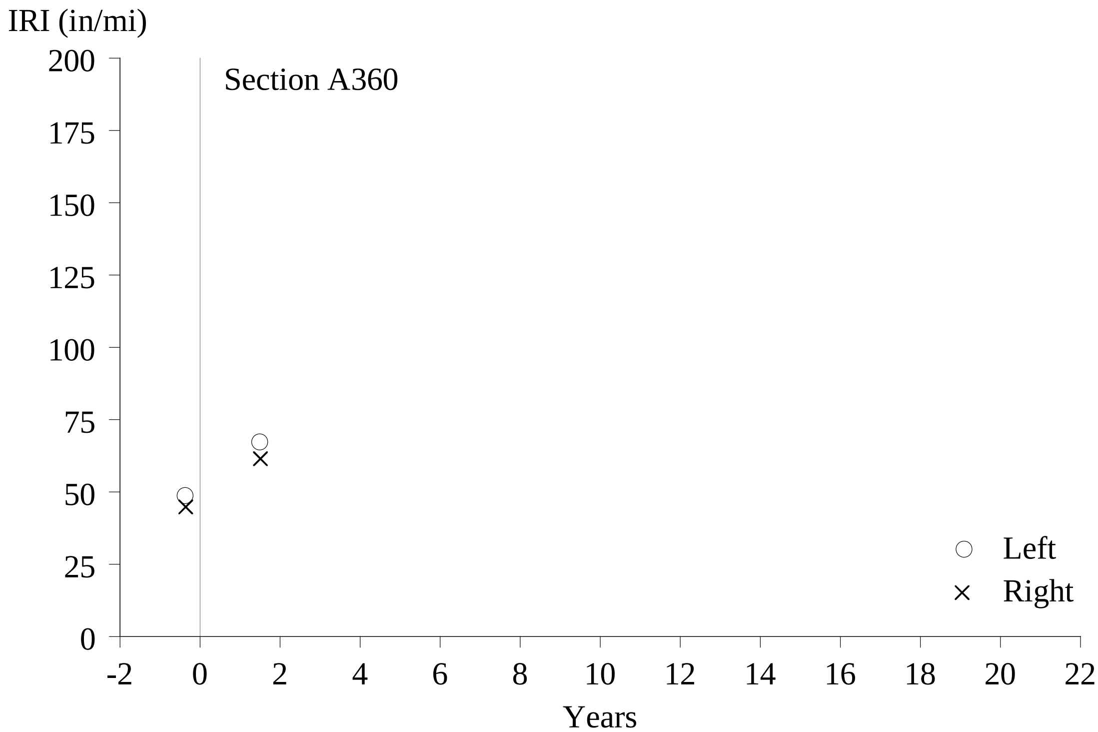

Figure 560. IRI Progression, Section 04A360

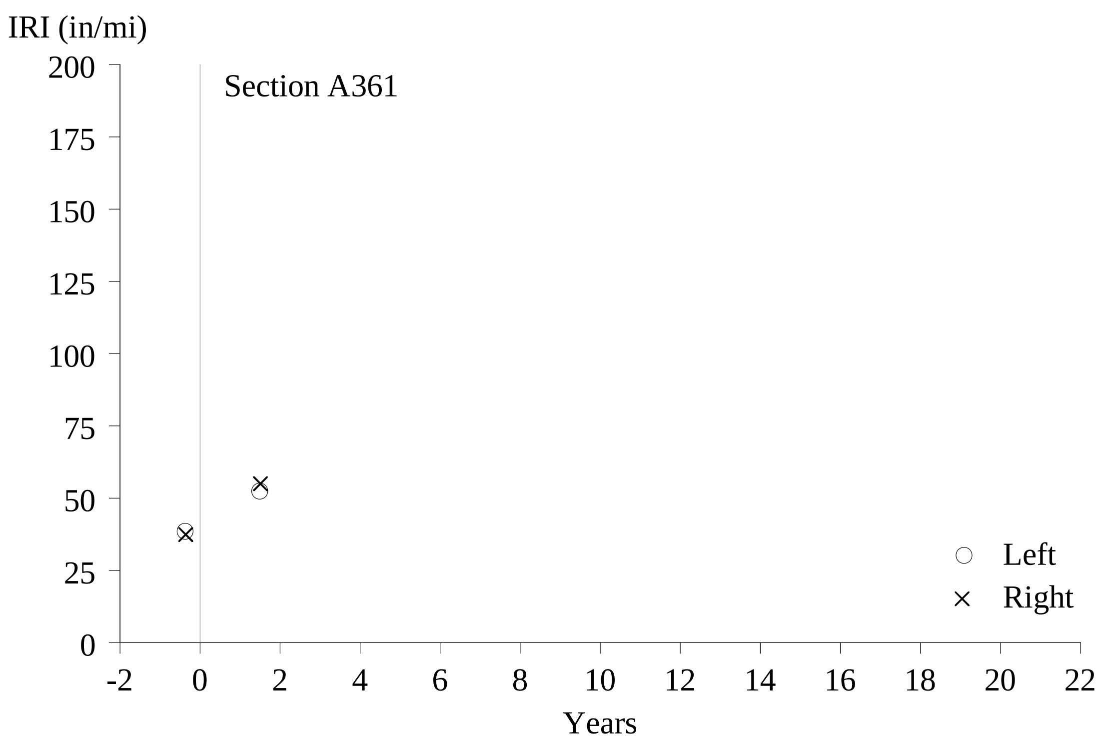

Figure 61. IRI Progression, Section 04A361

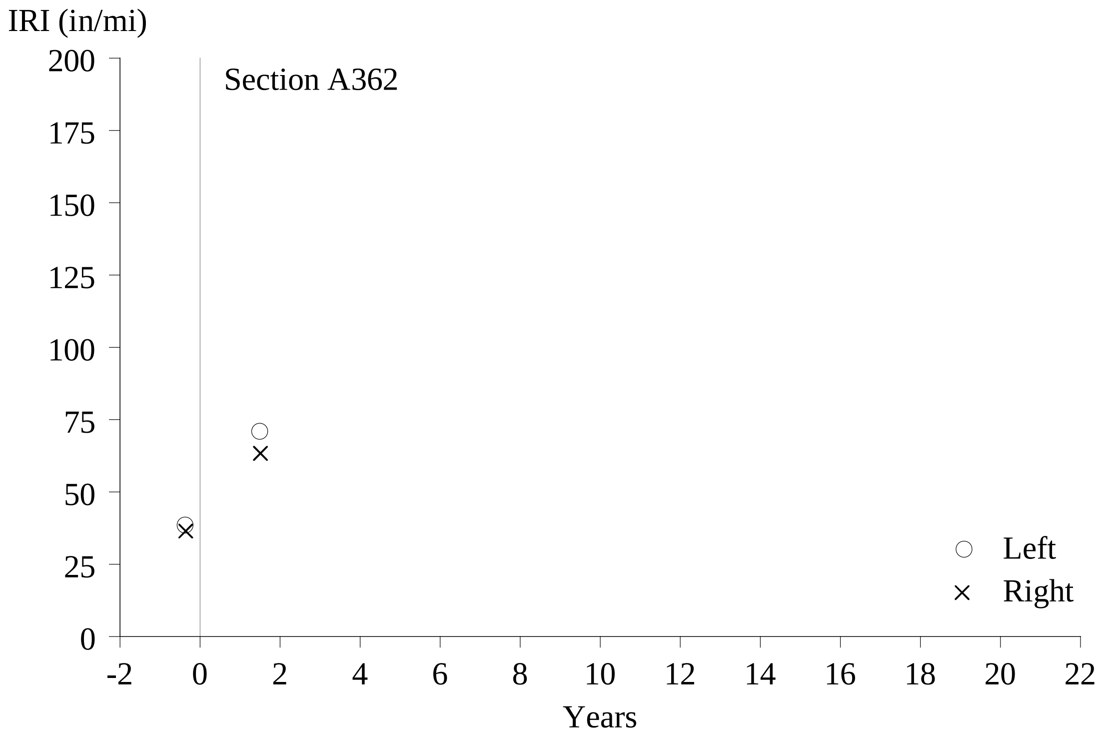

Figure 62. IRI Progression, Section 04A362

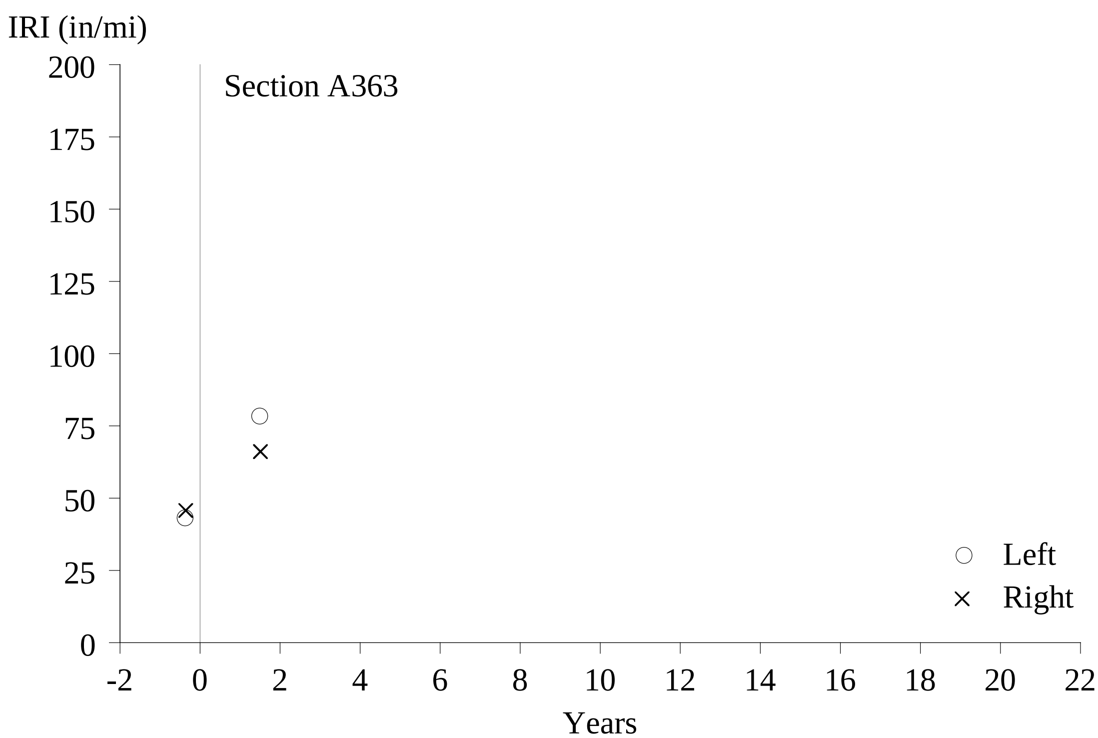

Figure 63. IRI Progression, Section 04A363

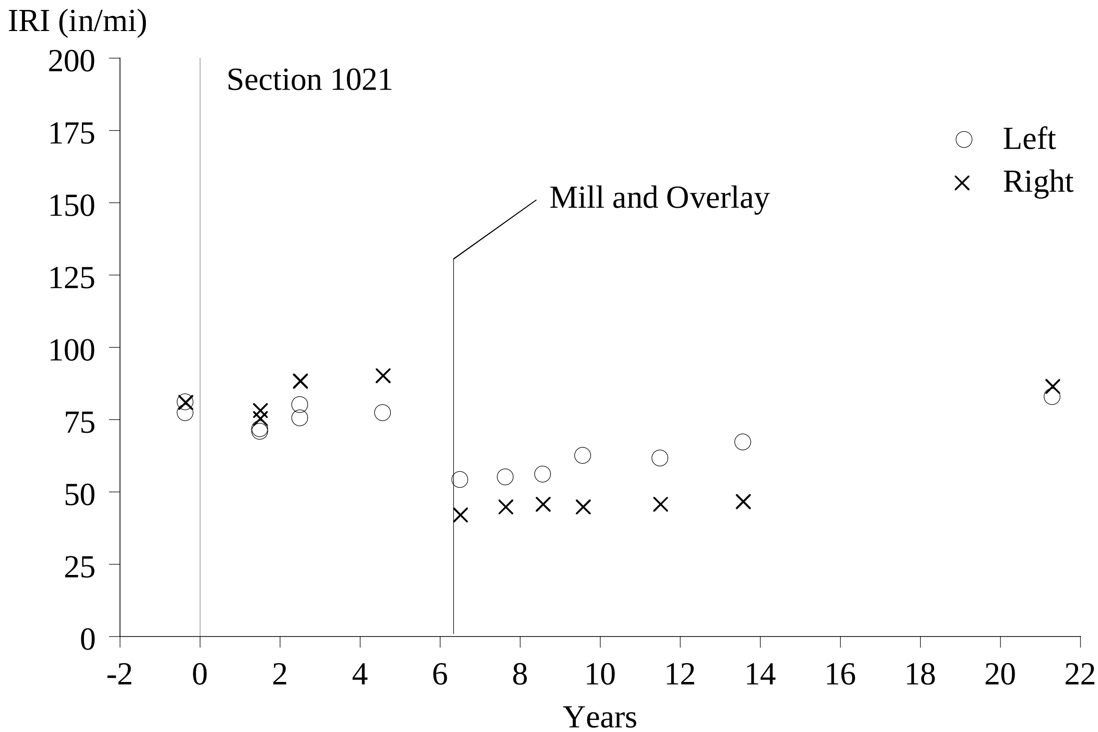

Figure 64. IRI Progression, Section 041021

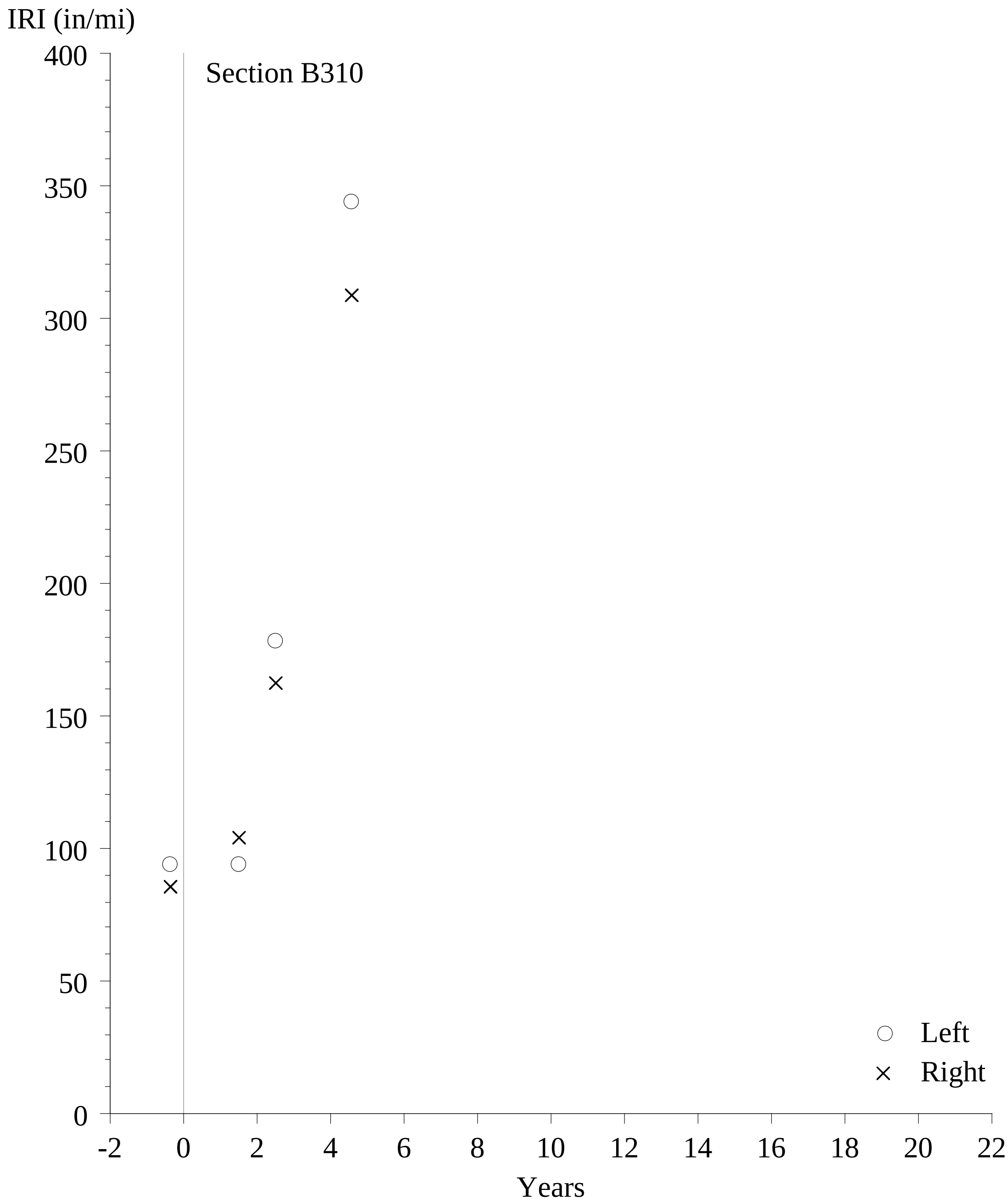

Figure 65. IRI Progression, Section 04B310

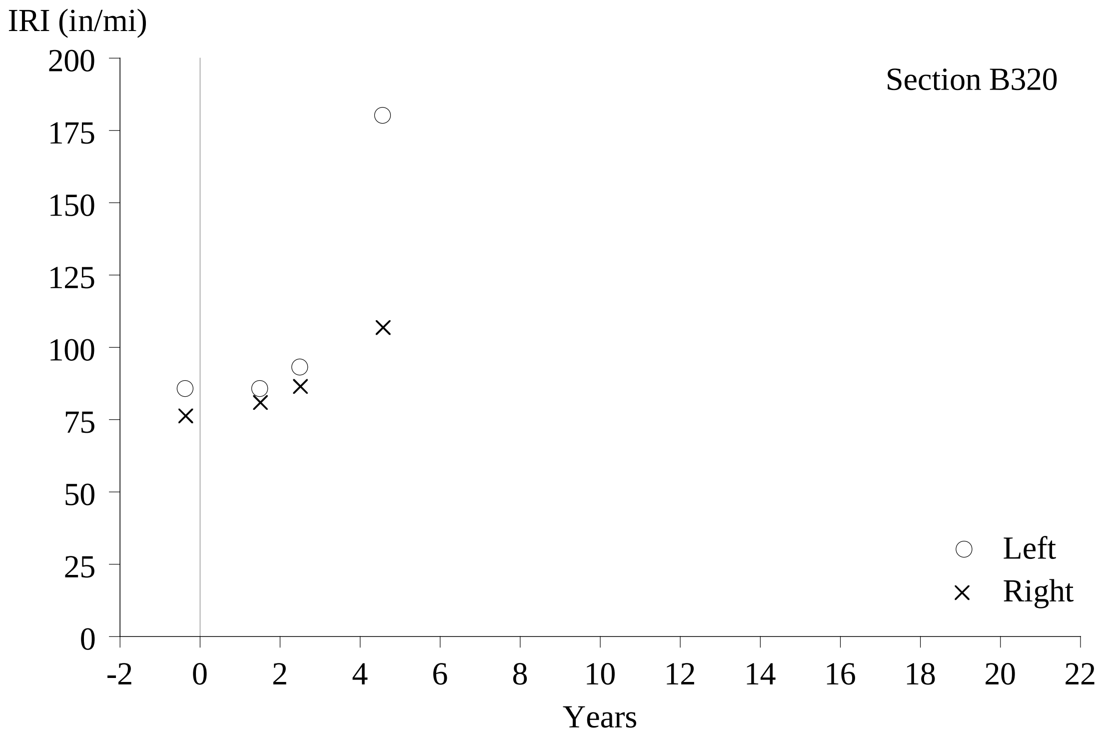

Figure 66. IRI Progression, Section 04B320

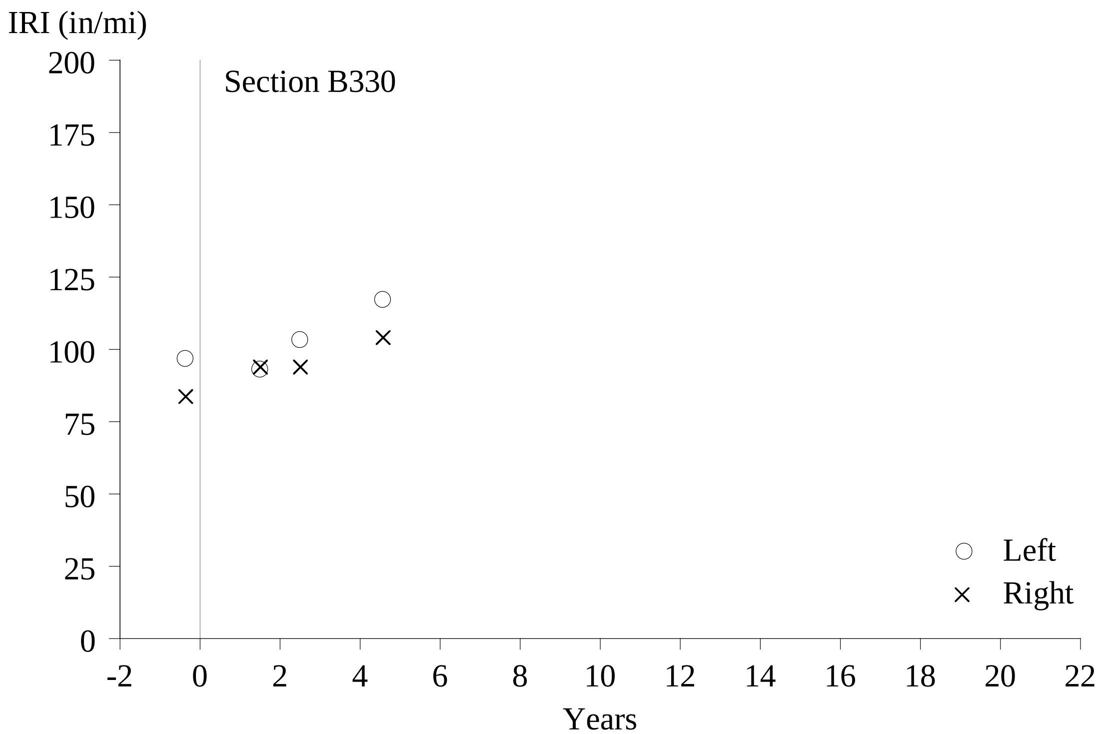

Figure 67. IRI Progression, Section 04B330

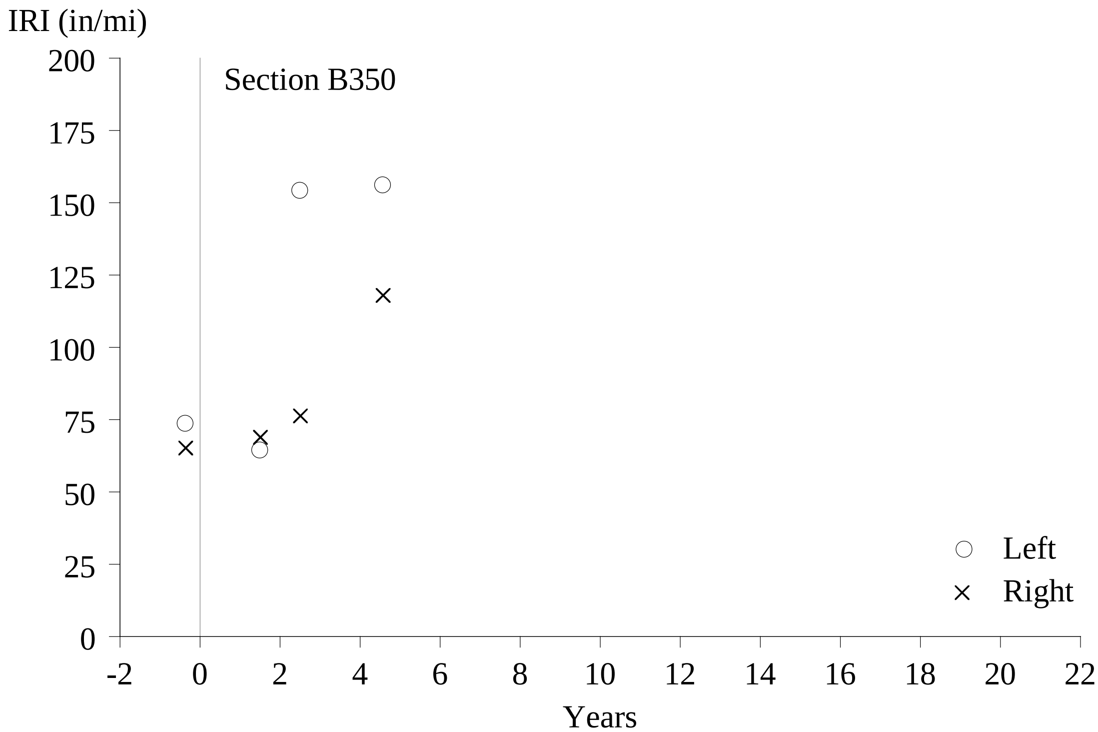

Figure 68. IRI Progression, Section 04B350

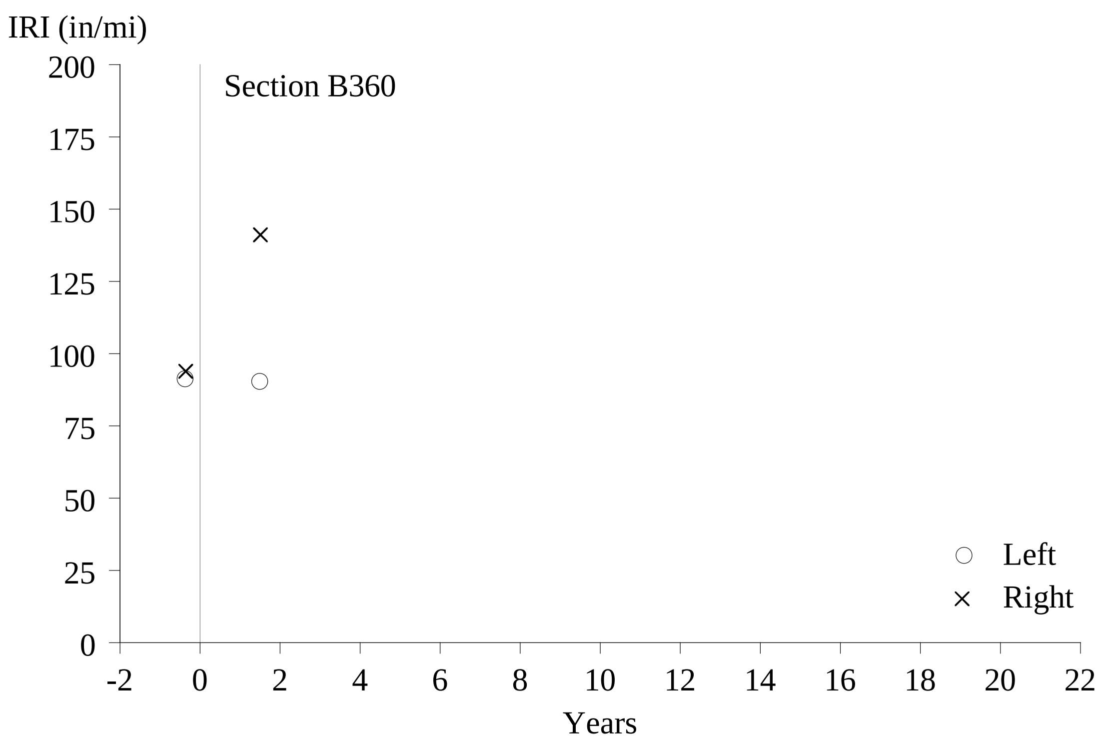

Figure 69. IRI Progression, Section 04B360

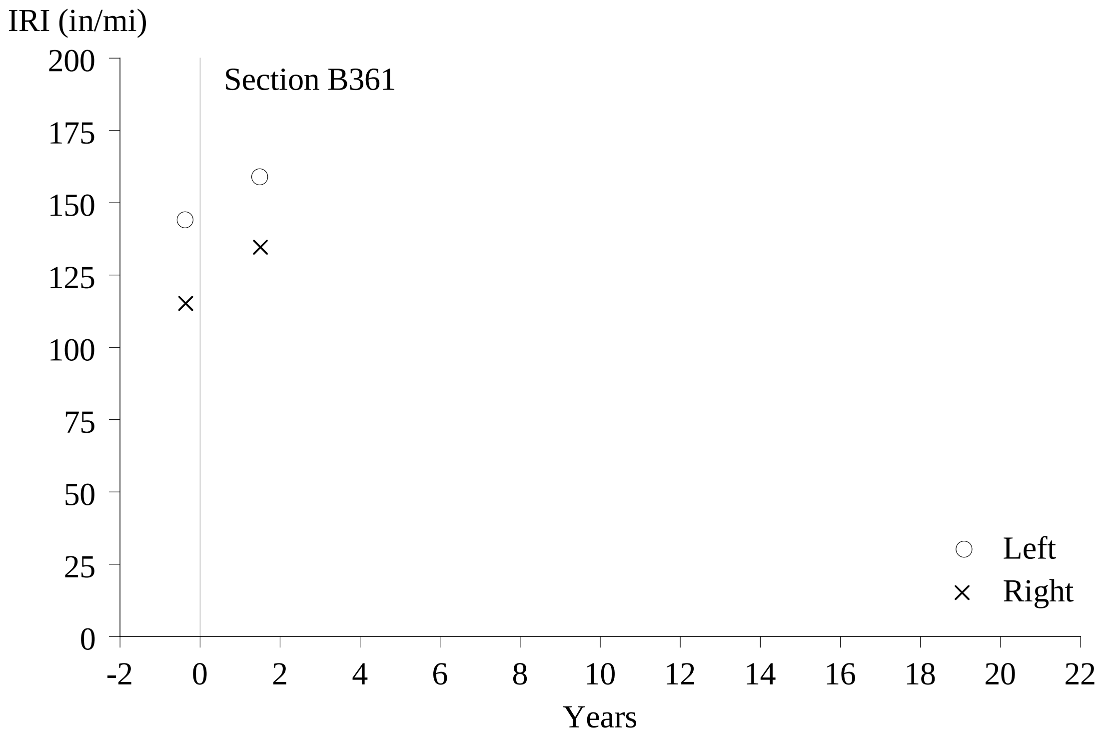

Figure 70. IRI Progression, Section 04B361

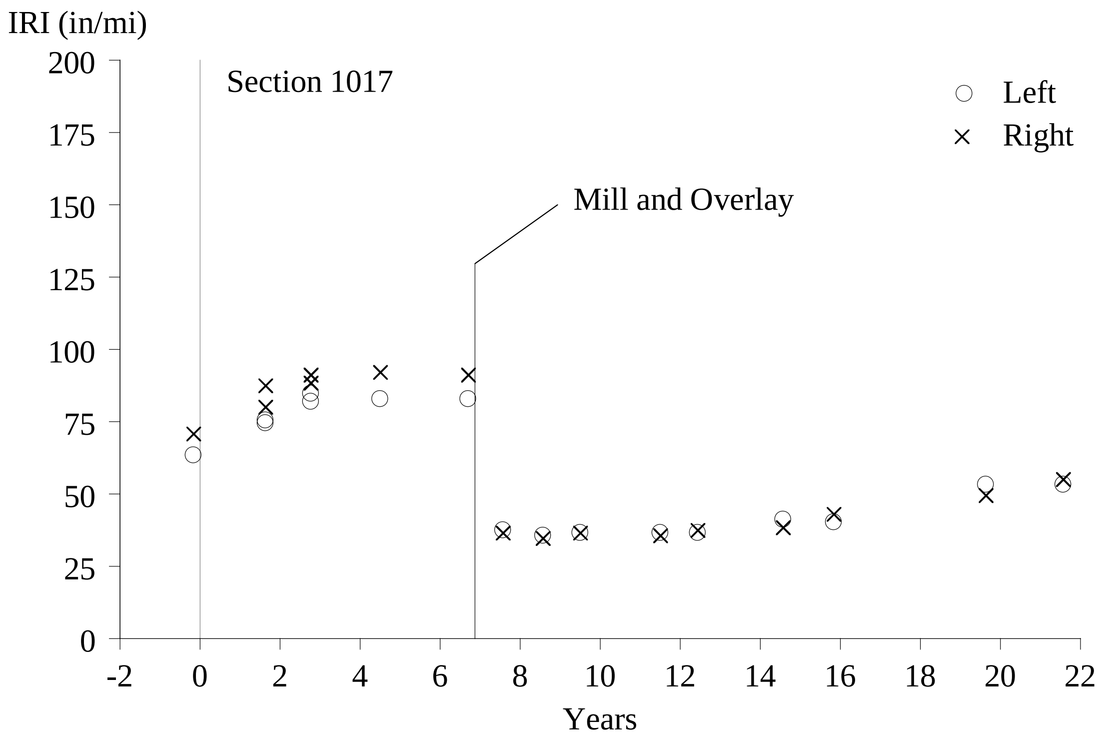

Figure 71. IRI Progression, Section 041017

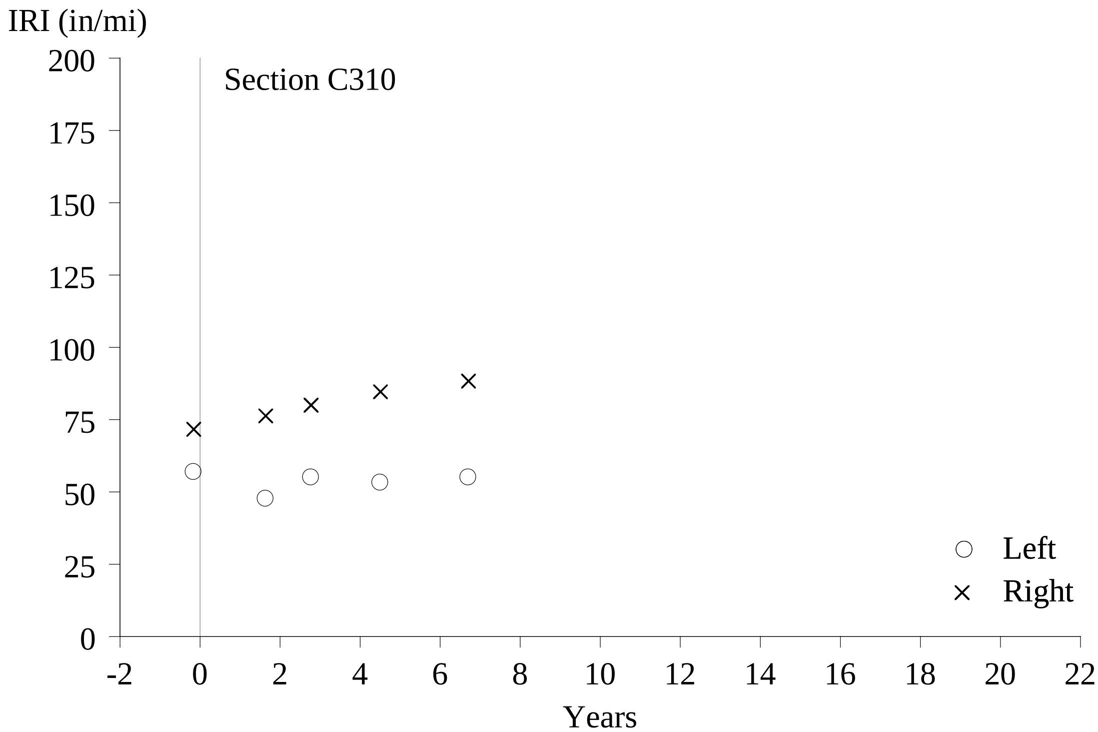

Figure 72. IRI Progression, Section 04C310

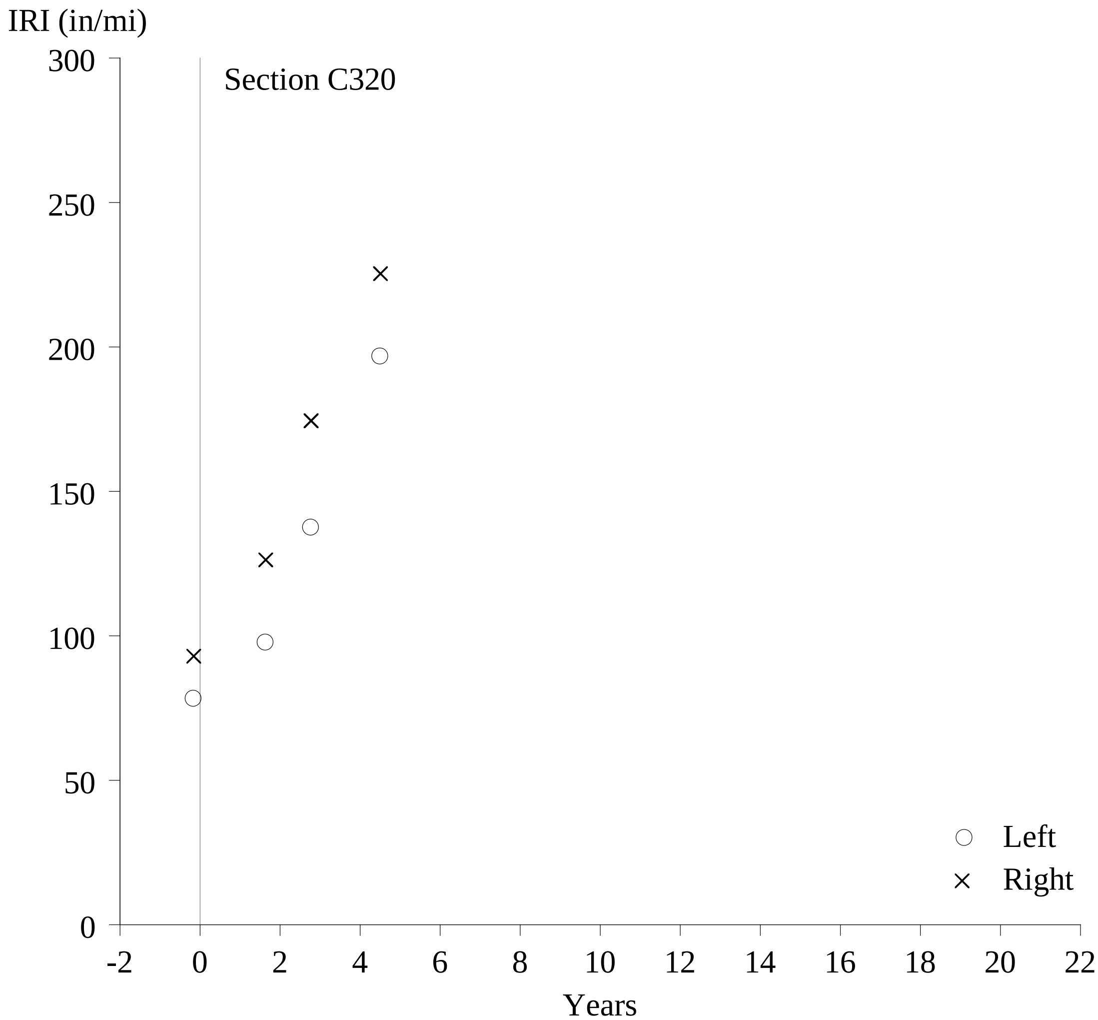

Figure 73. IRI Progression, Section 04C320

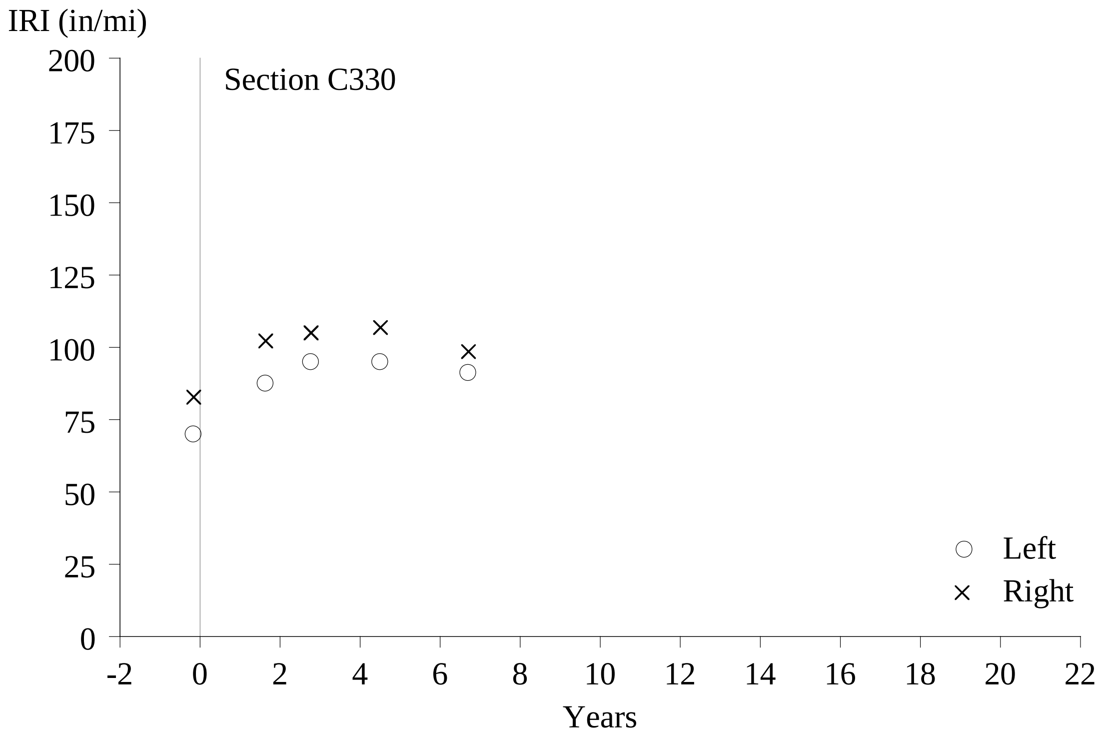

Figure 74. IRI Progression, Section 04C330

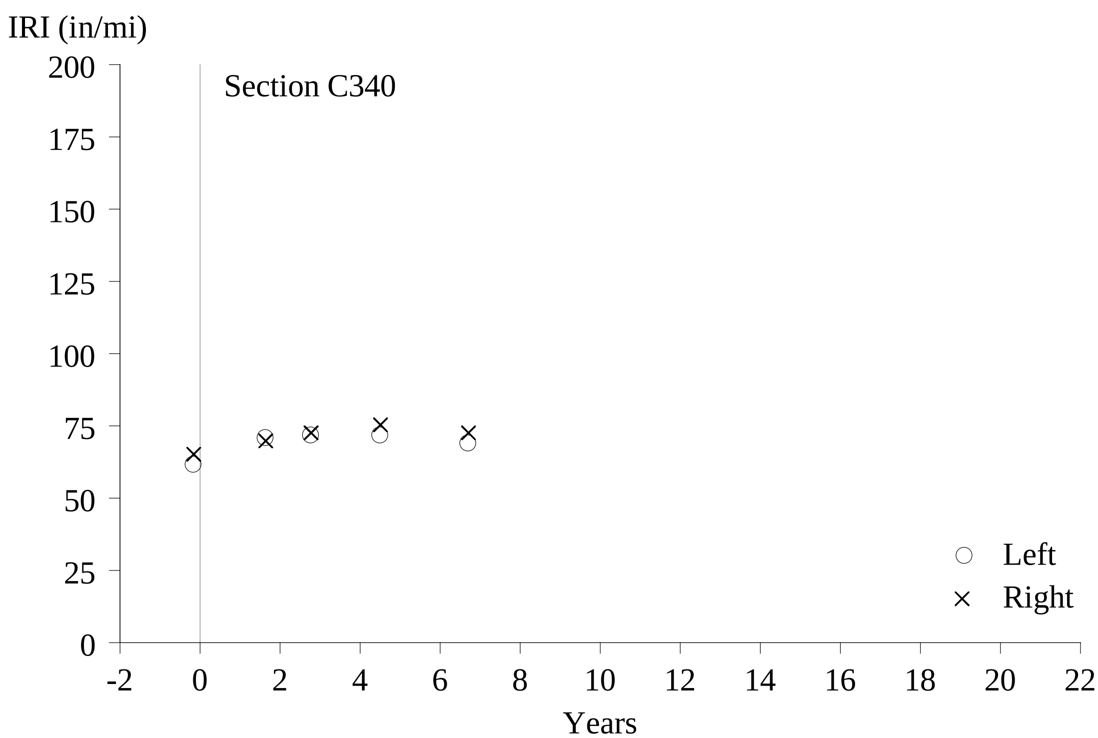

Figure 75. IRI Progression, Section 04C340

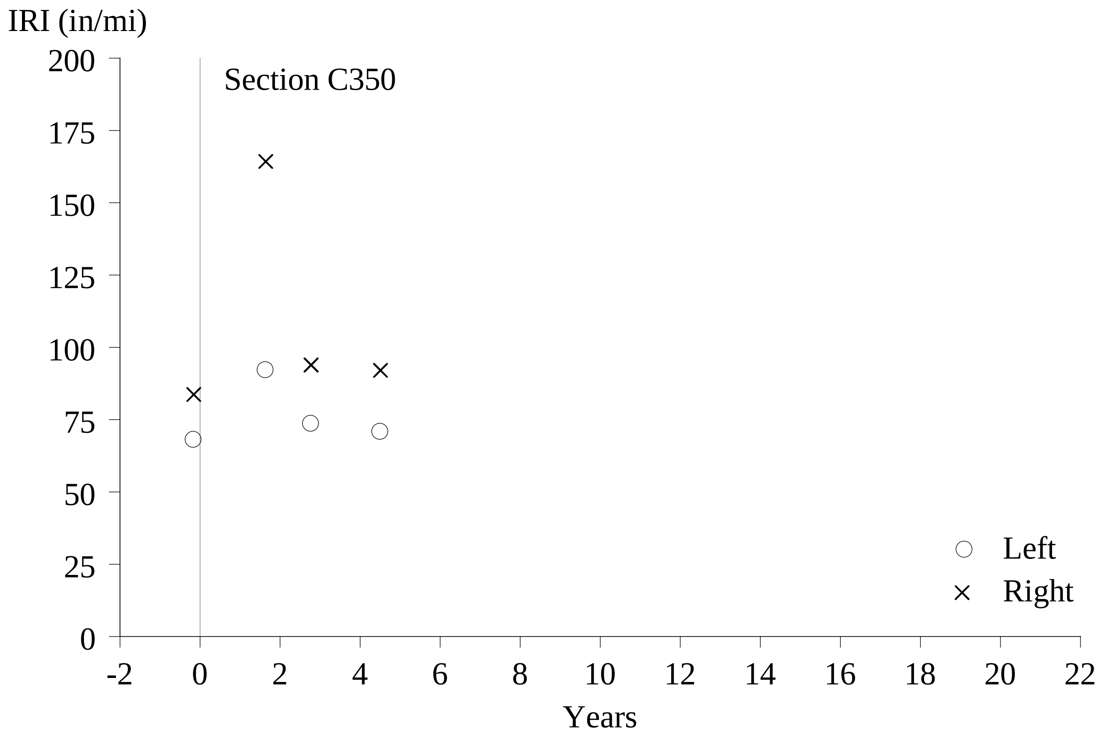

Figure 76. IRI Progression, Section 04C350

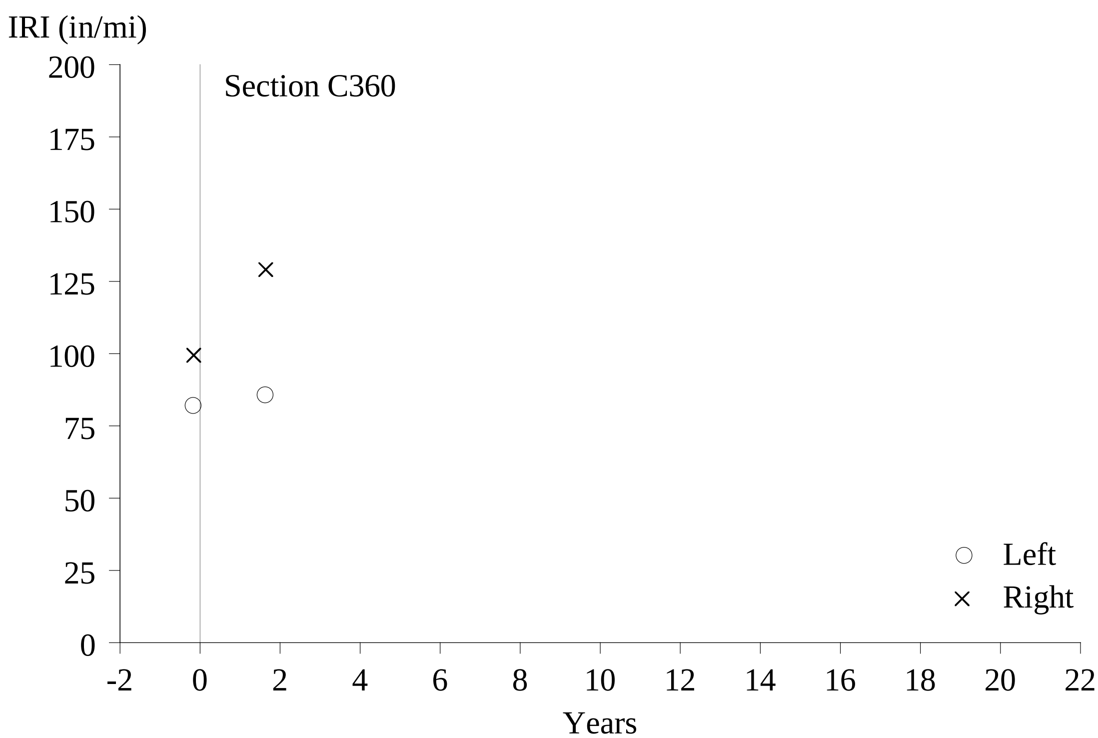

Figure 77. IRI Progression, Section 04C360

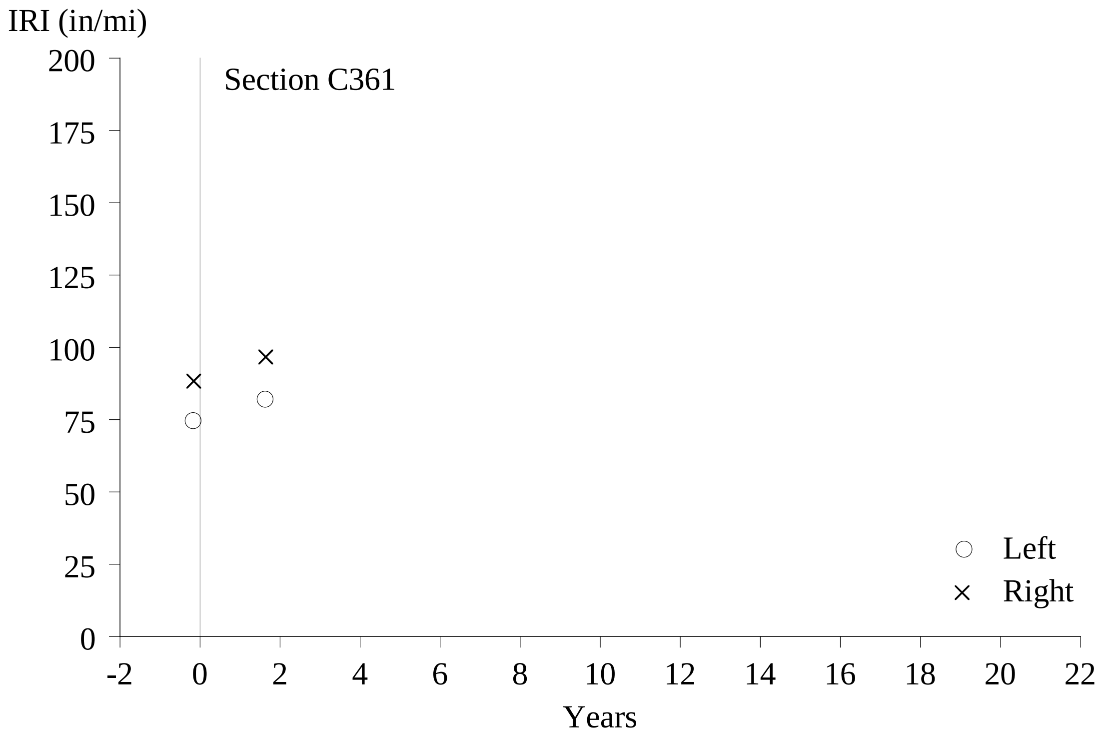

Figure 78. IRI Progression, Section 04C361

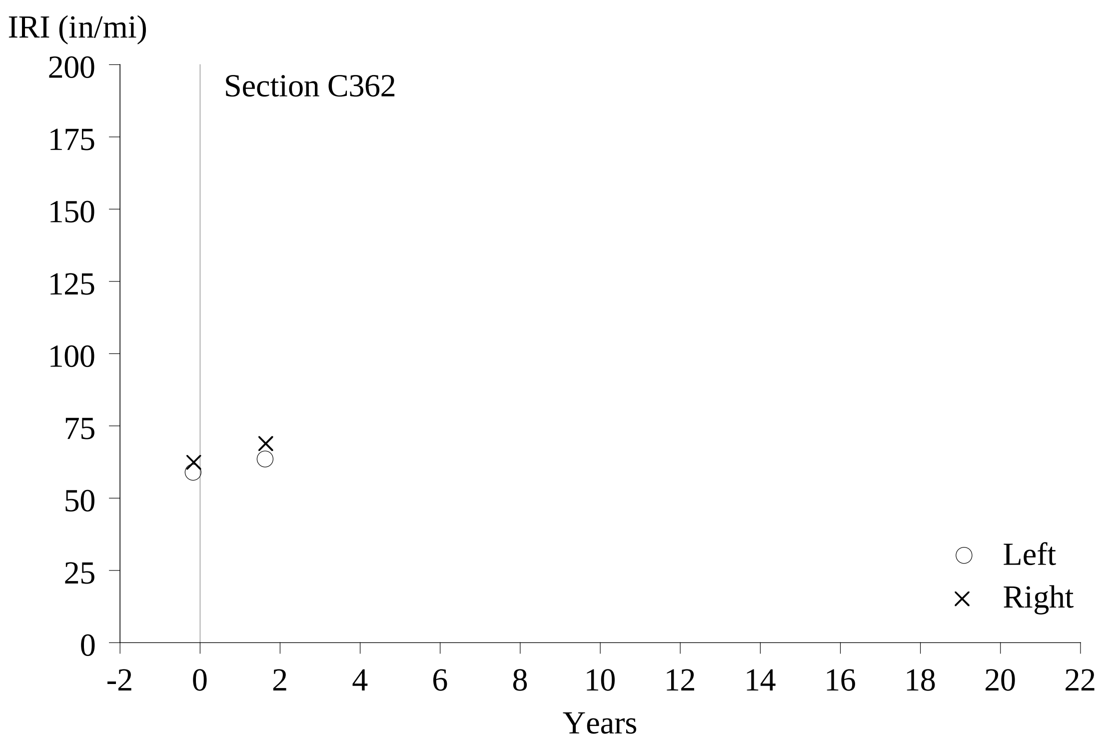

Figure 79. IRI Progression, Section 04C362

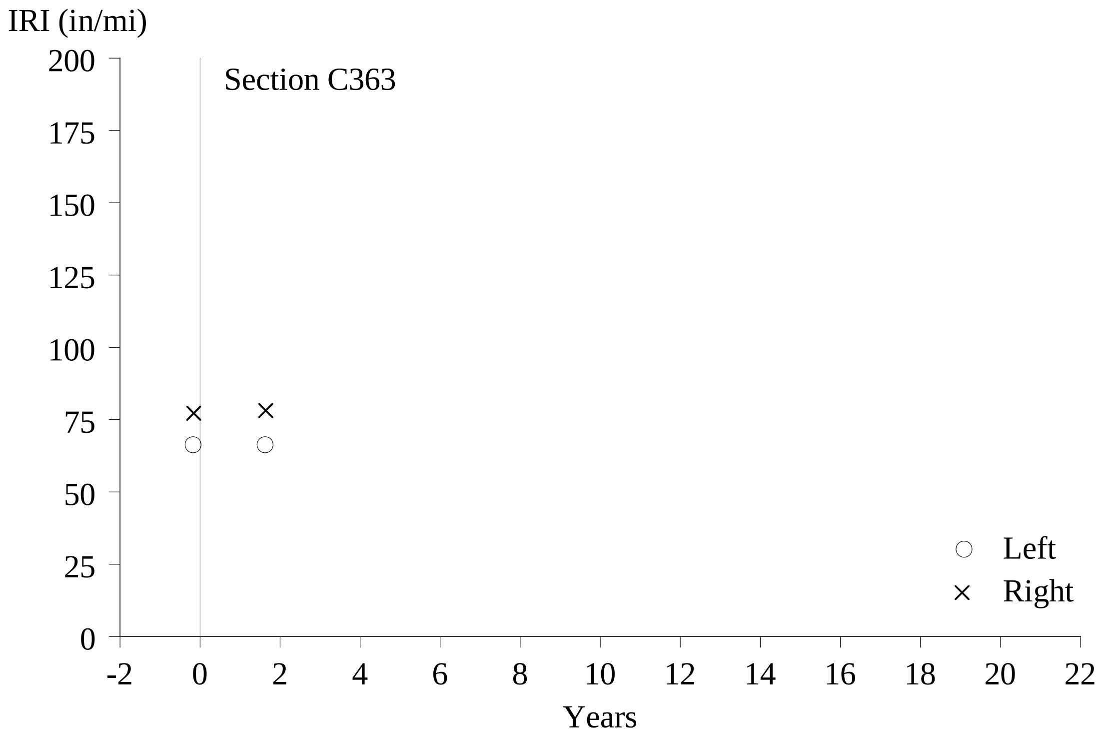

Figure 80. IRI Progression, Section 04C363

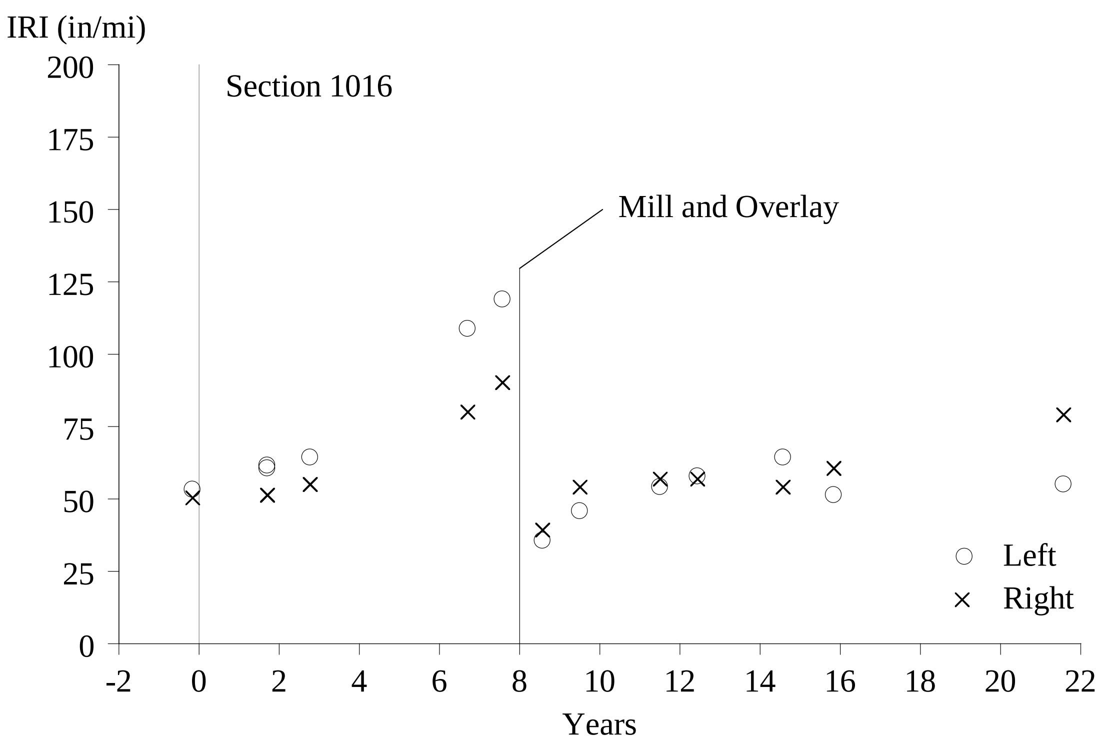

Figure 81. IRI Progression, Section 041016

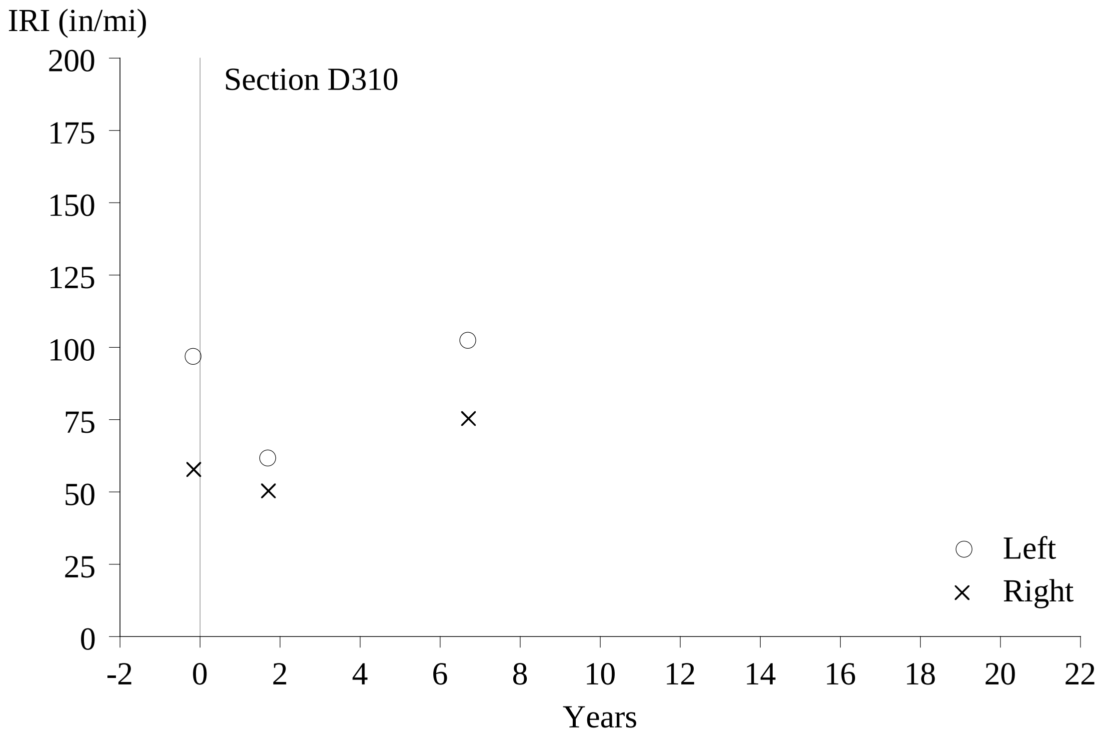

Figure 82. IRI Progression, Section 04D310

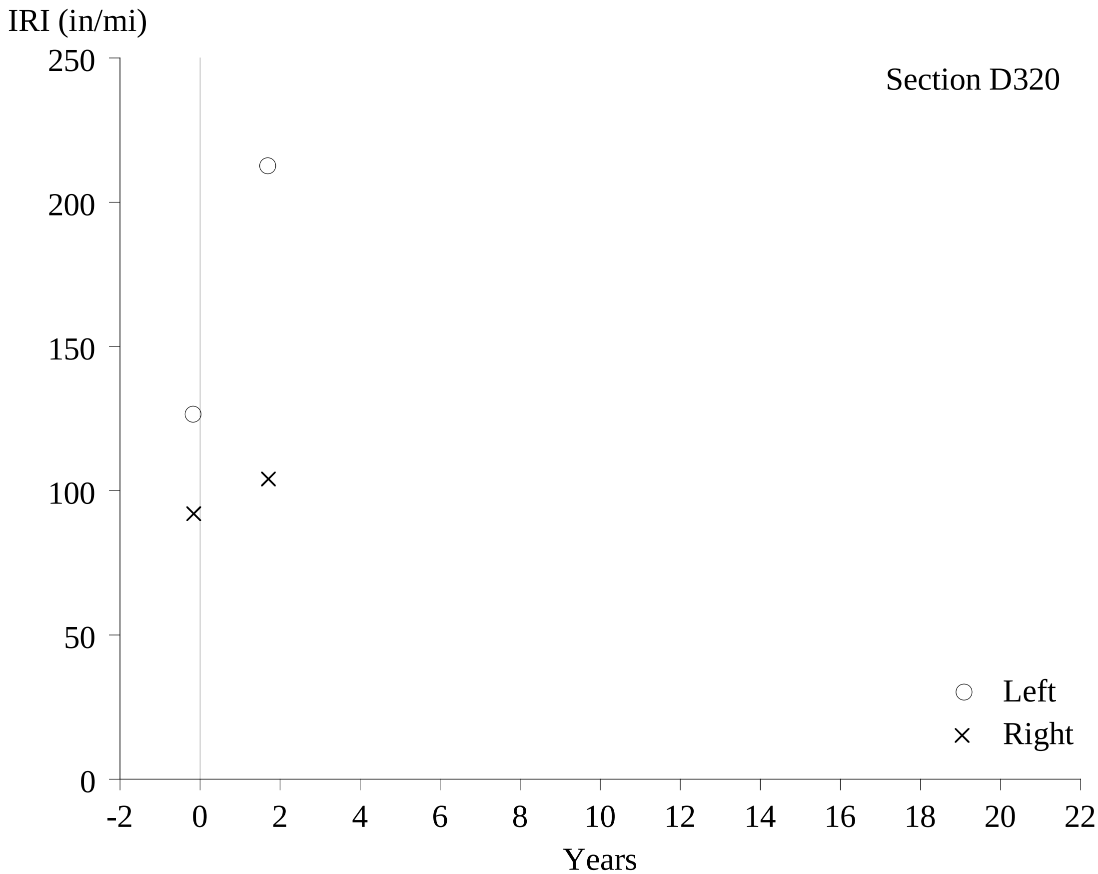

Figure 83. IRI Progression, Section 04D320

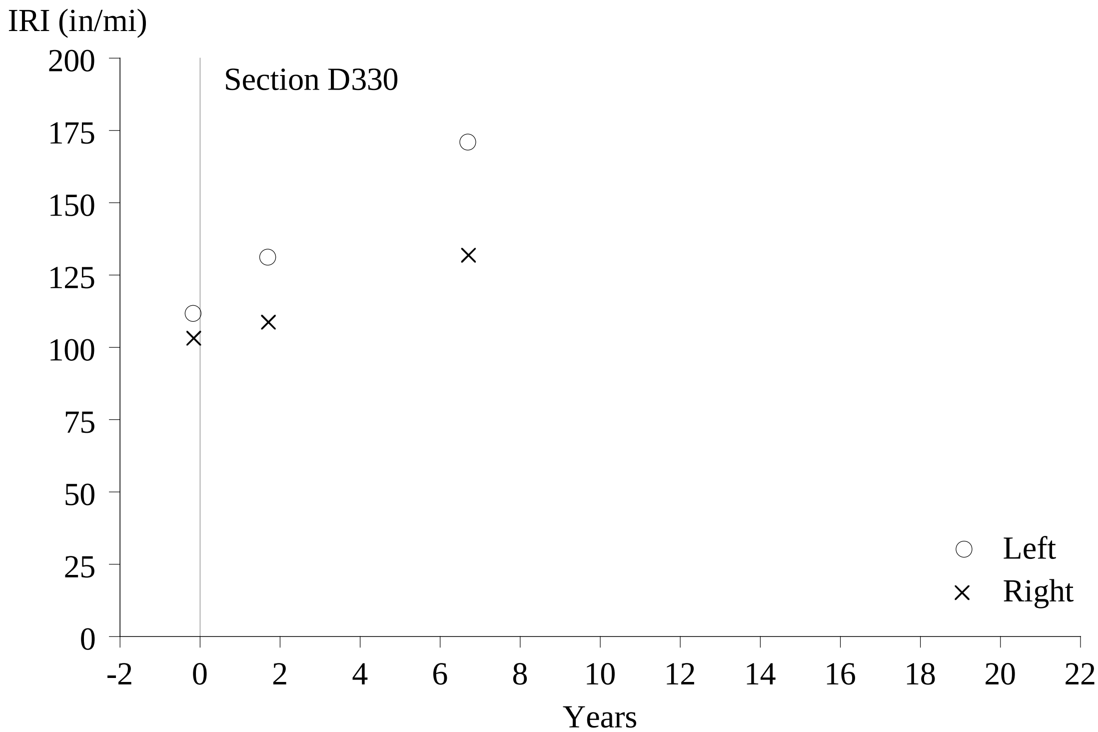

Figure 84. IRI Progression, Section 04D330

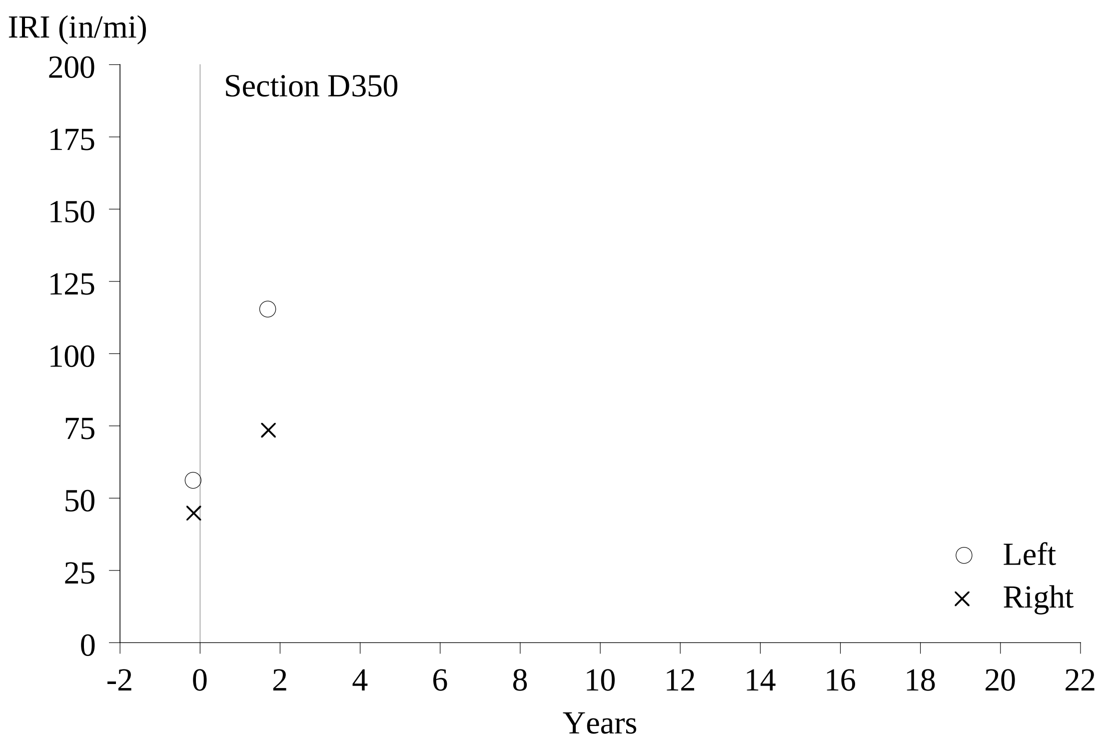

Figure 85. IRI Progression, Section 04D350

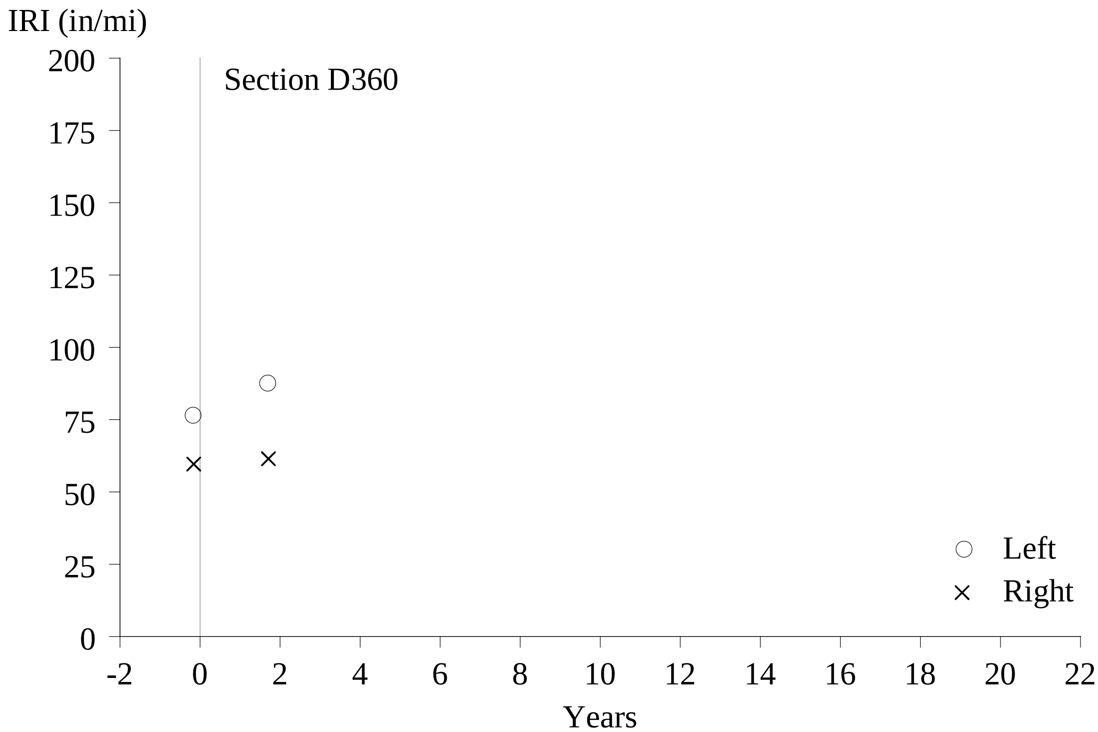

Figure 86. IRI Progression, Section 04D360

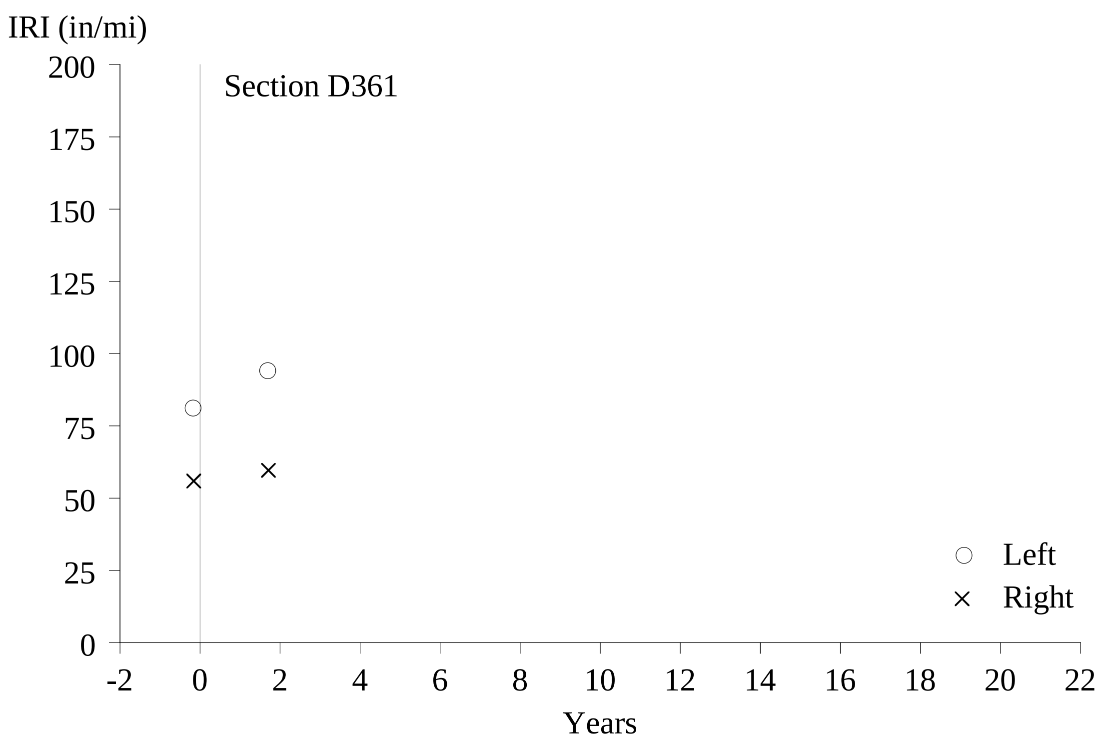

Figure 87. IRI Progression, Section 04D361

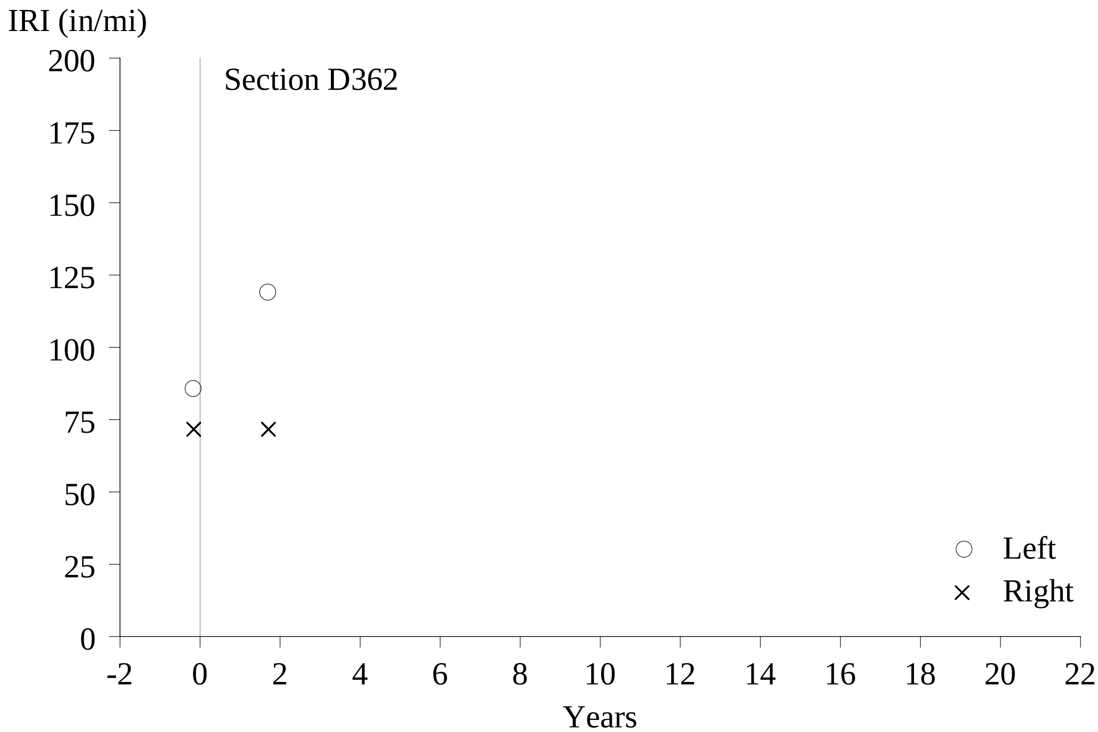

Figure 88. IRI Progression, Section 04D362

OBSERVATIONS FROM PROFILE ANALYSIS

This section provides observations from traditional profile analysis. This tool helps study roughness, roughness distribution, and roughness progression, including concentrated roughness that may be linked to pavement distress. For the analyses of the SPS-3 sites, investigators viewed filtered elevation profile plots, roughness profiles, and power spectral density (PSD) plots. Sayers and Karamihas (1996, 1998) provide tutorial demonstrations of these methods. Karamihas and Senn applied them to other SPS sites in Arizona (Karamihas 2007a; Karamihas 2007b; Karamihas 2007c; Karamihas and Senn 2009; Karamihas and Senn 2010; Karamihas and Senn 2012).

The observations for each section begin with a brief description of the changes in IRI with time in each wheelpath. When the same trend has been observed for the left and right wheelpath, the changes in Mean Roughness Index (MRI), which is the average of the left and right IRI values, are described.

The spectral content from the left-side profiles included a high level of content concentrated at a wavelength of about 2.5 ft in the earlier visits to some of the test sections. These were visits made by the DNC 690 profiler. The concentration of wavelength content was most obvious in visits 02 (March 28, 1990), 04 (February 5, 1993), 05 (January 28, 1994), and 06 (February 28, 1995) to the 04A300 site; visits 01 (March 30, 1990) and 02 (March 31, 1990) to the 04B300 site; and visits 05 (February 4, 1997) and 06 (December 17, 1997) to the 04D300 site.

Section 041036

A sand seal was applied to this section on September 17, 1993.

The left-side IRI grew from 41 inches/mi at visit 01 (August 8, 1989) to 199 inches/mi at visit 06 (February 28, 1995). It then decreased to 167 inches/mi at visit 07 (January 22, 1997) and 162 inches/mi at visit 08 (April 7, 1998). Shallow, narrow dips, typically less than 0.15 inch deep and less than 5 ft wide, appeared throughout the section at visit 03 (February 19, 1992). These had progressed in severity at visit 04 (February 5, 1993) and visit 06. By visit 06, many of the dips were more than 0.25 inch deep. Many of the dips were no longer present at visits 07 and 08. However, the profiles from visits 07 and 08 included short-wavelength "chatter" that was present at earlier visits. This is demonstrated in the spectral content, which includes a blunt peak spreading out from a wavelength near 1 ft.

The right-side IRI grew from 55 inches/mi at visit 01 to 100 inches/mi at visit 04. It decreased to 84 inches/mi at visit 06 and grew modestly to 92 inches/mi by visit 08. Profiles from visits 03 and 04 were uniformly rough over the length of the section, without any localized features that stood out. Although the roughness decreased between visits 04 and 06, the profiles from those two visits were similar. The decrease in roughness owed primarily to a decrease in the depth of narrow dips at several locations.

Section 04A310

An thin overlay of asphalt concrete was placed on this section on August 24, 1990. Some of the long-wavelength content, but none of the medium- and short-wavelength content, was preserved after the overlay. On the left side, the IRI was 38 inches/mi before and after the overlay, and it remained at 45 inches/mi or less through visit 06 in 1995. The IRI rose to 65 inches/mi by visit 08 in 1998. On the right side, the IRI increased from 39 inches/mi before the overlay to 49 inches/mi after the overlay. The IRI remained below 60 inches/mi through visit 06, but it increased to 109 inches/mi by visit 08.

Uncorrelated narrow downward spikes in the left-side profiles appeared at visits 07 and 08 that were not present in previous visits. These spikes were up to 0.2 inch deep.

Several shallow, narrow downward spikes less than 0.1 inch deep appeared at visit 06. Many more appeared at visit 07. In addition, very narrow dips less than 1 ft wide and of varying depths appeared at different distances from the start of the section: At 155 ft from the starting point, the dips were 0.15-0.6 inch deep; at 309 ft, they were up to 0.8 inch deep; and at 368 ft, they were up to 0.4 inch deep.

At visit 08, several narrow downward spikes and some upward spikes appeared, many of them not correlated among the repeat measurements. The most severe (> 1 inch deep in at least two repeats) appeared at 146 ft, 209.5 ft, 242 ft, 250 ft, 302.5 ft, 309.5 ft, and 369 ft from the start of the section.

Section 04A320

A slurry seal was applied to this section on August 24, 1990. The MRI of the section was 36 inches/mi at the visit before the seal coat and 48 inches/mi afterward. By visit 08 (April 7, 1998), the MRI had increased to 63 inches/mi. A rough area appeared at visits 07 (January 22, 1997) and 08 on the left side that featured a 0.15-inch drop in elevation over less than 2 ft about 70 ft from the start of the section.

Section 04A330

This section received crack sealing on August 24, 1990. At visit 02 (March 28, 1990), which was prior to the crack sealing, the MRI was 50 inches/mi. The MRI increased steadily at visits 03 (February 19, 1992) through 07 (January 22, 1997) from 62 inches/mi to 105 inches/mi, but had decreased to 73 inches/mi by visit 08 (April 7, 1998). Profiles from visit 07 included many narrow downward spikes, typically 0.2 inch deep but up to 0.75 inch deep, throughout the section. The shallower spikes were uncorrelated among the repeat measurements. The number and severity of the spikes was greatly reduced by visit 08.

Section 04A350

This section received a chip seal on September 11, 1990. At visit 02 (March 28, 1990), which was prior to the chip seal, the MRI was 42 inches/mi. At visit 03 (February 19, 1992), which was afterward, the MRI was 81 inches/mi, and it increased to 125 inches/mi by visit 04 (February 5, 1993). However, the MRI decreased to 73 inches/mi by visit 05 (January 28, 1994). The MRI subsequently increased to 142 inches/mi by visit 07 (January 22, 1997), but decreased to 126 inches/mi by visit 08 (April 7, 1998).

The growth in roughness between visits 02 and 04 was confined to the wavelength range below 30 ft. Profiles from visit 03 included short-wavelength “chatter” throughout the section, which was more severe and more systematically reproduced among repeat measurements at each visit on the right side, and grew more severe on both sides by visit 04. The fluctuations in elevation were typically less than 0.1 inch in magnitude, and they were difficult to classify as bumps or dips in most areas, because the reversals in elevation continued over most of the section.

Several dips less than 5 ft wide and up to 0.2 inch deep appeared at visit 04 on the right side. Several bumps and dips less than 5 ft wide and up to 0.25 inch in depth appeared at visit 04 on the left side. On both sides, these features were sufficiently well repeated among the visit 04 profiles to indicate that they were associated with features that ran in the transverse direction, such as transverse cracks or transverse joints (as opposed to texture or longitudinal cracks). An exception was a shallow (< 0.1 inch-deep) dip at 125-146 ft from the start of the section, with a narrow dip up to 0.4 inch deep at its center. The chatter, narrow bumps, and narrow dips were no longer present at visit 05, although the long- and medium-wavelength content in the profiles from visit 04 was preserved.

Some chatter and narrow dips began to appear again in the profiles from visit 06. By visit 07, large areas of well-repeated narrow dips appeared throughout the profiles on both side. These were more severe on the right side, particularly in the last 140 ft of the section. The most severe roughness on the left side appeared about 103 ft from the start of the section. In many areas, well-repeated, very narrow (0.5-1.5 ft wide) dips up to 0.6 inch deep appeared from 0.5 ft to 2 ft apart. These were present at visit 08, but they were not as severe in some areas.

Section 04A360

The MRI rose from 47 inches/mi to 62 inches/mi between visits 02 (March 28, 1990) and 03 (February 19, 1992). The left-side profiles from visit 03 included shallow narrow dips less than 0.2 inch deep at 13 ft, 26-39.5 ft, 98 ft, and 138 ft from the start of the section. The left-side profiles also included many uncorrelated narrow dips from 340 ft to 400 ft.

The right-side profiles included narrow downward spikes < 0.08 inch deep at visit 03 that were not present at visit 02; these spikes were seen at 38 ft, 102 ft, 114.5 ft, 321 ft, 362.5 ft, and 445.5 ft from the start of the section. The right-side profiles also included a dip 1.5 ft wide that was 135 ft from the start of the section. It was 0.1 inch deep at visit 02 and grew to 0.25 inch deep by visit 03, so that it stood out as localized roughness. At visit 03 only, another dip appeared 92 ft from the start of the section that was about 7 ft wide and 0.12 inch deep.

Section 04A361

The MRI rose from 39 inches/mi to 54 inches/mi between visits 02 (March 28, 1990) and 03 (February 19, 1992). Some narrow dips up to 0.06 inch deep appeared in the right-side profiles at 39-57 ft from the start of the section. These were present at visit 03, but not at visit 02.

Section 04A362

The MRI rose from 38 inches/mi to 68 inches/mi between visits 02 (March 28, 1990) and 03 (February 19, 1992). Several narrow dips, less than 3 ft wide and up to 0.25 inch deep, appeared in the right-side profiles from visit 03 that were not present at visit 02. They were at 20.5 ft, 50.5 ft, 113 ft, 157 ft, 178.5 ft, 221 ft, 231.5 ft, 266.5 ft, 288 ft, 353.5 ft, and 444 ft from the start of the section.

The spectral content from both sides included a high level of content concentrated at a wavelength of about 2.5 ft at visit 02. It also stood out on the left side at visit 03. (This peak in the PSD plot was submerged under the contribution of the narrow dips to the short-wavelength content in the right-side profiles from visit 03.)

Section 04A363

The MRI rose from 45 inches/mi to 73 inches/mi between visits 02 (March 28, 1990) and 03 (February 19, 1992). Several areas of shallow, narrow downward spikes and uncorrelated short-wavelength content appeared in the right-side profiles from visit 03 that were not present at visit 02. On the left side, a series of very narrow downward spikes appeared in the visit 03 profiles at 348-368 ft from the start of the section. The spikes were up to 0.3 inch deep and not very well correlated among the repeat measurements.

The spectral content from the right-side profiles included a high level of content concentrated at a wavelength of about 1.25 ft at visit 02, 0.83 ft at visit 03, and 2.7 ft at both visits. The spectral content from the left-side profiles included a high level of content concentrated at a wavelength of about 2.5 ft at visit 02.

Section 04A390

This section received a chip seal on August 24, 1990. At visit 02 (March 28, 1990), prior to the chip seal, the MRI was 42 inches/mi. At visit 03 (February 19, 1992), which was afterward, the MRI was 76 inches/mi.

Profiles from visit 03 included short-wavelength chatter throughout the section. The fluctuations in elevation were typically less than 0.05 inch in magnitude, and they were difficult to classify as bumps or dips in most areas, because the reversals in elevation continued over most of the section.

Section 041021

Crack sealing was performed on this section on January 1, 1990, which was before the first profiling visit. The MRI from visits 01 (March 30, 1990) and 02 (March 31, 1990) was 80 and 81 inches/mi, respectively. Patching of potholes took place on January 1,1991, after which the MRI declined to 74 inches/mi at visit 03 (February 19, 1992) and held at 85 inches/mi or less through visit 06 (February 9, 1993). Crack sealing was performed on May 1, 1994. The MRI at the next visit (visit 07, March 21, 1995) was 84 inches/mi. A mill and overlay was performed on January 1, 1997. This reduced the MRI to 49 inches/mi at visit 08 (February 21, 1997), and the MRI held at 57 inches/mi or less through visit 13 (March 12, 2004). The MRI rose to 86 inches/mi by visit 14 (November 29, 2011).

In visits 01 through 07, the left-side profiles included a 0.3-inch reduction in elevation over 13 ft starting 102 ft from the beginning of the section. The reduction included a sharp change in slope at the far end. The right-side profiles at visits 01 through 07 included a 2-ft wide dip 0.05-0.1 inch deep that was at the peak of a long swell 102 ft from the start of the section. These were the roughest features seen during those visits.

Very little of the long-wavelength content and none of the medium- and short-wavelength content from the earlier visits was preserved after the mill and overlay.

After the mill and overlay, the following special features appeared in the left-side profiles: (1) a bump 0.1 inch high and 6 ft wide that was 320 ft from the start of the section at visits 12 and 13; (2) a rough area at the top of a long swell over the first 100 ft of the section with a sharp slope break at about 50 ft; (3) a series of very shallow (< 0.05 inch) bumps and dips that appeared from 144 to 171 ft from the start of the section at visit 13; and (4) a bump 3 ft wide and about 0.1 inch high that appeared 431 ft from the start of the section at visits 8 through 13. The right-side profiles included a bump 5 ft wide and about 0.12 inch high that appeared 23 ft from the start of the section.

At visit 14, the following rough features appeared in the profiles in addition to those present at visit 13: (1) a bump on the left side 8 ft wide and about 0.2 inch high that was 304 ft from the start of the section; and (2) a flat area on both sides from 466 to 478 ft from the start of the section that was about 0.15 inch lower than the surrounding pavement on the left side and shallower on the right side.

Section 04B310

An AC thin overlay was placed on this section on August 28, 1990. At visit 02 (March 31, 1990), before the overlay, the MRI was 90 inches/mi. Afterward, at visit 04 (February 23, 1992), it was 100 inches/mi. The MRI rose to 171 inches/mi at visit 06 (February 9, 1993) and 327 inches/mi at visit 07 (March 21, 1995). Very little of the long-wavelength content and none of the medium- and short-wavelength content from visit 02 was preserved after the overlay.

The growth in roughness was caused by the presence of many narrow (< 3 ft wide) bumps and dips that appeared throughout the profile. Many of them were as much as 0.5 inch in magnitude. These began to appear at visit 06, but were much more numerous at visit 07.

Section 04B320

A slurry seal was applied to this section on August 27, 1990, which was between visits 02 (March 31, 1990) and 04 (February 23, 1992). The IRI for the left side was 86 inches/mi at both visits, and the IRI increased from 77 inches/mi at visit 02 to 81 inches/mi at visit 04. On the right side, the IRI progressed to 107 inches/mi by visit 07 (March 21, 1995). On the left side, the IRI increased to 94 inches/mi by visit 06 (February 9, 1993) and to 180 inches/mi by visit 07.

On the right side, growth in roughness over time occurred in three areas: (1) shallow (< 0.1 inch), narrow (< 1.5 ft wide) dips that grew in number and severity at 128-174 ft from the start of the section; (2) narrow (< 1.5 ft wide) dips that grew in severity to up to 0.15 inch deep at 352-403 ft from the start of the section; and (3) an area with several steep reversals in elevation that became sharper over time at 458-486 ft from the start of the section.

On the left side, visit 07 profiles included many narrow bumps (1.5-3 ft wide). These had begun to appear at visit 04, particularly in the area from 128 to 174 ft from the start of the section. The most severe bumps at visit 07 were 0.4 inches high and appeared 163 ft and 209 ft from the start of the section.

Section 04B330

This section received crack sealing on August 27, 1990. Roughness increased overall at visits 02 (March 31, 1990), before the treatment, 04 (February 23, 1992), 06 (February 9, 1993), and 07 (March 21, 1995) so that the MRI rose from 91 inches/mi at visit 02 to 111 inches/mi at visit 07.

The left-side profiles from all visits included a bump about 0.4 inch high at 69-95 ft from the start of the section (with a peak at about 83.5 ft), and a bump about 0.5 inch high at 479-508.5 ft from the start of the section (with a peak at about 489 ft). These were the roughest areas of the section on the left side.

The right-side profiles included narrow dips 343 ft from the start of the section that grew to 0.2 inch deep by visit 07, and shallower dips 236 ft and 249 ft from the start of the section that grew to about 0.1 inch deep by visit 07.

Section 04B350

This section received a chip seal on August 27, 1990. At visit 02 (March 31, 1990), prior to the chip seal, the IRI was 74 inches/mi on the left side and 66 inches/mi on the right side. At visit 04 (February 23, 1992), which was afterward, the IRI was 65 inches/mi on the left side and 69 inches/mi on the right side. The IRI rose to values above 150 inches/mi on the left side by visit 06 (February 9, 1993), and rose to 119 inches/mi on the right side by visit 07 (March 21, 1995).

On the left side, the profiles were very similar at visits 02 and 04. Visit 06 profiles were much rougher than those at visits 02 and 04, particularly in the range from 300 ft (after the start of the section) to the end of the section. The additional roughness included four deep, narrow dips less than 3 ft wide that caused localized roughness: (1) a dip more than 0.5 inch deep that was 321 ft from the start of the section; (2) a dip 0.5-1 inch deep that was 399 ft from the start of the section; (3) a dip 0.3-1 inch deep that was 402 ft from the start of the section; and (4) a dip 0.3-0.6 inch deep that was 483 ft from the start of the section. Visit 07 profiles were roughest in the second half of the section on the left side, but the roughest features from visit 06 were no longer present. In addition to several narrow bumps and dips of lesser severity, visit 07 profiles included: (1) a narrow dip less than 2 ft wide and 0.5 inch deep that was 286 ft from the start of the section; and (2) a bump about 3 ft wide and 0.5 inch high that was 462 ft from the start of the section.

Shallow, narrow dips appeared throughout the right-side profiles from visit 07 that were not present in previous visits.

Section 04B360

The IRI on the right side rose from 93 inches/mi to 116 inches/mi between visits 02 (March 31, 1990) and 04 (February 23, 1992), but held steady at about 90 inches/mi on the left side. An area of severe localized roughness appeared on the right side at visit 04 from 365 to 399 ft from the start of the section. The roughness appears in the profiles as four closely spaced dips 4-9 ft wide and up to 0.3 inch deep that include wide, flat troughs. (This area was responsible for 10-20 inches/mi of the growth in roughness between visits 02 and 04.) Roughness also increased on the right side because of a dip about 4 ft wide and up to 0.3 inch deep that was 441 ft from the start of the section.

The spectral content for the right side at visit 04 included a high level of roughness concentrated at a wavelength of about 1.2 ft.

Section 04B361

The MRI rose from 130 inches/mi to 147 inches/ mi between visits 02 (March 31, 1990) and 04 (February 23, 1992).

On the right side, the section was twice as rough from 100 to 380 ft from the start of the section as it was in the other areas. The roughness was exacerbated by the growth in severity of the following features between visits 02 and 04: (1) two narrow dips about 105 ft from the start of the section that grew to 0.25 inch deep; (2) an area 139-160 ft from the start of the section that was up to 0.15 inch lower than the surrounding pavement; (3) a dip about 3 ft wide and 0.25 inch deep that was 238 ft from the start of the section; (4) a change in elevation (which appeared as a bump followed by a dip) of more than 0.25 inch over 4 ft starting 273 ft from the start of the section; and (5) a dip 4 ft wide and 0.3 inch deep that was 316 ft from the start of the section.

On the left side, profiles from visit 02 included a narrow (< 2 ft wide) dip up to 0.3 inch deep that was 150 ft from the start of the section. At visit 04, narrow dips appeared 8.5 ft, 13 ft, and 40 ft from the start of the section that were 0.4 inch, 0.25 inch, and 0.45 inch deep, respectively. On the left side, the section was roughest in this area.

The spectral content from both sides included a high level of roughness concentrated at a wavelength of about 39.4 ft at both visits. On the right side, content also stood out at a wavelength of about 11 ft, particularly at visit 04.

Section 041017 (Control 1)

Surface grinding was performed on this section on January 1, 1989, which was before the first profiling visit. The MRI from visit 01 (March 19, 1990) was 68 inches/mi, and it held at between 78 inches/mi and 88 inches/mi at visits 02 (January 12, 1992) through 07 (February 5, 1997). A mill and overlay was performed on May 12, 1997, which reduced the MRI to 36 inches/mi at visit 08 (December 17, 1997). The MRI held at 43 inches/mi or less through visit 14 (March 23, 2006), and increased above 50 inches/mi for visits 15 (January 15, 2010) and 16 (December 6, 2011).

Prior to the mill and overlay, the roughest feature on the right side was a dip 455 ft from the start of the section that was about 0.5 ft wide and grew to 0.15 inch deep by visit 07. The roughest feature on the left side was a flat area from 448 to 470 ft from the start of the section that was about 0.2 inch higher than the surrounding pavement.

Some of the long-wavelength content, but none of the medium- and short-wavelength content, from the earlier visits was preserved after the mill and overlay.

Section 04C310

An AC thin overlay was placed on this section on June 5, 1990. The overlay changed the IRI from 57 inches/mi on the left and 72 inches/mi on the right side at visit 01 (March 19, 1990) to 48 inches/mi on the left side and 77 inches/mi on the right side after the overlay (at visit 03, January 14, 1992). Long-wavelength content within the profile (> 30 ft) was preserved after the overlay, but the medium- and short-wavelength content were not similar to the pre-overlay values.

The roughness of the section on the left side rose to 55 inches/mi by visit 05 (February 25, 1993) and stayed near that value through visit 07 (February 5, 1997). On the right side, the roughness of the section steadily increased to 89 inches/mi through visit 07. The increase on the right was caused by (1) the growth in severity of a downward fault at the trailing edge of an elevated area from 21 to 29 ft from the start of the section; (2) the growth in severity of an upward fault to about 0.2 inch at the leading edge of an elevated area from 172 to 183 ft from the start of the section; and (3) the growth in severity of an upward fault to about 0.25 inch at the leading edge of an elevated area from 272 to 281 ft from the start of the section. (Note that “machine premix patch” is listed for this section on January 1, 1993, which may explain the presence of these elevated areas.)

Section 04C320

A slurry seal was applied to this section on September 6, 1990, which was between visits 01 (March 19, 1990) and 03 (January 14, 1992). The MRI increased from 86 inches/mi at visit 01 to 113 inches/mi at visit 03 and further increased to 213 inches/mi by visit 06 (November 17, 1994).

The overall increase in roughness on the right side was caused primarily by the appearance of localized rough features at specific locations. Two localized rough features appeared at visit 03: (1) a raised area from 58 to 71 ft from the start of the section, which was 0.6 inch above the surrounding pavement; and (2) a raised area of pavement from 384 to 402.5 ft from the start of the section with a 0.35 inch downward fault at the trailing end. Three additional localized rough features appeared at visit 05 (February 25, 1993): (1) a bump about 0.25 inch high from 192 to 209 ft from the start of the section; (2) a raised area of pavement from 384 to 402.5 ft from the start of the section with a 0.35 inch downward fault at the trailing end; and (3) a raised area about 0.25 inch above the surrounding pavement from 290 to 314 ft from the start of the section. By visit 06, the changes in elevation at the borders of some of the raised areas had increased from visit 05. A narrow dip about 2.5 ft wide and 0.5 inch deep also appeared 39 ft from the start of the section.

The overall increase in roughness on the left side was caused primarily by the appearance of localized rough features at specific locations. Three localized rough features appeared at visit 03: (1) a raised area from 50 to 58 ft from the start of the section, which was 0.4 inch above the surrounding pavement at the leading edge and 0.2 inch above the surrounding pavement at the trailing edge; (2) a bump about 298.5 ft from the start of the section; and (3) a raised area of pavement from 361 to 385 ft from the start of the section, with faults up to 0.2 inch high at either end. Three additional localized rough features appeared at visit 05: (1) a dip 86.5 ft from the start of the section; (2) a dip 169 ft from the start of the section; and (3) a bump about 0.25 inch high from 287 to 309 ft from the start of the section. By visit 06, the upward fault at the leading edge of the raised area beginning 50 ft from the start of the section had grown to greater than 0.75 inch high. A narrow dip about 2 ft wide and 0.6 inch deep also appeared 39 ft from the start of the section.

Note that “machine premix patch” is listed for this section on January 1, 1993, which may explain the presence of the elevated areas and localized roughness.

Section 04C330

This section received crack sealing on September 4, 1990. Roughness increased on both sides at visits 01 (March 19, 1990), 03 (January 14, 1992), 05 (February 25, 1993), and 06 (November 17, 1994), with the

MRI rising from 77 inches/mi at visit 01 to 102 inches/mi at visit 06. The MRI decreased to 95 inches/mi by visit 07 (February 5, 1997).

The increase in roughness over time was distributed throughout the section on both sides. At visit 07, a narrow upward spike about 0.25 inch high appeared 64 ft from the start of the section. The right-side profiles at visits 03 through 07 included an area of severe localized roughness caused by dips less than 3 ft wide and up to 0.5 inch deep from 271.5 ft to 279 ft from the start of the section. At visit 07, the dips made a smaller contribution (by 20 percent) to the right-side IRI than they had at visits 05 and 06.

Section 04C340 (Control 2)

The MRI for the section was 63 inches/mi at visit 01 (March 19, 1990) and held at between 70 inches/mi and 75 inches/mi at visits 03 (January 14, 1992) through 07 (February 5, 1997). A narrow bump less than 3.5 ft wide appeared 115 ft from the start of the section on the left side.

Section 04C350

This section received a chip seal on September 6, 1990. Roughness increased on both sides between visits 01 (March 19, 1990) and 03 (January 14, 1992), with the MRI rising from 76 inches/mi to 128 inches/mi. However, the MRI declined to 85 inches/mi by visit 05 (February 25, 1993) and was 82 inches/mi at visit 06 (November 17, 1994).

Visit 03 profiles were similar to those at visit 01 on the left side and in many areas (0-130 ft, 400-460 ft, and others) on the right side, but included several steep changes in slope in other areas that appeared to be at the border between raised and lowered areas of pavement. Filtered elevation profile plots and spectral content at visits 05 and 06 were similar to each other, but were not similar at all to those for visit 03.

Section 04C360

The IRI on the left side rose from 83 inches/mi to 87 inches/mi between visits 01 (March 19, 1990) and 03 (January 14, 1992) and from 100 inches/mi to 130 inches/mi on the right side. The increase in roughness on the right side was caused primarily by the appearance of localized rough features at two locations: (1) a raised area from 56 to 70 ft from the start of the section, which was 0.3 inch above the surrounding pavement; and (2) a pair of raised areas from 263 to 275 ft and from 281 to 290 ft from the start of the section, which were about 0.25 inch above the surrounding pavement.

Section 04C361

The MRI rose from 82 inches/mi to 90 inches/mi between visits 01 (March 19, 1990) and 03 (January 14, 1992). Localized roughness appeared in the right-side profiles from visits 01 and 03 near 123 ft from the start of the section; the roughness was caused by a series of short (< 8 ft long), shallow (< 0.15 inch high) bumps. Visit 03 profiles also included a bump about 5 ft long and 0.15 inch high on the right side about 266 ft from the start of the section.

Section 04C362

The MRI rose from 61 inches/mi to 67 inches/mi between visits 01 (March 19, 1990) and 03 (January 14, 1992). At both visits, a bump 4 ft wide and about 0.1 inch high appeared on the right side at 246 ft from the start of the section.

Section 04C363

The MRI changed from 72 inches/mi to 73 inches/mi between visits 01 (March 19, 1990) and 03 (January 14, 1992).

Section 041016

The MRI of this section rose slowly from 52 inches/mi at visit 01 (March 18, 1990) to 60 inches/mi at visit 04 (February 26, 1993), then it increased to 95 inches/mi at visit 05 (February 4, 1997) and 105 inches/mi at visit 06 (December 17, 1997). After a mill and overlay, the MRI decreased to 38 inches/mi at visit 07 (December 10, 1998) and increased to 67 inches/mi by visit 13 (December 6, 2011).

Growth in roughness at visits 01 through 05 was caused primarily by dips in the profile that appeared in isolated areas, primarily between visits 04 and 05.

On the left side, a pair of dips about 0.15 inch deep appeared beginning at visit 02 (February 12, 1992) at 389 to 400 ft from the start of the section. The dips appeared with lesser severity at visit 04 than at visits 03 (February 13, 1992) and 05. Starting at visit 05, profiles of the dips included a series of very narrow dips within them. (Visit 05 profiles included more detail than those from previous visits, because of the change in profiler from the DNC 690 to the T-6600.) Visit 05 profiles included other narrow dips and areas with narrow dips and spikes within them at 44 to 49.5 ft, 75 to 86 ft, 141 to 160 ft, and 212 to 220 ft. The short-interval roughness profiles showed increased roughness caused by these dips between visits 04 and 05, and their presence at visit 06. Four narrow dips also appeared at 459 to 479 ft from the start of the section at visit 04, and grew in severity by visits 05 and 06, but they did not appear consistently among the five repeat measurements at any of those visits.

On the right side, the profiles from visits 01 through 04 included a dip 0.25 inch deep over the first 25 ft of the section, with a sharp slope break at the center. The profiles from visits 01 through 04 also included a narrow dip at 207 ft from the start of the section that was 0.15-0.2 inch deep. At visits 05 and 06, the first 80 ft of the section grew in roughness caused by narrow dips and other short-wavelength content. The more severe feature was a set of dips up to 0.3 inch deep at 27.5 to 31 ft. Profiles from visits 05 and 06 also included a narrow dip up to 0.6 inch deep at 208 ft from the start of the section, and a dip 0.4 inch deep at 408.5 ft from the start of the section.

The pre- and post-overlay profiles showed no similarity, except in the long-wavelength trends in raw elevation. All of the dips described above were removed on both sides of the lane. The growth in roughness from visits 07 through 13 appeared as very narrow, shallow (typically < 0.1 inch deep) downward spikes in profile that did not have the same location and severity at repeat measurements.

The right-side profiles of some repeat measurements from visits 07 and 08 included a narrow bump (< 1 ft wide) that was 150 ft from the start of the section and up to 0.2 inch high.

Section 04D310

An AC thin overlay was placed on this section on June 2, 1990. The overlay reduced the IRI from 97 inches/mi on the left side and 58 inches/mi on the right side at visit 01 (March 18, 1990) to 62 inches/mi on the left side and 51 inches/mi on the right side at visit 03 (February 13, 1992). Long-wavelength content within the profile (> 30 ft) was preserved after the overlay, but the medium- and short-wavelength content pre- and post-overlay were not similar. PSD plots from the right side at visit 01 showed isolated content at wavelengths of about 65 ft and 14 ft that was not present at subsequent visits.

At all visits, profiles from both sides included a bump over the first 70 ft of the section. The bump came to a peak on the right side with a sharp slope break 29 ft from the start of the section. The profiles also included a sharp slope break on the left side at visits 03 and 05 (February 4, 1997) that was 27 ft from the start of the section.

Between visits 03 and 05, the initial slope at the leading edge of long bumps on the right side at 205 ft, 355 ft, and 490 ft grew more severe. Much of the roughness development between visits was isolated in these locations. On the right side, much of the roughness development was caused by the appearance of shallow (0.075-0.15 inch deep) dips about 5-10 ft wide at various locations, including at 90 ft, 290 ft, 340 ft, and 435-465 ft from the start of the section.

Section 04D320

A slurry seal was applied to this section on September 6, 1990, which was between visits 01 (March 18, 1990) and 03 (February 13, 1992). The IRI increased from 127 inches/mi on the left side and 92 inches/mi on the right side at visit 01 to 213 inches/mi on the left side and 104 inches/mi on the right side at visit 03.

Visit 03 profiles included upward faults at 40 ft and 64 ft from the start of the section on the right side that were not present at visit 01. The right-side profiles from both visits included a bump from 170 to 225 ft from the start of the section. The bump was about 0.75 inch high with a sharp slope break at 210 ft.

The left-side profiles from both visits included a bump from 200 to 225 ft from the start of the section. The bump was about 0.6 inch high with a sharp slope break at 210 ft. At visit 03, the profiles included narrow dips throughout the section that were 1-3 ft wide and 0.075-0.2 inch deep. These dips were prevalent in the last third of the section, and accounted for most of the increase in roughness.

Section 04D330

This section received crack sealing on September 6, 1990, and January 1, 1995. Roughness increased on both sides at visits 01 (March 18, 1990), 03 (February 13, 1992), and 05 (February 4, 1997), with the MRI rising from 108 inches/mi at visit 01 to 152 inches/mi at visit 05.

Short- and medium-wavelength roughness increased throughout the section due to shallow, narrow bumps and dips. The roughness increase was highest at narrow dips near 75.5 ft, 144 ft, 200 ft, 368 ft, and 432 ft from the start of the section, and at shallow bumps near 257 ft and 310 ft from the start of the section. A narrow dip appeared 190.5 ft from the start of the section at visit 05 that was 0.4-0.6 inch deep.

Right-side profiles from all visits included (1) a peak at the leading edge of a long dip 141.5 ft from the start of the section; and (2) a reduction in elevation of about 0.75 inch from 187 ft to 197 ft from the start of the section, leading to the low point of the long dip. Both of these features registered as localized roughness.

Section 04D350

This section received a chip seal on September 6, 1990. Roughness increased on both sides between visits 01 (March 18, 1990) and 03 (February 13, 1992), with the MRI rising from 51 inches/mi to 95 inches/mi. The increase in roughness on the right side between visits 01 and 03 was caused by the development of narrow (< 5 ft wide) dips in the profile at five locations—53 ft, 163 ft, about 200 ft, 362 ft, and 495 ft from the start of the section. The largest contributor was a series of three dips of up to 0.3 inch deep in the area from 186 to 210 ft from the start of the section. The increase in roughness on the left side was also caused by the development of narrow dips, but they were not as isolated or as well repeated between profiler passes. The largest increases in roughness on the left side occurred from 174 to 256 ft from the start of the section (with a large disturbance at 219 ft) and from 387 to 440 ft from the start of the section.

Section 04D360

The MRI rose from 68 inches/mi to 75 inches/mi between visits 01 (March 18, 1990) and 03 (February 13, 1992), with most of the increase occurring on the left side. The roughness development on the left side was strongest where shallow, narrow dips appeared at visit 03 that were 192 ft and 307 ft from the start of the section, and where a narrow bump appeared that was 237 ft from the start of the section.

The spectral content on the left side included concentrated roughness near a wavelength of 30 ft at visits 01 and 03, and a secondary peak in the PSD plot at a wavelength of about 9 ft. The spectral content on the right side included high content in the wavelength range from 30 to 40 ft at both visits.

Section 04D361

The MRI rose from 69 inches/mi to 77 inches/mi between visits 01 (March 18, 1990) and 03 (February 13, 1992), with most of the increase occurring on the left side. The highest level of localized roughness occurred at visit 01, where the elevation within the profile increased by more than 0.25 inch over less than 3 ft beginning at 85 ft from the start of the section. Much of the increase in roughness on the left side between visits 01 and 03 occurred because of disturbances in the profile near 128 ft, 308 ft, and 343 ft from the start of the section.

Section 04D362

The IRI on the left side rose from 86 inches/mi to 119 inches/mi between visits 01 (March 18, 1990) and 03 (February 13, 1992), but held steady at 72 inches/mi on the right side. At visit 01, profiles from the left side included areas of roughness with reversals in profile (i.e., bumps and dips) of up to 0.15 inch every 10-15 ft. These grew in severity by visit 03.

PROFILE ANALYSIS KEY FINDINGS

The profile data captured in the SPS-3 experiment provide insight into the performance of AC pavement maintenance strategies. Specialized analyses were applied to profile measurements to provide a clear picture of the IRI progression and profile features of interest from each test section. Since the monitoring period for many of the sections was short, few trends were identified that linked progression of roughness or profile features to the maintenance treatment applied to each section. The following list provides highlights from the SPS-3 profile analysis.

- Within the core experiment, the rank order of roughness progression was different for each of the four sites, and it is likely that their original condition and traffic loading overshadowed the influence of surface treatment.
- The analyses confirmed that some long-wavelength features, but no medium- or short-wavelength features, are preserved after application of a thin overlay.
- Although application of a “machine premix patch” may have helped reduce structural deterioration, the patches were often evident in the profile and caused additional roughness by virtue of the difference between their surface elevation and that of the surrounding pavement.
- Among those surfaces that progressed in roughness the most, the roughness was caused primarily by densely spaced narrow dips in the profile. This is typical of heavily cracked pavement.

CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

As part of the LTPP program, ADOT constructed 36 SPS-3 test sections over four different project sites in four different locations across Arizona. The SPS-3 experiment was designed to study a variety of preventive maintenance strategies for existing asphalt concrete pavements. Construction of the 36 sections was staggered, beginning in June 1990 and concluding in November 1990, and all SPS-3 sections had been removed from study by mid-1998.

ADOT initiated this project with the expectation that its findings could provide a foundation for future maintenance decisions. Surface distress and profile data were used as the basis for assessing maintenance strategy performance, and each category of data was analyzed as part of this study.

Conclusions drawn from this study must be considered carefully. While the SPS-3 project is intended to offer the ability to directly compare the performance of various pavement maintenance procedures, the experimental design did not offer replicate structures under the same conditions to verify findings, as the four project sites contained different in situ conditions, different traffic loading, and slightly different climate conditions. Therefore, the findings reported may be unique to the conditions and construction of the four sites.

There were some limitations to the experiment. One was the timing of the application of preventive maintenance measures. Based on the level of distress of the pavements prior to application, it is likely that the pavements had distresses beyond the severity level to be considered reasonable candidates for preventive maintenance. Additionally, the analysis did not consider cost factors due to the lack of available information. Cost is an important consideration for agencies in assessing treatment effectiveness.

Despite these complications, the analysis provides valuable insight into pavement maintenance procedures and their effectiveness. Following is a summary of lessons learned:

- Every section exhibited some level of improvement after the maintenance treatment, whether in overall structural damage, environmental damage, or rutting.
- A comparison of the structural and environmental damage indices and amount of rutting indicated that generally, the crack seal was associated with the highest levels of post-treatment distress, followed by the slurry seal and then by the chip seal. The thin overlay was associated with the least amount of structural and environmental damage and the lowest rutting levels.
- A comparison of the calculated life extension provided by each treatment method revealed that the thin overlay provided the largest increase in life span, followed by the slurry seal, followed by the chip seal. The crack seal provided the smallest increase in life span. This ranking is based on the findings with respect to environmental distress and rutting; the life extension results with respect to structural distress were inconsistent.

- The time series distress data revealed that, in general, the thin overlay performed the best among the four treatment methods, while the slurry seal generally performed the worst. The chip seal performed slightly worse than the thin overlay, followed by the crack seal.
- Distress data from a single point in time indicated that the thin overlay performed the best, followed by the chip seal and then by the slurry seal. The crack seal exhibited the worst performance.
- Measurements of treatment effectiveness showed that the thin overlay performed best in preventing rutting, followed by the crack seal, then the slurry seal, and then the chip seal. In protecting against environmental distresses, the thin overlay performed better than the crack seal, but other conclusions could not be drawn from the scattered data.
- Within the core experiment, the rank order of roughness progression was different for each of the four sites, and it is likely that their original condition and traffic loading overshadowed the influence of surface treatment.
- The analyses confirmed that some long-wavelength features, but no medium- or short-wavelength features, are preserved after application of a thin overlay.
- Although use of a "machine premix patch" may have helped reduce structural deterioration, the patches were often evident in the pavement profile and caused additional roughness by virtue of the difference between their surface elevation and that of the surrounding pavement.
- With surfaces that progressed in roughness the most, the roughness was caused primarily by densely spaced narrow dips in the profile. This is typical of heavily cracked pavement.

Based on these findings, the research team presents the following conclusions for consideration by ADOT:

- Overall, the thin overlay performed the best in countering both rutting and structural distresses. The slurry seal overall was the best performer in countering environmental distresses.
- The maintenance treatments in the SPS-3 experiment were placed on existing pavements that were in very poor condition. By most standards, the pavements had deteriorated past the point where a maintenance treatment would be effective. Proper timing in applying maintenance treatments is critical to successfully extending pavement life.

To address changes over time and to incorporate lessons learned during this project, the research team recommends that ADOT consider initiating a new study of asphalt concrete preventive maintenance that would include:

- Updated techniques (asphalt rubber friction course, microsurfacing, rubberized chip seals, etc.)
- Improved timing of maintenance treatments (time to first treatment and intervals between subsequent treatments)
- Treatment cost

With respect to this recommendation of a new study, it should be noted that the Long Term Pavement Performance program is developing a new experiment investigating preservation of asphalt concrete pavements.

REFERENCES

Huang, Yang. 1993. *Pavement Analysis and Design*. Englewood Cliffs, NJ: Prentice Hall.

Karamihas, Steven M. 2004. "Development of Cross Correlation for Objective Comparison of Profiles." *International Journal of Vehicle Design.* 36 (2/3): 173-193.

Karamihas, Steven M. 2007a. *Profile Analysis of the LTPP SPS-1 Site in Arizona.* Publication UMTRI-2007-16. Ann Arbor: University of Michigan Transportation Research Institute.

Karamihas, Steven M. 2007b. *Profile Analysis of the LTPP SPS-9A Site in Arizona.* Publication UMTRI-2007-17. Ann Arbor: University of Michigan Transportation Research Institute.

Karamihas, Steven M. 2007c. *Profile Analysis of the LTPP SPS-9P Site in Arizona.* Publication UMTRI-2007-18. Ann Arbor: University of Michigan Transportation Research Institute.

Karamihas, Steven M. and Kevin Senn. 2009. "Profile Analysis of Arizona Specific Pavement Studies 5 Project." *Transportation Research Record*: *Journal of the Transportation Research Board* 2095: 144–152.

Karamihas, Steven M. and Kevin Senn. 2010. *Profile Analysis of the LTPP SPS-6 Site in Arizona.* Publication UMTRI-2010-17. Ann Arbor: University of Michigan Transportation Research Institute.

Karamihas, Steven M. and Kevin Senn. 2012. *Curl and Warp Analysis of the LTPP SPS-2 Site in Arizona.* Publication FHWA-HRT-12-068. McLean, VA: Federal Highway Administration.

Miller, John S. and William Y. Bellinger. 2003. *Distress Identification Manual for the Long-Term Pavement Performance Program*. Fourth edition. Publication FHWA-RD-03-031. McLean, VA: Federal Highway Administration.

Puccinelli, Jason, Steven M. Karamihas, Sam Shih-Hsien Yang, Jonathan Minassian, and Kevin Senn. 2016. *Performance Evaluation of Arizona's LTPP SPS-9 Project: Strategic Study of Flexible Pavement Mix Design Factors*. FHWA-AZ-16-396(9B). Phoenix: Arizona Department of Transportation.

Puccinelli, Jason, Steven Karamihas, Kathleen T. Hall, Jonathan Minassian, and Kevin Senn. 2015. *Performance Evaluation of Arizona's LTPP SPS-9 Project: Strategic Study of Flexible Pavement Binder Factors*. FHWA-AZ-15-396(9A). Phoenix: Arizona Department of Transportation.

Puccinelli, Jason, Steven M. Karamihas, Kathleen T. Hall, and Kevin Senn. 2013. *Performance Evaluation of Arizona's LTPP SPS-6 Project: Strategic Study of Rehabilitation Techniques*. FHWA-AZ-13-396(6). Phoenix: Arizona Department of Transportation.

Puccinelli, Jason, Steven M. Karamihas, Kathleen T. Hall, and Kevin Senn. 2012. *Performance Evaluation of Arizona's LTPP SPS-1 Project: Strategic Study of Flexible Pavement Structural Factors*. FHWA-AZ-12-396. Phoenix: Arizona Department of Transportation.

Rada, G. R., C. L. Wu, R. K. Bhandari, A. R. Shekharan, G. E. Elkins, and J. S. Miller. 1999. *Study of LTPP Distress Data Variability*. Vol. I-II. Publications FHWA-RD-99-074 and FHWA-RD-99-075. McLean, VA: Federal Highway Administration.

Sayers, Michael W. and Steven M. Karamihas. 1996. *Interpretation of Road Roughness Profile Data*. Publication UMTRI-96-19. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Sayers, Michael W. and Steven M. Karamihas. 1998. *The Little Book of Profiling.* Ann Arbor: University of Michigan.

Simpson, A. L. 2001. *Characterization of Transverse Profiles*. Publication FHWA-RD-01-024. McLean, VA: Federal Highway Administration.

APPENDIX: ROUGHNESS VALUES

This appendix lists the left-side International Roughness Index (IRI), right-side IRI, Mean Roughness Index (MRI), Half-car Roughness Index (HRI), and Ride Number (RN) values for each visit to each section. The roughness values are the average of five repeat runs. The five runs were selected from a group of as many as nine by automated comparison of profiles, as described in the main report. Standard deviations (SDs) are also provided for left and right IRI values to reveal cases of high variability among the five measurements. However, the screening procedure used to select the five repeats usually helped reduce the level of scatter.

The discussion of roughness in the main report emphasizes the left and right IRI. Nevertheless, the other indexes do provide useful additional information. The MRI is simply the average of the left and right IRI values. The HRI is calculated by converting the IRI filter into a half-car model (Sayers 1989). This is done by collapsing the left and right profiles into a single profile in which each point is the average of the corresponding left and right elevation. The IRI filter is then applied to the resulting signal. The HRI is very similar to the IRI, except that side-to-side deviations in profile are eliminated. The result is that the HRI value for a pair of profiles will always be lower than the corresponding MRI value. Comparing the HRI and MRI values provides a crude indication of the significance of roll (i.e., side-by-side variation in profile) to the overall roughness. When the HRI is low compared to the MRI, roll is significant. This is common among asphalt pavements (Karamihas et al. 1995).

Figure A-1 compares the HRI to the MRI for all of the profile measurements that are covered in this appendix. The measurements consist of 154 pairs of roughness values. The figure shows a best-fit line with a zero intercept and a line of equality. The slope of the line is 0.789. This is an unusually large difference between the HRI and the MRI. Note that a better linear fit was found without forcing a zero intercept. A simple linear fit produced a slope of about 0.764 and an intercept of about 2.5 inches/mi.

The RN has shown a closer relationship to road user opinion than the other indexes (Sayers and Karamihas 1996). Therefore, it may help distinguish the segments from each other by ride quality. Further, when a particular type of distress dominates the roughness of a section, the effect on RN may help quantify the impact of that distress on ride. In particular, a very low RN value coupled with moderate IRI values indicates a high level of short-wavelength roughness, and a potential sensitivity to narrow dips and measurement errors caused by coarse surface texture.

Table A-1 provides the roughness values. The table also lists the date of each measurement, the time in years since the maintenance treatments were applied, and the standard deviations (SD) for the IRI values. Negative values indicate measurements that were made before the SPS-3 maintenance activities.

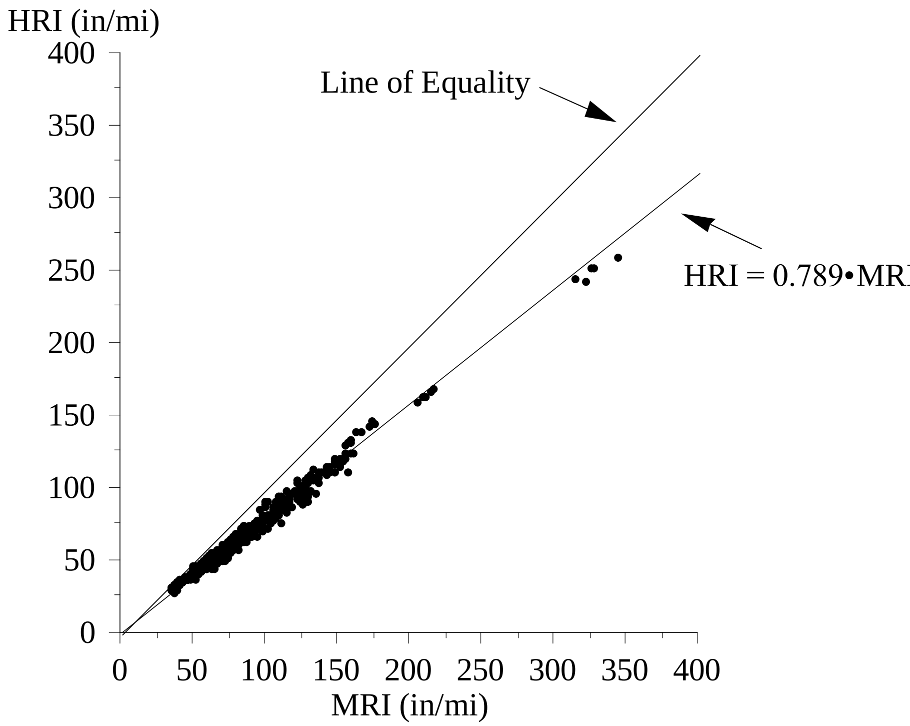

Figure A-1. Comparison of the HRI to the MRI

Table A-1. Roughness Values

Section	Date	Years	Left IRI (inches/mi)		Right IRI (inches/mi)		MRI (inches /mi)	HRI (inches /mi)	RN
			Avg	SD	Avg	SD			
041036	8/8/89	-1.04	41	1.0	55	8.0	48	41	3.51
041036	2/19/92	1.49	125	4.6	96	5.1	111	87	3.21
041036	2/5/93	2.45	150	16.0	100	2.5	125	93	2.80
041036	2/28/95	4.51	199	23.5	84	2.5	141	108	2.73
041036	1/22/97	6.41	167	2.4	88	2.0	127	90	2.33
041036	4/7/98	7.62	162	19.2	92	1.5	127	90	2.19
04A310	3/28/90	-0.41	38	0.8	40	2.0	39	34	4.32
04A310	2/19/92	1.49	38	1.2	59	2.8	49	40	4.15
04A310	2/5/93	2.45	40	1.2	57	1.9	48	39	4.06
04A310	1/28/94	3.43	43	1.2	59	1.7	51	41	3.95
04A310	2/28/95	4.51	45	2.3	73	2.4	59	48	3.77
04A310	1/22/97	6.41	54	2.2	101	2.4	78	57	3.00
04A310	4/7/98	7.62	65	3.5	153	36.4	109	83	2.30
04A320	3/28/90	-0.41	37	1.6	34	0.6	36	31	4.38
04A320	2/19/92	1.49	49	1.9	47	2.5	48	40	4.10
04A320	2/5/93	2.45	51	1.4	53	1.8	52	41	3.98
04A320	1/28/94	3.43	53	1.1	44	2.1	49	39	3.97
04A320	2/28/95	4.51	52	1.7	51	2.9	52	41	3.94
04A320	1/22/97	6.41	57	1.7	53	2.0	55	44	3.51
04A320	4/7/98	7.62	62	2.1	64	2.0	63	50	3.36
04A330	3/28/90	-0.41	50	0.7	51	0.6	50	45	4.18
04A330	2/19/92	1.49	58	1.0	66	2.7	62	54	3.82
04A330	2/5/93	2.45	61	3.8	66	1.4	63	55	3.71
04A330	1/28/94	3.43	71	1.2	72	1.4	71	59	3.58
04A330	2/28/95	4.51	78	1.4	83	1.5	80	65	3.22
04A330	1/22/97	6.41	99	2.6	111	4.3	105	82	2.19
04A350	3/28/90	-0.41	46	2.8	38	0.5	42	35	4.28
04A350	2/19/92	1.49	72	6.3	89	14.8	81	63	3.17
04A350	2/5/93	2.45	112	7.8	138	7.1	125	95	2.32
04A350	1/28/94	3.43	69	3.0	76	3.1	73	57	3.38
04A350	2/28/95	4.51	97	8.8	118	3.4	108	82	2.56
04A350	1/22/97	6.41	111	4.0	173	4.9	142	112	1.49
04A350	4/7/98	7.62	105	22.9	147	31.1	126	93	1.69
04A360	3/28/90	-0.41	49	1.5	46	0.9	47	39	4.15
04A360	2/19/92	1.49	67	4.6	62	1.7	65	51	3.68
04A361	3/28/90	-0.41	39	0.8	38	0.8	39	34	4.36
04A361	2/19/92	1.49	52	1.9	56	1.1	54	44	3.96
04A362	3/28/90	-0.41	39	1.2	37	1.3	38	30	4.32
04A362	2/19/92	1.49	71	3.2	64	1.0	68	51	3.64

Table A-1. Roughness Values (Continued)

Section	Date	Years	Left IRI (inches/mi)		Right IRI (inches/mi)		MRI (inches /mi)	HRI (inches /mi)	RN
			Avg	SD	Avg	SD			
04A363	2/28/90	-0.41	44	3.8	46	1.7	45	36	4.22
04A363	2/19/92	1.49	79	4.0	67	0.8	73	55	3.34
04A390	3/28/90	-0.41	44	0.8	40	1.1	42	37	4.33
04A390	2/19/92	1.49	69	4.1	83	0.9	76	60	3.33
041021	3/30/90	-0.41	81	4.3	81	4.8	81	66	3.60
041021	3/31/90	-0.41	78	2.5	82	5.5	80	64	3.62
041021	2/19/92	1.48	72	2.5	76	4.1	74	60	3.75
041021	2/23/92	1.49	72	0.9	79	4.1	75	61	3.88
041021	2/9/93	2.45	76	3.1	89	0.8	82	66	3.61
041021	2/9/93	2.45	81	6.5	89	2.5	85	67	3.47
041021	3/21/95	4.56	78	2.1	91	1.0	84	67	3.49
041021	2/21/97	6.49	54	0.4	43	0.6	49	40	4.14
041021	4/16/98	7.63	56	1.4	45	1.2	51	42	4.05
041021	3/3/99	8.51	56	1.1	46	0.5	51	41	4.04
041021	3/15/00	9.55	63	1.5	46	0.5	54	44	4.08
041021	2/19/02	11.48	62	0.9	46	0.2	54	44	4.09
041021	3/12/04	13.54	67	0.5	48	0.7	57	46	4.06
041021	11/29/11	21.25	84	1.6	87	0.6	86	64	3.63
04B310	3/31/90	-0.41	94	5.9	86	0.5	90	74	3.40
04B310	2/23/92	1.49	95	2.5	105	1.7	100	89	3.39
04B310	2/9/93	2.45	178	7.4	163	3.9	171	142	1.98
04B310	3/21/95	4.56	344	12.0	309	13.4	327	250	0.99
04B320	3/31/90	-0.41	86	3.4	77	4.9	81	67	3.45
04B320	2/23/92	1.49	86	2.0	81	2.6	84	72	3.42
04B320	2/9/93	2.45	94	3.1	87	2.6	90	74	3.31
04B320	3/21/95	4.56	180	5.3	107	3.3	144	114	2.35
04B330	3/31/90	-0.41	97	4.6	84	3.4	91	73	3.44
04B330	2/23/92	1.49	93	1.6	95	5.3	94	77	3.50
04B330	2/9/93	2.45	104	3.8	94	3.1	99	78	3.20
04B330	3/21/95	4.56	118	5.2	105	2.3	111	88	3.12
04B350	3/31/90	-0.41	74	4.7	66	1.8	70	55	3.63
04B350	2/23/92	1.49	65	1.1	69	2.9	67	55	3.67
04B350	2/9/93	2.45	154	12.3	77	1.4	116	99	2.43
04B350	3/21/95	4.56	157	9.0	119	13.3	138	108	2.48
04B360	3/31/90	-0.41	92	5.2	94	3.2	93	73	3.38
04B360	2/23/92	1.49	90	1.8	142	9.2	116	93	2.98
04B361	3/31/90	-0.41	145	7.5	115	3.1	130	108	2.57
04B361	2/23/92	1.49	159	8.8	135	4.2	147	115	2.19
041017	3/19/90	-0.21	64	4.4	72	3.9	68	53	3.93
041017	1/12/92	1.60	75	2.0	81	1.8	78	60	3.82
041017	1/14/92	1.61	76	4.2	88	2.4	82	63	3.70
041017	2/24/93	2.72	85	1.1	91	1.6	88	67	3.59
041017	2/25/93	2.73	82	4.2	89	1.6	86	65	3.58

Table A-1. Roughness Values (Continued)

Section	Date	Years	Left IRI (inches/mi)		Right IRI (inches/mi)		MRI (inches /mi)	HRI (inches /mi)	RN
			Avg	SD	Avg	SD			
041017	11/17/94	4.45	84	1.5	92	3.1	88	67	3.58
041017	2/5/97	6.67	83	1.0	91	1.2	87	67	3.34
041017	12/17/97	7.53	38	0.3	37	0.2	38	32	4.14
041017	12/10/98	8.51	36	0.5	35	0.3	36	32	4.25
041017	11/12/99	9.44	37	0.4	37	0.9	37	33	4.26
041017	11/14/01	11.44	37	1.0	36	0.8	37	33	4.29
041017	11/7/02	12.42	37	0.7	38	0.5	37	32	4.15
041017	12/9/04	14.51	41	0.7	39	0.6	40	35	4.09
041017	3/23/06	15.80	41	0.5	43	0.8	42	35	3.99
041017	1/15/10	19.61	54	1.0	50	0.9	52	44	3.61
041017	12/6/11	21.50	54	1.3	55	0.7	54	46	3.44
04C310	3/19/90	-0.21	57	0.8	72	1.6	64	52	3.97
04C310	1/14/92	1.61	48	2.0	77	3.8	63	50	3.89
04C310	2/25/93	2.73	55	1.3	80	1.4	68	53	3.80
04C310	11/17/94	4.45	54	0.7	85	1.4	69	55	3.80
04C310	2/5/-97	6.67	55	1.2	89	1.2	72	56	3.68
04C320	3/19/90	-0.21	79	1.6	93	2.6	86	71	3.83
04C320	1/14/92	1.61	98	2.0	127	5.2	113	92	3.31
04C320	2/25/93	2.73	138	6.0	175	3.2	157	123	2.92
04C320	11/17/94	4.45	198	5.7	226	3.8	212	164	2.20
04C330	3/19/90	-0.21	70	0.8	83	3.5	77	61	3.88
04C330	1/14/92	1.61	88	2.8	103	0.8	95	73	3.57
04C330	2/25/93	2.73	95	1.7	106	2.4	100	79	3.38
04C330	11/17/94	4.45	96	3.3	108	3.7	102	78	3.25
04C330	2/5/97	6.67	92	1.0	99	3.5	95	74	3.24
04C340	3/19/90	-0.21	62	1.4	66	1.5	64	46	3.92
04C340	1/14/92	1.61	71	2.6	71	2.4	71	51	3.77
04C340	2/25/93	2.73	72	2.9	73	2.7	73	52	3.68
04C340	11/17/94	4.45	72	1.6	76	2.2	74	52	3.64
04C340	2/5/97	6.67	69	1.5	73	2.6	71	53	3.49
04C350	3/19/90	-0.21	68	3.3	84	6.7	76	64	3.94
04C350	1/14/92	1.61	93	1.6	164	7.0	128	103	3.21
04C350	2/25/93	2.73	74	2.7	95	1.7	85	70	3.66
04C350	11/17/94	4.45	71	2.7	93	2.5	82	70	3.73
04C360	3/19/90	-0.21	83	1.9	100	1.6	92	71	3.58
04C360	1/14/92	1.61	87	1.5	130	2.1	108	81	3.33
04C361	3/19/90	-0.21	75	1.9	88	2.3	82	64	3.71
04C361	1/14/92	1.61	82	2.1	97	4.0	90	71	3.60
04C362	3/19/90	-0.21	59	3.1	63	1.3	61	50	4.05
04C362	1/14/92	1.61	64	1.8	70	1.3	67	55	3.93
04C363	3/19/90	-0.21	67	1.7	77	0.7	72	60	3.96
04C363	1/14/92	1.61	67	1.3	79	2.9	73	61	3.99

Table A-1. Roughness Values (Continued)

Section	Date	Years	Left IRI (inches/mi)		Right IRI (inches/mi)		MRI (inches /mi)	HRI (inches /mi)	RN
			Avg	SD	Avg	SD			
041016	3/18/90	-0.22	54	3.5	51	1.8	52	43	4.10
041016	2/12/92	1.69	61	1.9	52	1.4	57	47	3.98
041016	2/13/92	1.69	62	0.7	52	1.1	57	48	3.98
041016	2/26/93	2.73	65	2.8	56	0.8	60	49	3.79
041016	2/4/97	6.67	110	5.1	81	1.8	95	70	2.59
041016	12/17/97	7.53	119	7.2	91	3.2	105	79	2.43
041016	12/10/98	8.51	36	1.0	40	1.8	38	29	4.07
041016	11/12/99	9.44	46	1.2	55	2.7	50	38	3.88
041016	11/14/01	11.44	55	0.6	58	0.2	56	43	3.90
041016	11/6/02	12.42	58	1.5	58	1.0	58	45	3.82
041016	12/9/04	14.51	65	3.3	54	2.2	60	46	3.82
041016	3/22/06	15.79	52	1.3	61	2.8	57	44	3.72
041016	12/6/11	21.50	55	4.3	79	2.8	67	51	3.44
04D310	3/18/90	-0.22	97	2.2	58	1.4	78	64	3.89
04D310	2/13/92	1.69	62	1.2	51	0.9	56	48	4.22
04D310	2/4/97	6.67	103	1.7	75	0.9	89	70	3.75
04D320	3/18/90	-0.22	127	3.8	92	0.8	110	92	3.63
04D320	2/13/92	1.69	213	3.5	104	0.2	159	132	3.03
04D330	3/18/90	-0.22	112	1.4	104	0.7	108	87	3.62
04D330	2/13/92	1.69	132	2.5	110	0.5	121	97	3.46
04D330	2/4/97	6.67	172	2.6	132	1.9	152	119	2.44
04D350	3/18/90	-0.22	57	4.5	46	2.3	51	42	4.04
04D350	2/13/92	1.69	116	4.0	74	3.0	95	75	3.35
04D360	3/18/90	-0.22	77	1.4	60	1.0	68	56	3.90
04D360	2/13/92	1.69	88	1.3	62	0.8	75	60	3.81
04D361	3/18/90	-0.22	82	1.7	57	1.0	69	57	4.00
04D361	2/13/92	1.69	94	1.8	60	2.0	77	62	3.91
04D362	3/18/90	-0.22	86	11.0	72	3.2	79	62	3.80
04D362	2/13/92	1.69	119	2.4	72	0.6	96	75	3.66

APPENDIX REFERENCES

Karamihas, Steven M., Thomas D. Gillespie, and Stephen M. Riley. 1995. "Axle Tramp Contribution to the Dynamic Wheel Loads of a Heavy Truck." *Proceedings of the Fourth International Symposium on Heavy Vehicle Weights and Dimensions*. Christopher B. Winkler, ed. 425-434.

Sayers, Michael W. 1989. "Two Quarter-Car Models for Defining Road Roughness: IRI and HRI." *Transportation Research Record: Journal of the Transportation Research Board* 1215: 165-172.

Sayers, Michael and Steven Karamihas. 1996. "Estimation of Rideability by Analyzing Longitudinal Road Profile." *Transportation Research Record: Journal of the Transportation Research Board* 1536: 110-116.