Performance Evaluation of Arizona's LTPP SPS-1 Project:

Strategic Study of Flexible Pavement Structural Factors

Final Report 396-1
February 2012

Arizona Department of Transportation
Research Center

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16. Abstract

As part of the Long Term Pavement Performance (LTPP) Program, Arizona DOT constructed 16 SPS-1 test sections on U.S. Route 93 near Kingman. The SPS-1 study was designed to study a variety of structural sections in new asphalt concrete construction. Opened to traffic in 1993, the project was monitored at regular intervals until it was rehabilitated in 2006. Surface distress, profile, and deflection data collected throughout the life of the pavement were used to evaluate the performance of various flexible pavement design features, layer configurations, and thickness. This report documents the analyses conducted as well as practical findings and lessons learned that will be of interest to Arizona DOT.

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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 ABBREVIATIONS AND SYMBOLS

AB	Aggregate Base
AC	Asphalt Concrete
ACFC	Asphalt Concrete Friction Course
ATB / BTB	Asphalt Treated Base / Bituminous Treated Base
DGA	Dense Graded Aggregate
ESAL	Equivalent Single Axle Loads
FWD	Falling Weight Deflectometer
HRI	Half-car Roughness Index
IRI	International Roughness Index
ksi	Kips per square inch
LTPP	Long Term Pavement Performance
MRI	Mean Roughness Index
PATB / PBTB	Permeable Asphalt Treated Base / Permeable Bituminous Treated Base
PCC	Portland Cement Concrete
PSD	Power Spectral Density
RCC	Roller Compacted Concrete
RN	Ride Number
SMP	Seasonal Monitoring Program
SN	Structural Number
SPS	Specific Pavement Studies
WIM	Weigh-In-Motion

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EXECUTIVE SUMMARY

As part of the Long Term Pavement Performance (LTPP) Program, the Arizona Department of Transportation (ADOT) constructed 16 Specific Pavement Studies (SPS)-1 test sections on U.S. Route 93 near Kingman. The SPS-1 study was designed to study a variety of structural sections in new asphalt concrete (AC) construction. This project had two sets of test sections: 12 core sections to match similar projects constructed by other highway agencies and four supplemental sections to investigate alternative design characteristics as selected by ADOT. Fifteen of the sections were AC; one was Portland cement concrete. Construction of all 16 sections was completed in the summer of 1993, and the AC sections were placed out-of-study in the spring of 2006, right before they received a mill-and-overlay.

This report provides general information of the project location including climate, traffic, and subgrade conditions, as well as details on the layer configurations of each test section. All 16 of the SPS-1 test sections were constructed consecutively and so were exposed to the same traffic loading, climate, and subgrade conditions. This allows direct comparisons between layer configurations and design features without the confounding effects introduced by different *in situ* conditions.

Results from the study revealed that roughness and roughness progression alone cannot be used to represent the health of a test section. Several test sections did not exhibit changes in roughness in proportion to the amount of fatigue cracking and sections that had clearly reached the end of their first service life cycle did not necessarily have roughness values that would trigger a rehabilitation event.

Nine of the sections received a slurry seal coat in 2002, which altered the profile features significantly. This masked the raveling that started in 1999, but did not otherwise provide a significant improvement in environmental cracking. The sections not receiving the slurry seal had a very poor surface condition at the end of their service lives. Most sections had a clear increase in magnitude of environmental distress approximately 10 years after construction. The slurry seal was applied after considerable cracking was present. The slurry seal would likely have been more effective at slowing deterioration had it been placed a few years earlier, prior to the development of cracking, possibly at the first sign of raveling.

The vast majority of sections showed significant growth in longitudinal, and consequently, fatigue cracking. This occurred 9 to 10 years after construction, with the rate of crack growth slowing until the sections were placed out of study. All sections performed well with regard to rut resistance. Rutting would not have triggered a rehabilitation event for any section.

Unfortunately, much of the longitudinal and fatigue cracking was a result of surface cracking that seemed to be associated with a construction joint located within the right wheel path on the final paving course. The deflection data indicates that most of the pavement sections remained structurally competent through the life of the study.

Using deflection data from all of the test sections, an equation for asphalt concrete modulus as a function of temperature was developed.

INTRODUCTION

Understanding the contribution of design features to long-term performance can be extremely valuable to pavement designers looking to optimize resources and improve overall performance. The objective of this research was to document the overall performance trends of the SPS-1 project, to identify key differences in performance between the various pavement configurations, and to document key findings that would be of use to ADOT.

This report provides the results of surface distress, deflection, profile, and roughness analyses for the Long-Term Pavement Performance (LTPP) Specific Pavement Studies 1 (SPS-1) site in Arizona. SPS-1 sites were designed to study flexible pavement structural factors, including drainage, base type and thickness, and asphalt surface thickness.[1] Twelve sections were constructed as part of the standard experiment. These sections have the same properties as 12 of the 24 standard sections in the LTPP program-wide SPS-1 experimental design. This SPS-1 site also included four supplemental test sections designed by ADOT.

Table 1 summarizes the structural design of the test sections. Sections 0113 through 0124 comprise a standard half-factorial matrix of structural factors. Section 0160 was included as an approach to a weigh-in-motion scale and as a Portland cement concrete alternative. Section 0161 provided an alternative to a design with more top layer thickness than was standard in Arizona. Section 0162 provided a pavement with no prepared base, and section 0163 provided a comparison to roller compacted concrete. The construction report provides more detail on the layout and structural properties of the site. [1]

The test pavements were constructed on northbound U.S. Route 93 in Mohave County, Arizona, from October 1992 through August 1993. The site extends from Milepost 52.61 to Milepost 49.48, which is north of Kingman and south of the Nevada/Arizona border. The terrain surrounding the test section is rolling hills, with grades sometimes reaching 3 percent. The soil is covered with various desert-type brush and small trees. Low foothills surround the test sections in the distance. The approximate elevation of the test section is 952 m, with a latitude of 35°18'N and longitude of 114°05'W. The layout of the SPS-1 project can be found in Figures 1 and 2. Five SPS-9 test sections were constructed concurrently with the SPS-1 project. The SPS-9 project is discussed in a separate report.

The subgrade consisted of well-graded sands and gravels with some sections of silty sands with gravel. The majority of the project consisted of fill material with depths of up to 3 meters. Several cut sections occurred near the end of the project (i.e., test sections 040113, 040161, 040162, and 040163). The subgrade fill was built with roadway excavation and borrow material.

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1. Nichols Consulting Engineers, "Construction Report on Site 040100" (Federal Highway A, 1996).

Table 1. Arizona SPS-1 Site Structural Factors.

Section	Layer Thickness (in)			Layer Type		
	Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3
0113	4	8	—	AC	AB	—
0114	7	12	—	AC	AB	—
0115	7	8	—	AC	BTB	—
0116	4	12	—	AC	BTB	—
0117	7	4	4	AC	BTB	AB
0118	4	8	4	AC	BTB	AB
0119	7	4	4	AC	PBTB	AB
0120	4	4	8	AC	PBTB	AB
0121	4	4	12	AC	BTB	AB
0122	4	4	4	AC	BTB	PBTB
0123	7	8	4	AC	BTB	PBTB
0124	7	12	4	AC	BTB	PBTB
0160	10	4	—	PCC	AB	—
0161	5	4	—	AC	AB	—
0162	7	—	—	AC	—	—
0163	1	15	—	ACFC	RCC	—

AB — Aggregate Base
ACFC — Asphalt Concrete Friction Course
PBTB — Permeable Bituminous Treated Base
RCC — Roller Compacted Concrete
AC — Asphalt Concrete
BTB — Bituminous Treated Base
PCC — Portland Cement Concrete

The climate for the SPS-1 project is considered to be a dry, no-freeze environment by LTPP definitions. Environmental details can be found in Table 2. The temperature and precipitation information was derived from data collected at nearby weather stations and represents 35 years of recorded data. The solar radiation and humidity data were summarized from 12 years of on-site weather station data.

Table 2. Climatic information for SPS-1.

	35-year Average	**35-year Maximum**	**35-year Minimum**
Annual Average Daily Mean Temperature (°F)	67	70	63
Annual Average Daily Maximum Temperature (°F)	81	86	75
Annual Average Daily Minimum Temperature (°F)	54	57	50
Absolute Maximum Annual Temperature (°F)	111	118	104
Absolute Minimum Annual Temperature (°F)	23	30	9
Number of days per year above 32 °F	128	168	88
Number of days per year below 32 °F	23	54	4
Annual Average Freezing Index (°F-days)	4	28	0
Annual Average Precipitation (in)	8.1	17.5	3.1
Annual Average Daily Mean Solar Radiation (kW/ft^2)	21.5	39.9	1.1
Annual Average Daily Max Relative Humidity (%)	55	99	7
Annual Average Daily Min Relative Humidity (%)	18	10	1

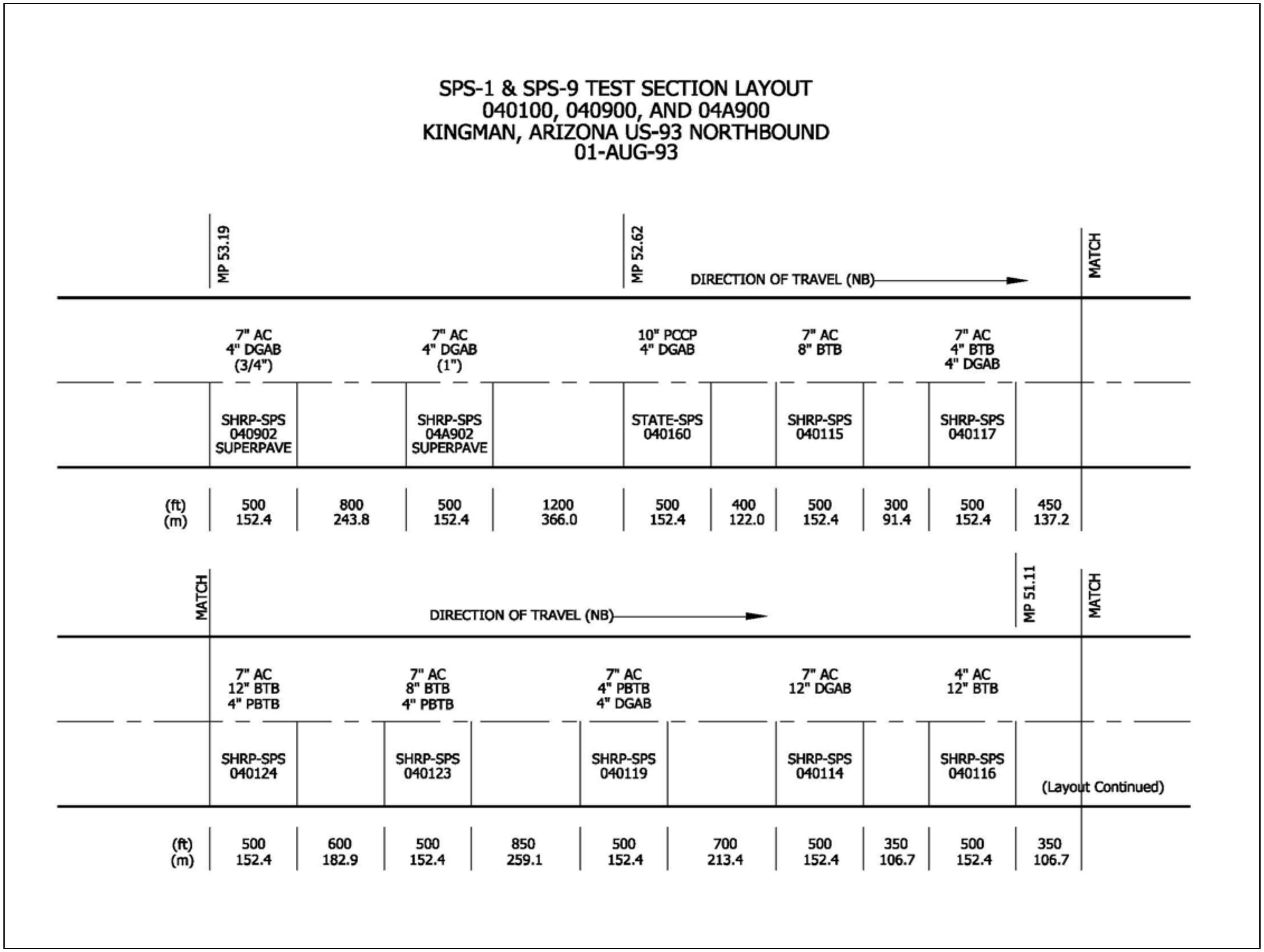

Figure 1. Layout of the SPS-1 project.

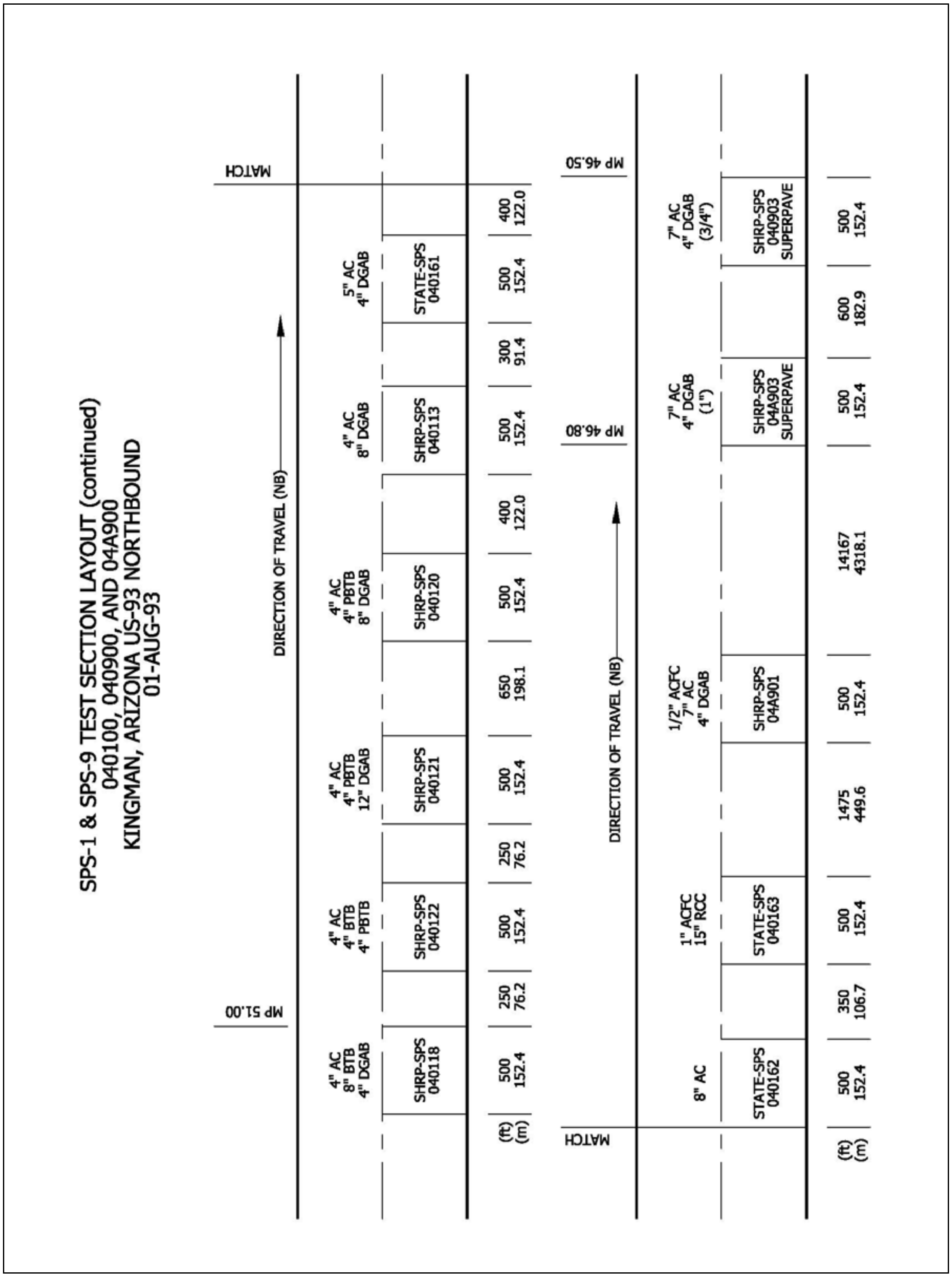

Figure 2. Layout of the SPS-1 project (cont'd).

Table 3 provides a summary of the total Equivalent Single Axle Loads (ESALs) computed from traffic loading information collected at the SPS-1 site. For 1993, no monitoring traffic data were available; therefore, the ESAL value reported in the table was derived from estimates provided by ADOT. The significant reduction after 2001 is due to the restriction of truck traffic on Hoover Dam implemented following September 11, 2001.

Table 3. Traffic Loading Summary.

Year	ESALs
1993	230,000
1994	247,794
1995	252,299
1996	273,576
1997	260,773
1998	279,649
1999	299,002
2000	351,066
2001	380,213
2002	--
2003	52,847
2004	59,826
2005	57,837

Note: 2002 data unavailable.

Sections 0113 and 0114 were included in LTPP's Seasonal Monitoring Program (SMP), thereby being subjected to increased performance monitoring (typically monthly testing with a falling weight deflectometer (FWD), profile, and distress monitoring) and equipped with the following:

- Subsurface moisture sensors in the base and subgrade layers.
- Subsurface temperature sensors in the AC, base, and subgrade layers.
- Air temperature thermometer.
- Precipitation gauge.

The objective of the SMP monitoring was to provide a source of data for studying daily and seasonal variation in layer properties and their effect on pavement response and long term performance.

After original construction in 1993, the following maintenance activities were performed:

- **0113:** 2002 slurry seal
- **0114:** 2002 slurry seal
- **0115:** 2001 and 2002 crack seal

- **0116:** 2001 wheelpath patching, 2002 slurry seal
- **0117:** 2001 and 2002 crack seal
- **0118:** 2001 crack seal, 2002 slurry seal
- **0119:** 2002 crack seal
- **0120:** 2002 slurry seal
- **0121:** 2002 slurry seal
- **0122:** 2001 pothole patching, 2002 slurry seal
- **0123:** 2001 and 2002 crack seal
- **0124:** 2001 crack seal
- **0160:** no maintenance activities recorded
- **0161:** 2001 wheelpath patching, 2002 slurry seal
- **0162:** 2002 slurry seal
- **0163:** 2001 pothole patching

All test sections were placed out-of-study due to reconstruction in the summer of 2006.

Three analyses were conducted on the SPS-1 project to evaluate pavement performance. The following pages of the report are separated by each distinct analysis—distress, deflection, and profile. Within each section, a description of the research approach is provided along with performance comparisons between test sections, overall trends, a summary of the results, and key findings.

SPS-1 DEFLECTION ANALYSIS

Falling weight deflectometer (FWD) data provide information on the overall strength (i.e., stiffness) of the pavement structure, as well as of individual layers. This information was used to evaluate changes with time or—in the case of the asphalt-bound layers—variation due to temperature. Additional analysis was performed to gain insight on the impact of various design features on structural performance.

OVERALL PERFORMANCE TREND OBSERVATIONS

Maximum Deflections

The normalized average maximum deflection (D_0, measured at the center of the FWD load plate, normalized to a load level of 9,000 pounds and an asphalt concrete mix temperature of 68°F) of each of the test sections increased between the first round of testing in 1994 and the last round of testing in 2004, as shown in Figure 3 and Table 4. The test sections are listed in the order of their layout in the direction of traffic (with the Portland cement concrete (PCC) test section—0160—excluded).

The normalized average maximum deflection is an indicator of the total stiffness of the pavement structure (surface and base) and the underlying subgrade. The increases in normalized average maximum deflection observed over time may thus be due to weakening of the pavement structure and/or weakening of the subgrade.

Backcalculated Subgrade Modulus

The overall average initial subgrade modulus for the site, backcalculated from the first round of deflection data in 1994, was about 43.5 ksi. The average subgrade modulus of each of the test sections declined between the first round of deflection testing in 1994 and the most recent round of deflection testing in 2004, as shown in Figure 4 and Table 5. The overall average subgrade modulus for the site, backcalculated from the last round of deflection data in 2004, was about 29 ksi.

This decrease in subgrade modulus over time is presumed to be due to a gradual increase and leveling off of the subgrade moisture content after construction. The fairly steady trend in decreasing subgrade moduli over time is illustrated by the values backcalculated for SMP test section 0113, shown in Figure 5 and Table 6.

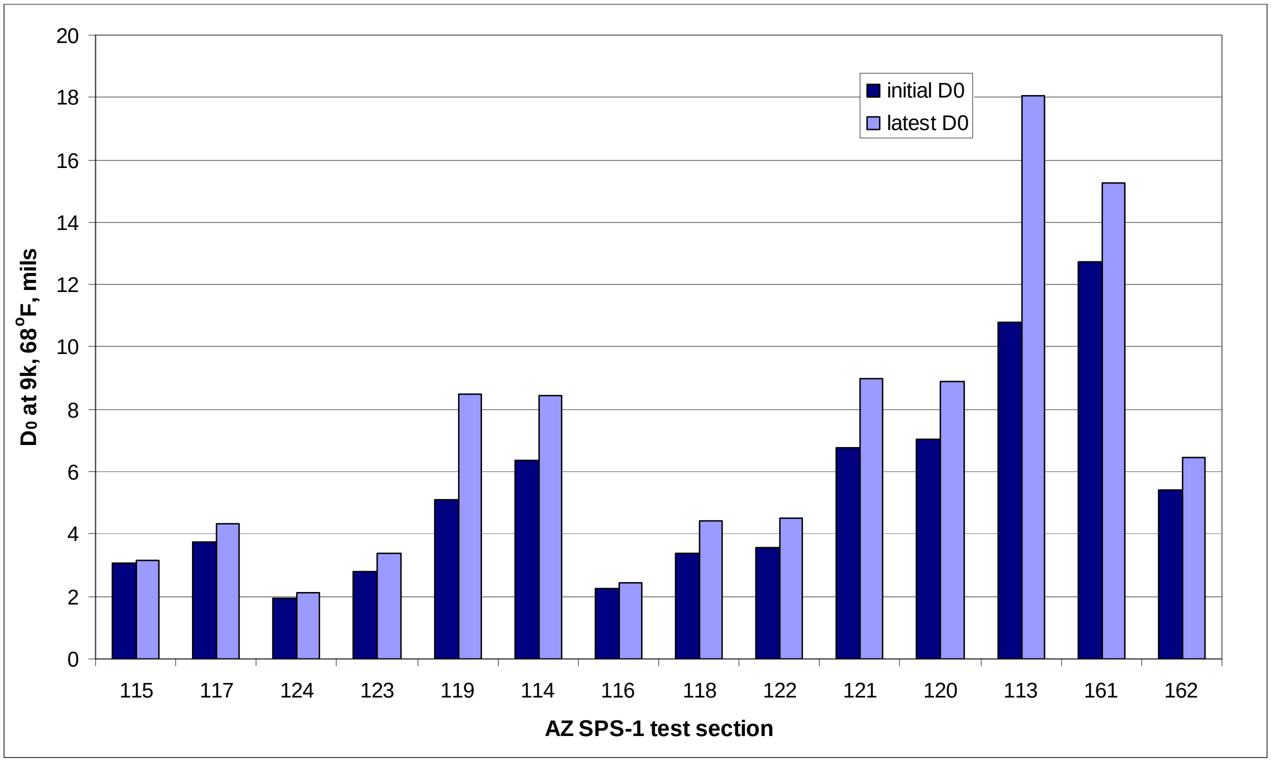

Figure 3. 1994 and 2004 average normalized maximum deflections by test section.

Table 4. Maximum deflections by test section.

Test section	Design surface thickness, inches	Design total base thickness, inches	Base type	Average 1994 D_0, mils	Average 2004 D_0, mils	Increase in average D_0, mils	Increase in average D_0, percent
0115	7	8	ATB	3.09	3.17	0.08	2
0117	7	8	ATB/DGA	3.73	4.32	0.59	14
0124	7	16	ATB/PATB	1.95	2.13	0.18	8
0123	7	12	ATB/PATB	2.81	3.39	0.57	17
0119	7	8	PATB/DGA	5.11	8.50	3.39	40
0114	7	12	DGA	6.37	8.43	2.06	24
0116	4	12	ATB	2.27	2.46	0.19	8
0118	4	12	ATB/DGA	3.41	4.43	1.02	23
0122	4	8	ATB/PATB	3.56	4.50	0.94	21
0121	4	16	PATB/DGA	6.76	8.99	2.24	25
0120	4	12	PATB/DGA	7.03	8.88	1.85	21
0113	4	8	DGA	10.79	18.06	7.26	40
0161	6	4	DGA	12.74	15.24	2.50	16
0162	9	–	–	5.40	6.46	1.06	16

ATB — Asphalt Treated Base PATB — Permeable Asphalt Treated Base
DGA — Dense Graded Aggregate

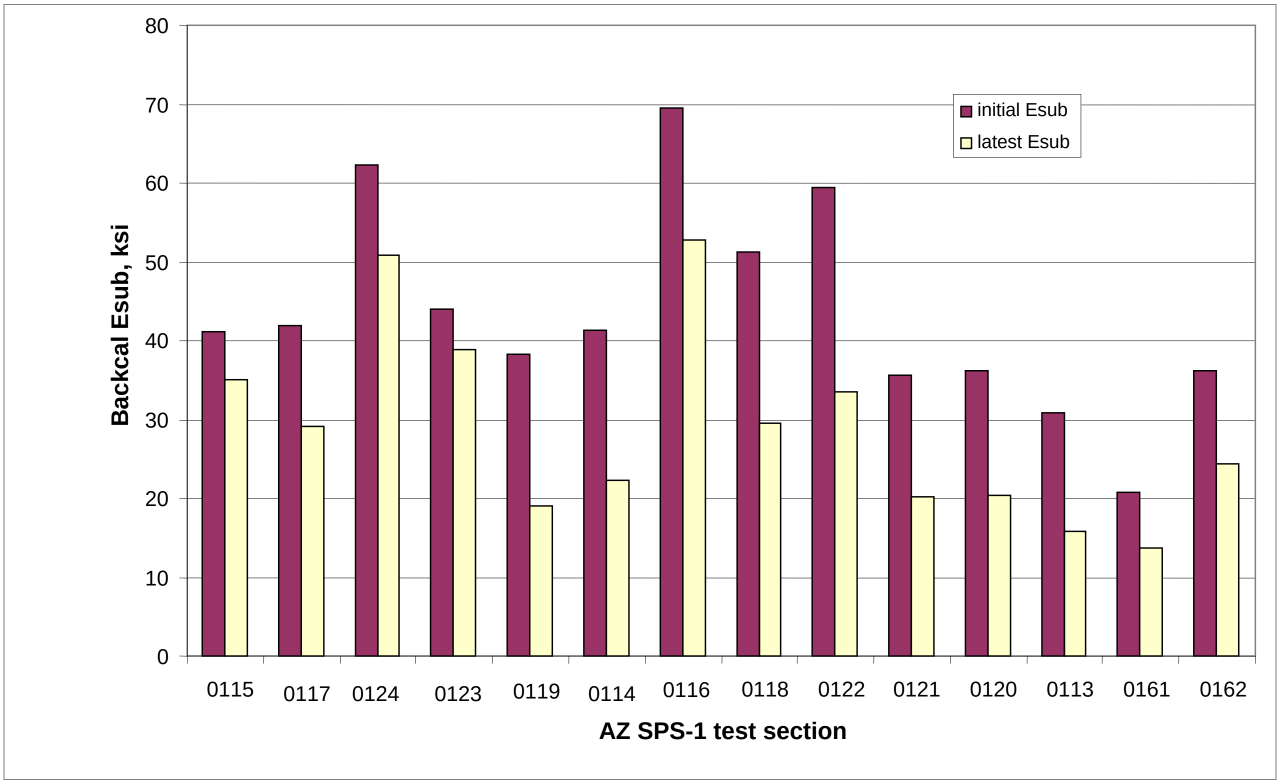

Figure 4. 1994 and 2004 backcalculated subgrade modulus by test section.

Table 5. Backcalculated subgrade modulus by test section.

Test section	Design surface thickness, inches	Design total base thickness, inches	Base type	Average 1994 E_{sub}, ksi	Average 2004 E_{sub}, ksi	Decrease in average E_{sub}, ksi	Decrease in average E_{sub}, percent
0115	7	8	ATB	41	35	6	15
0117	7	8	ATB/DGA	42	29	13	31
0124	7	16	ATB/PATB	62	51	11	18
0123	7	12	ATB/PATB	44	39	5	12
0119	7	8	PATB/DGA	38	19	19	50
0114	7	12	DGA	41	22	19	46
0116	4	12	ATB	70	53	17	24
0118	4	12	ATB/DGA	51	30	22	42
0122	4	8	ATB/PATB	60	33	26	44
0121	4	16	PATB/DGA	36	20	15	43
0120	4	12	PATB/DGA	36	20	16	44
0113	4	8	DGA	31	16	15	49
0161	6	4	DGA	21	14	7	34
0162	9	–	–	36	24	12	33
				43.5	29.0		

ATB — Asphalt Treated Base
DGA — Dense Graded Aggregate
PATB — Permeable Asphalt Treated Base

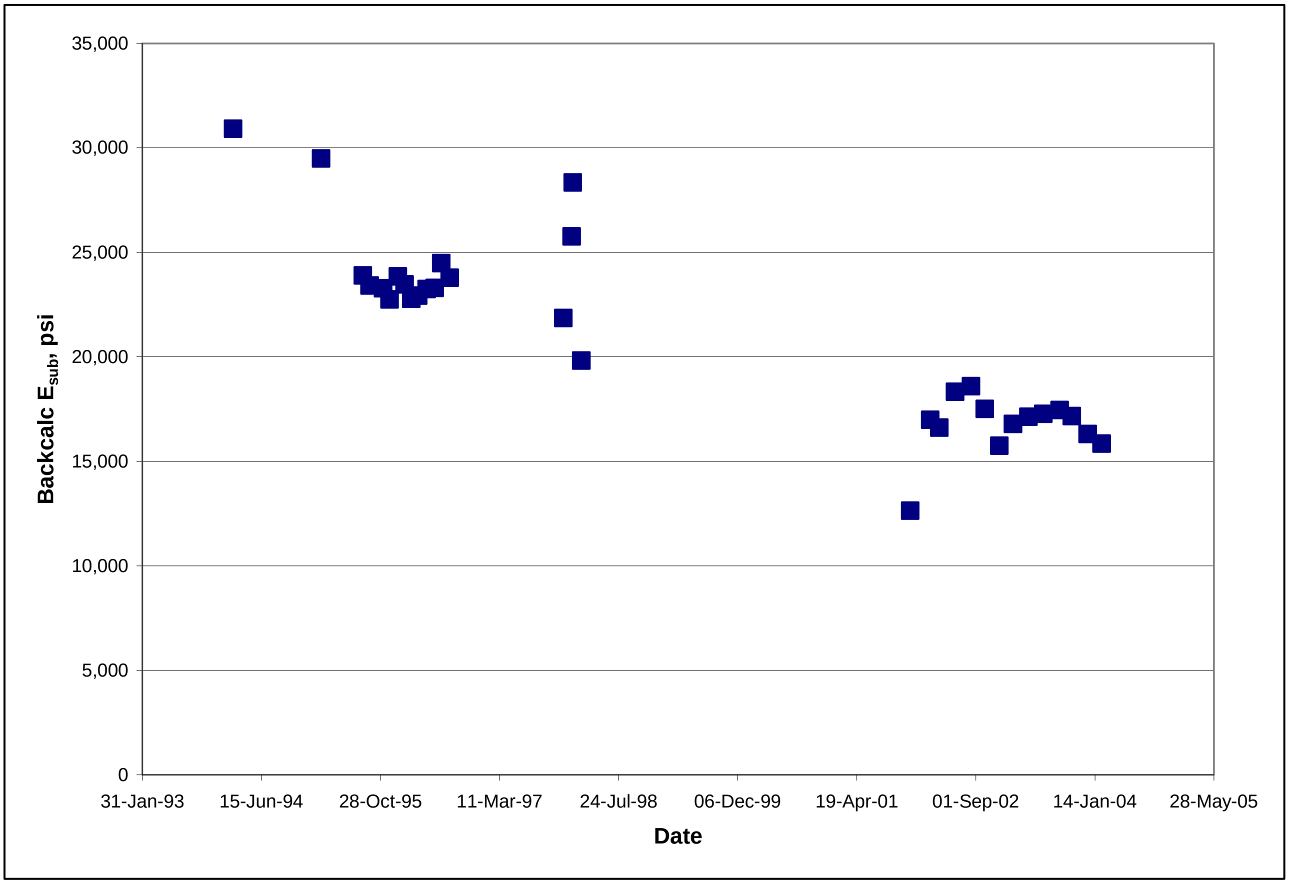

Figure 5. Backcalculated subgrade modulus decrease over time, section 0113.

Table 6. Backcalculated subgrade modulus by test date, section 0113.

Test date	Average E_{sub}, psi
17-Feb-94	30,916
21-Feb-95	29,494
16-Aug-95	23,893
13-Sep-95	23,409
08-Nov-95	23,289
06-Dec-95	22,744
10-Jan-96	23,854
07-Feb-96	23,467
06-Mar-96	22,781
03-Apr-96	22,928
09-May-96	23,240
12-Jun-96	23,295
10-Jul-96	24,481
14-Aug-96	23,785
04-Dec-97	21,859
08-Jan-98	25,760
13-Jan-98	28,344
18-Feb-98	19,819

Table 6 (con't). Backcalculated subgrade modulus by test date, section 0113.

Test date	Average E_{sub}, psi
30-Nov-01	12,636
22-Feb-02	16,990
01-Apr-02	16,616
06-Jun-02	18,329
12-Aug-02	18,596
09-Oct-02	17,510
09-Dec-02	15,751
04-Feb-03	16,789
10-Apr-03	17,128
12-Jun-03	17,271
19-Aug-03	17,456
09-Oct-03	17,164
15-Dec-03	16,302
12-Feb-04	15,848

Structural Capacity

The deflection data were used to assess the initial structural capacity of each test section and the change in structural capacity over time, with structural capacity expressed as an effective Structural Number (SN_{eff}). The initial and last average backcalculated SN_{eff} values are shown by test section in Figure 6 and Table 7. All but one of the test sections showed a decrease in backcalculated SN_{eff} between 1994 and 2004. This is presumed to be due to damage from traffic loadings. No correlation was detected between the magnitude of the initial SN_{eff} and the magnitude of the decrease in SN_{eff} over time.

Base Modulus

The initial and latest average backcalculated base modulus values are shown by test section in Figure 7 and Table 8. All but one of the test sections showed a decrease in base modulus between 1994 and 2004. This effect may be coupled with the commensurate decrease in subgrade modulus. Whether an increase in moisture content in any unbound aggregate layers also played a role is difficult to say. For example, AC-over-aggregate test sections 0113 and 0161 experienced fairly large decreases in backcalculated base modulus, but AC-over-aggregate test section 0114 did not.

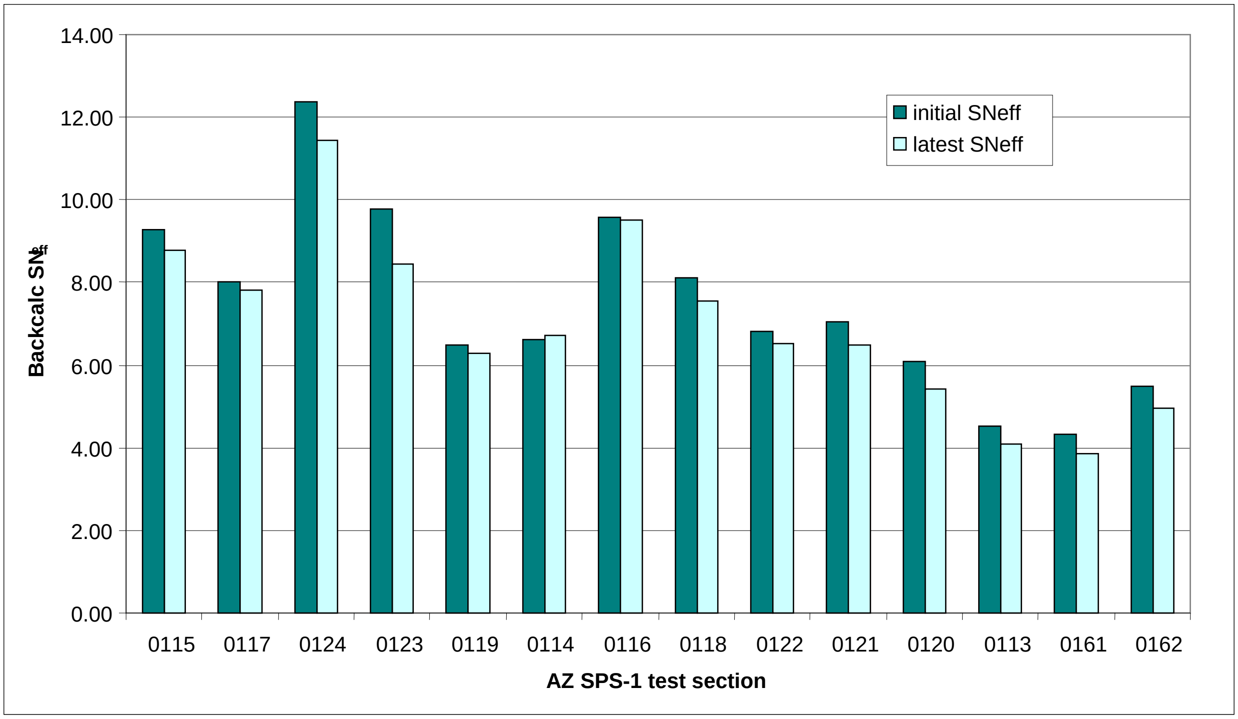

Figure 6. 1994 and 2004 backcalculated effective Structural Number by test section.

Table 7. Backcalculated effective Structural Number by test section.

Test section	Design surface thickness, inches	Design total base thickness, inches	Base type	Average 1994 SN_{eff}, inches	Average 2004 SN_{eff}, inches	Change in average SN_{eff}, inches	Change in average SN_{eff}, percent
0115	7	8	ATB	9.28	8.77	-0.51	-6
0117	7	8	ATB/DGA	8.02	7.82	-0.20	-2
0124	7	16	ATB/PATB	12.37	11.44	-0.93	-8
0123	7	12	ATB/PATB	9.76	8.44	-1.32	-16
0119	7	8	PATB/DGA	6.47	6.27	-0.20	-3
0114	7	12	DGA	6.62	6.73	0.11	2
0116	4	12	ATB	9.57	9.51	-0.06	-1
0118	4	12	ATB/DGA	8.11	7.56	-0.55	-7
0122	4	8	ATB/PATB	6.80	6.52	-0.28	-4
0121	4	16	PATB/DGA	7.07	6.48	-0.59	-9
0120	4	12	PATB/DGA	6.09	5.43	-0.66	-12
0113	4	8	DGA	4.54	4.08	-0.45	-11
0161	6	4	DGA	4.31	3.86	-0.46	-12
0162	9	–	–	5.50	4.96	-0.55	-11

ATB — Asphalt Treated Base
PATB — Permeable Asphalt Treated Base
DGA — Dense Graded Aggregate

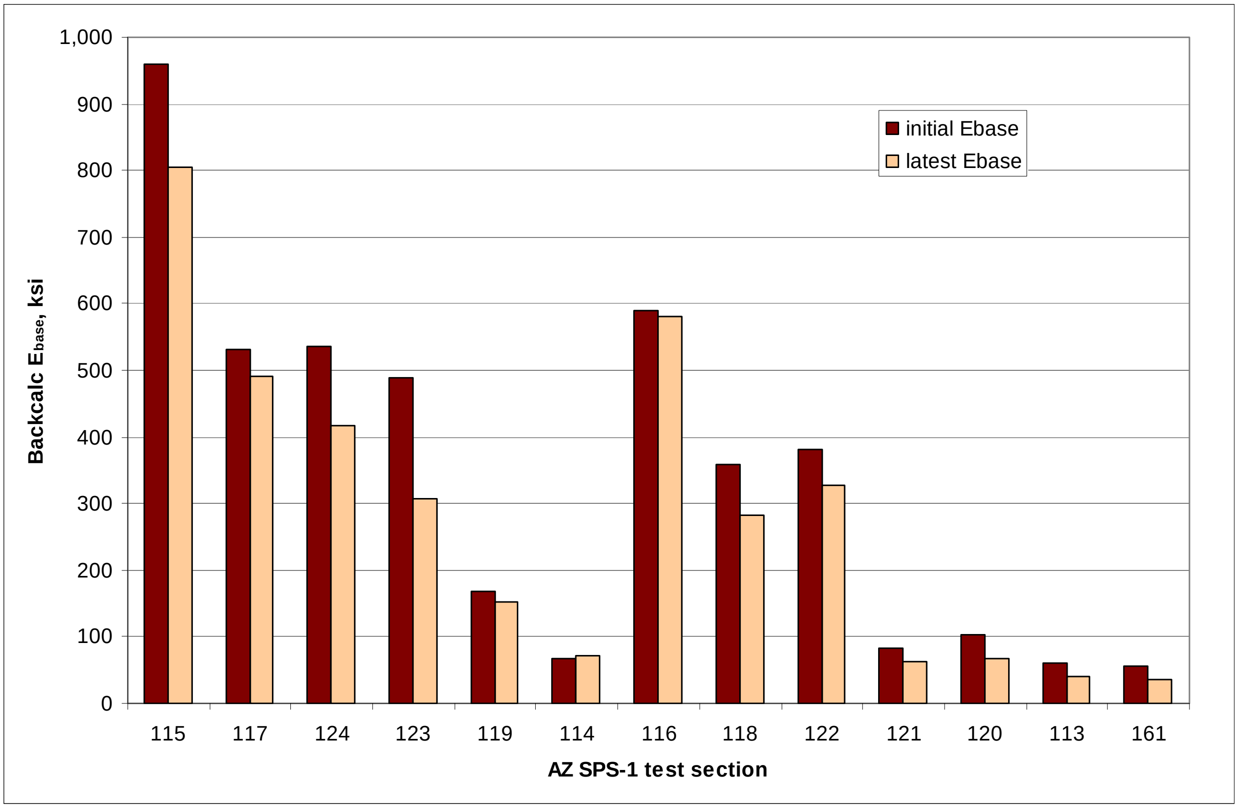

Figure 7. 1994 and 2004 backcalculated base modulus by test section.

Table 8. Backcalculated base modulus by test section.

Test section	Design surface thickness, inches	Design total base thickness, inches	Base type	Average 1994 E_{base}, ksi	Average 2004 E_{base}, ksi	Decrease in average E_{base}, ksi	Decrease in average E_{base}, percent
0115	7	8	ATB	960	804	156	16
0117	7	8	ATB/DGA	532	492	40	8
0124	7	16	ATB/PATB	536	417	119	22
0123	7	12	ATB/PATB	489	307	181	37
0119	7	8	PATB/DGA	168	152	15	9
0114	7	12	DGA	67	72	increase 4	increase 6
0116	4	12	ATB	590	580	10	2
0118	4	12	ATB/DGA	359	282	78	22
0122	4	8	ATB/PATB	381	328	53	14
0121	4	16	PATB/DGA	84	62	22	26
0120	4	12	PATB/DGA	103	67	35	34
0113	4	8	DGA	60	40	20	33
0161	6	4	DGA	57	36	21	36
0162	9	–	–	960	804	156	16

ATB — Asphalt Treated Base
PATB — Permeable Asphalt Treated Base
DGA — Dense Graded Aggregate

AC Modulus versus Temperature

The combined backcalculation results from all testing between 1994 and 2004 were used to assess the relationship of AC modulus to temperature. Figure 8 shows the results grouped together for the six types of pavement structures considered:

- AC over aggregate
- AC over ATB
- AC over ATB over aggregate
- AC over PATB over aggregate
- AC over ATB over PATB
- Full-depth AC over subgrade

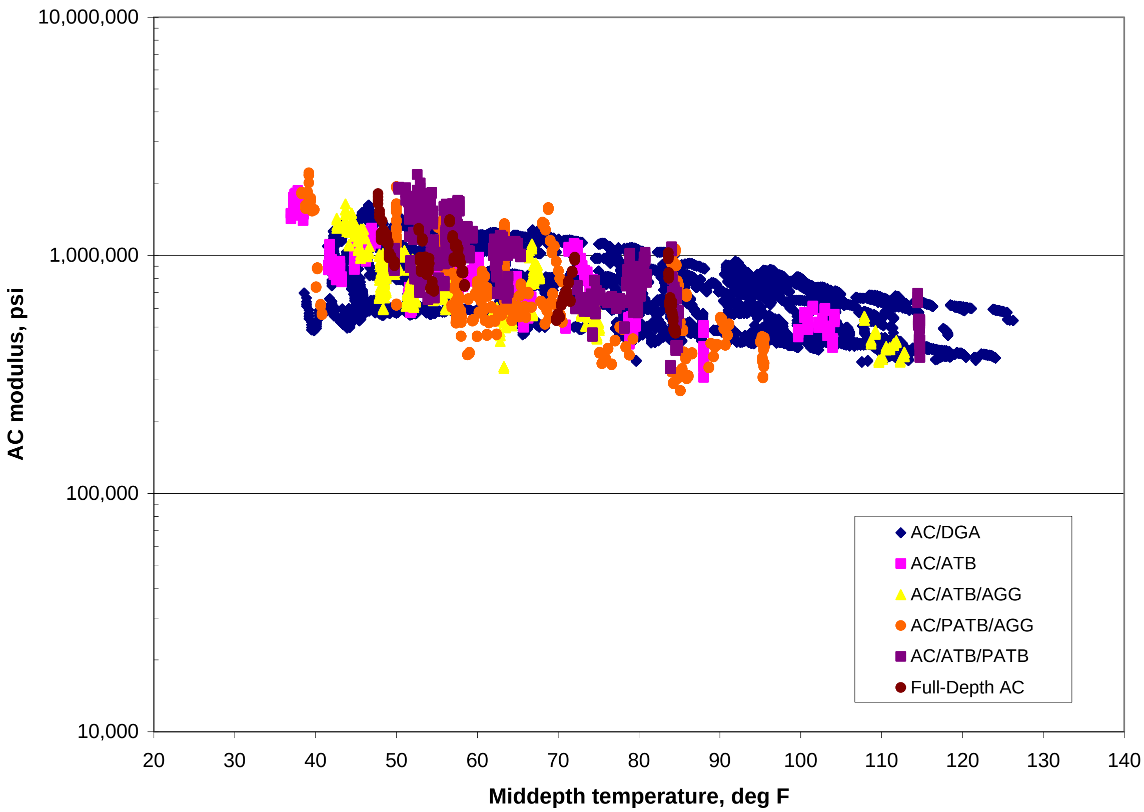

Figure 8. Backcalculated AC modulus versus temperature.

It should be noted that these backcalculated values of AC modulus as a function of temperature were determined by judicious selection of realistic values for the ratio of AC surface modulus to base modulus. This was necessary to decompose the backcalculated effective modulus of the entire pavement structure above the subgrade into two components, the modulus of the AC surface and the modulus of the underlying base.

The relationship of backcalculated AC modulus to mid-depth AC temperature for all of the pavement structure groups combined is illustrated in Figure 9. The regression equation obtained for the logarithm of E_{ac} in psi as a function of mid-depth AC temperature in degrees Fahrenheit is also shown.

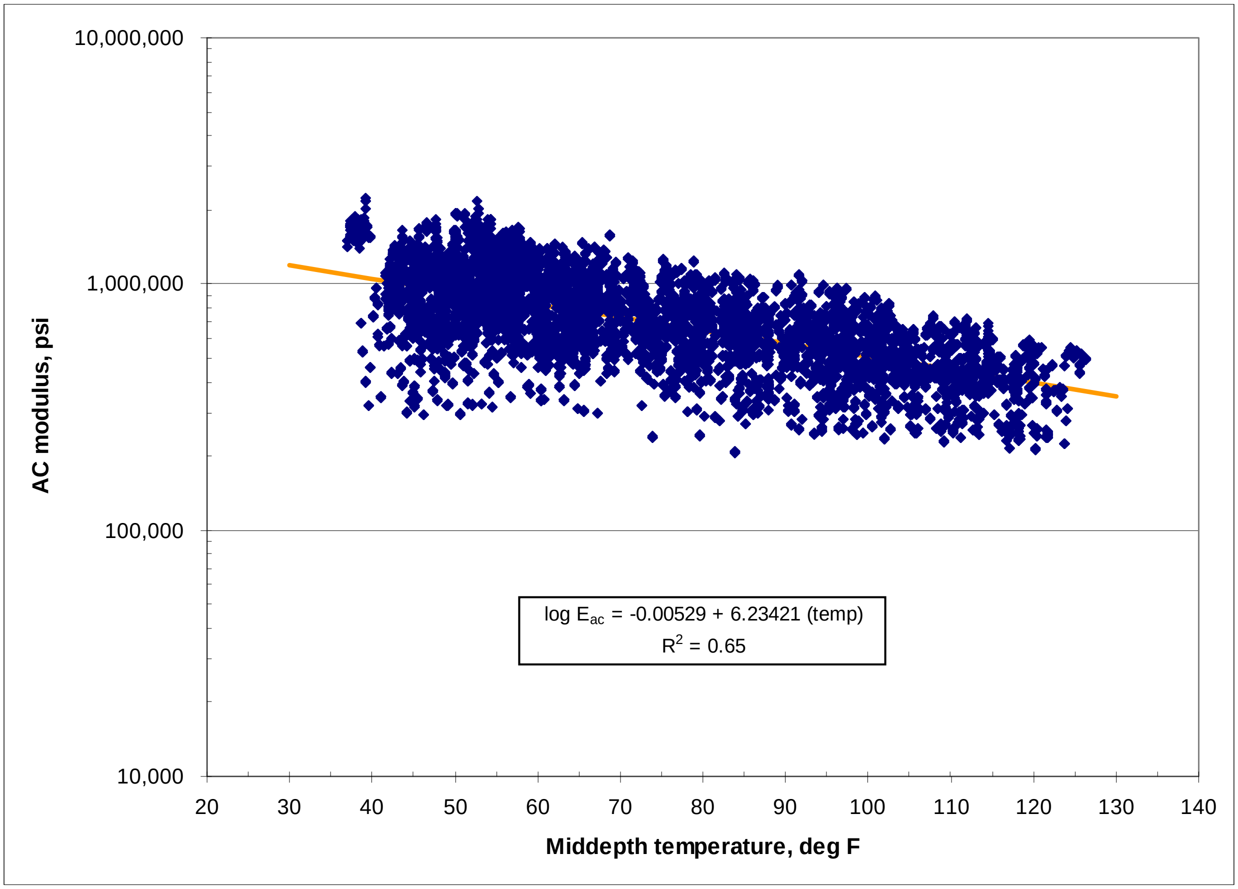

Figure 9. Backcalculated AC modulus versus temperature.

KEY FINDINGS FROM ARIZONA SPS-1 DEFLECTION ANALYSIS

- The average maximum deflection increased in every Arizona SPS-1 test section between the first round of deflection testing in 1994 and the most recent round of testing in 2004. This may be due to weakening of the subgrade and/or weakening of the pavement structure above the subgrade over time.
- The average backcalculated subgrade modulus declined fairly steadily in every test section between 1994 and 2004. The overall average backcalculated subgrade modulus for the site declined from 43.5 ksi to 29 ksi over this period. This is presumed to be due to a gradual increase and leveling off of the subgrade moisture content after construction.
- The average backcalculated effective Structural Number (SN_{eff}) declined in all but one of the test sections between 1994 and 2004. This is presumed to be due to damage from traffic loadings. No correlation was detected between the magnitude

of the initial backcalculated SN_{eff} and the magnitude of the decrease in backcalculated SN_{eff} over time. The one section for which the average backcalculated SN_{eff} did not decrease, but rather increased slightly, was section 0114.

- Sections with relatively thin structural sections resulted in the smallest SN_{eff}, while the thickest sections yielded larger SN_{eff} values. This is logical and expected based on FWD theory.
- Backcalculated base modulus values were largest for ATB base types. Base types consisting of a combination of ATB and PATB or dense graded aggregate base (DGAB) yielded the second largest modulus values. DGAB only and DGAB/PATB combination base types resulted in the lowest modulus values.
- The average backcalculated modulus of the base layer or layers (all layers between the subgrade and AC surface) decreased in all but one test section between 1994 and 2004. The one section for which the average backcalculated base modulus did not decrease, but rather increased slightly, was section 0114.
- The deflection data from all of the test sections together were used to develop a regression equation for AC surface modulus as a function of the temperature of the AC mix at the mid-depth of the AC surface layer. This AC modulus-temperature relationship may be useful in other analyses of deflection data from the Arizona SPS-1 site, as well as other sites in Arizona constructed with AC surfaces at about the same time and with similar mix characteristics.

SPS-1 DISTRESS ANALYSIS

This chapter describes analyses and results from evaluating distress data collected on the Arizona SPS-1 project using LTPP manual survey techniques.[2] Surface distress provides powerful information regarding 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 on service life.

All 15 of the flexible SPS-1 test sections were constructed consecutively and therefore, were exposed to the same traffic loading, climate, and subgrade conditions. This allows for direct comparisons between layer configurations/design features without confounding effects introduced by different *in situ* conditions.

Surface deterioration is composed of multiple distress types. Definitions of each type are as follows:[3]

Fatigue Cracking: A series of interconnecting cracks caused by repeated traffic loading. Cracking initiates 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 wheel path. 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 wheel path. This cracking is not load related and can come from paving seams or 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

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2. J. Miller and W. Bellinger, *Distress Identification Manual for the Long-Term Pavement Performance Program,* 4th ed. FHWA-RD-03-031 (McLean, VA: Federal Highway Administration, 2003).

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

during temperature changes. This type of distress indicates 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 surface 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 wheel paths that can be a result of 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 9 provides a summary of flexible pavement distress types and their associated failure mechanisms.

Table 9. Flexible pavement distress types and failure mechanism.

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-1 dataset was well within the acceptable range of variability.

Distress data collected for LTPP purposes is reported at three severity levels: low, moderate, and high. It has been well-documented that the inconsistencies between severity levels (within one distress type) is one of the largest sources of variability in distress data.[4] 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 analyses, the quantities from the three severity levels were summed into one composite value for the research presented.

As shown in Table 4, pavement deterioration (when not directly attributable to mix problems or construction deficiencies) can be grouped in two categories based on failure mechanisms: structural and 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.

The structural damage index consists of those distresses to the portion of the pavement that experiences loading (i.e., wheel paths). Therefore, the structural damage index was presented as the percentage of wheelpath damage and included fatigue and longitudinal wheelpath cracking. To normalize fatigue and longitudinal cracking, the structural damage index took the form of the following expression:

$$S = \frac{F + 1ft * C_{lwp}}{2 * W_{wp} * L_s}$$

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 is a composite of distresses that generally result from climatic affects. The entire pavement surface is subject to environmental distress; therefore, the environmental damage index was characterized as the percentage of total pavement area damaged. Typically, transverse cracking, longitudinal cracking (outside of the wheel paths), and block cracking are specific to environmental damage. To normalize the environmental distress for the total area, the environmental damage index took the form of the following expression:

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4. G. R. Rada, et al., *Study of LTPP Distress Data Variability*, volumes 1 & 2. FHWA-RD-99-074; FHWA-RD-99-075. (McLean, VA: Federal Highway Administration, 1999.)

$$E = \frac{B}{A_{tot}} + \frac{C_{nwp}}{L_s} + \frac{C_t}{L_s}$$

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 are clearly significant aspects of the performance of the Arizona SPS-1 in terms of structural and functional service life, the analyses also incorporated rutting, patching, and other surface defects (i.e., potholes, bleeding, and raveling). Rutting data reported in this study were generated using a 6-ft straightedge reference.[5]

The experimental design of the SPS-1 project is 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 from data collected at the same point in time. Because sections 0113, 0114, 0116, 0118, 0120, 0121, 0122, 0161, and 0162 received slurry seal treatment in May 2002, comparisons were made using distress data collected in March/April 2002 to eliminate any confounding effects from the slurry seal application.

OVERALL PERFORMANCE TREND OBSERVATIONS

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

All sections except 0160 and 0163, which were the PCC and roller-compacted concrete (RCC) pavement sections, exhibited distress initiating from a longitudinal paving seam between the midlane and the outside wheel path. As can be seen in Figure 10, this paving seam clearly affected the structural damage index. Observations made at the time of construction predicted the construction issues at the seam would have potential impact on the overall performance of the project. Separate analysis was conducted to address the

5. A. L. Simpson, *Characterization of Transverse Profiles*, FHWA-RD-01-024 (McLean, VA: Federal Highway Adminstration, 2001.)

contribution of the paving seam and will be described in subsequent sections of this report.

All test sections exhibited raveling in the wheel paths in 1999-2000. Those sections that received the slurry seal had significantly better surface condition for the remainder of project life. The sections not receiving slurry seal were marked by a very poor surface condition, dominated by large quantities of raveling, at the time of rehabilitation.

Figure 10. Photograph of paving seam.

The overall structural damage trends for each section can be found in Figures 11 and 12. The performance trends are relatively consistent and within the expected range of variation. The drop in damage after May 2002 is indicative of the slurry seal masking the underlying deterioration.

All sections (except 0162 and 0163) showed a rapid accumulation of structurally related distresses approximately 9 to 10 years after construction. The accumulation typically slowed in later years.

In comparison with the rest of the SPS-1 project, sections 0162 and 0163 exhibit significantly smaller amounts of structural damage accumulation. The pavement structure for section 0162 is composed of 200 mm asphalt concrete placed directly on the subgrade. Section 0163 has a pavement structure consisting of an asphalt concrete friction course over roller compacted concrete.

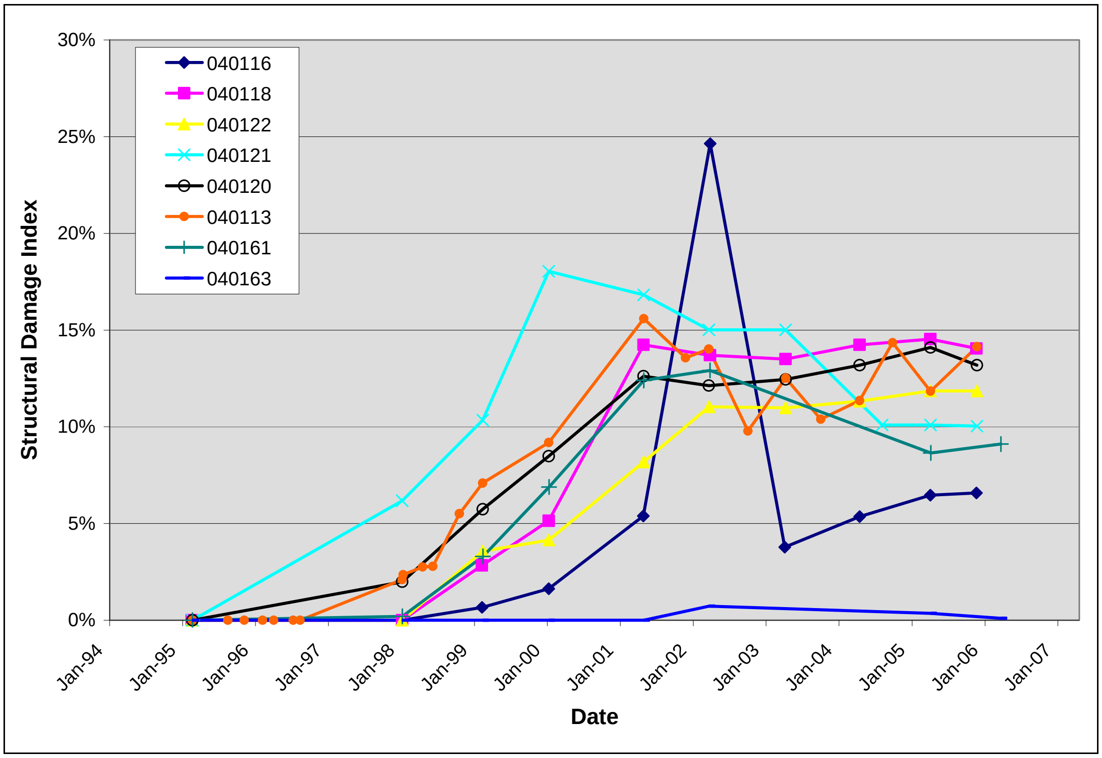

Figure 11. Structural damage trends for SPS-1 test sections with 5 inches or less of AC.

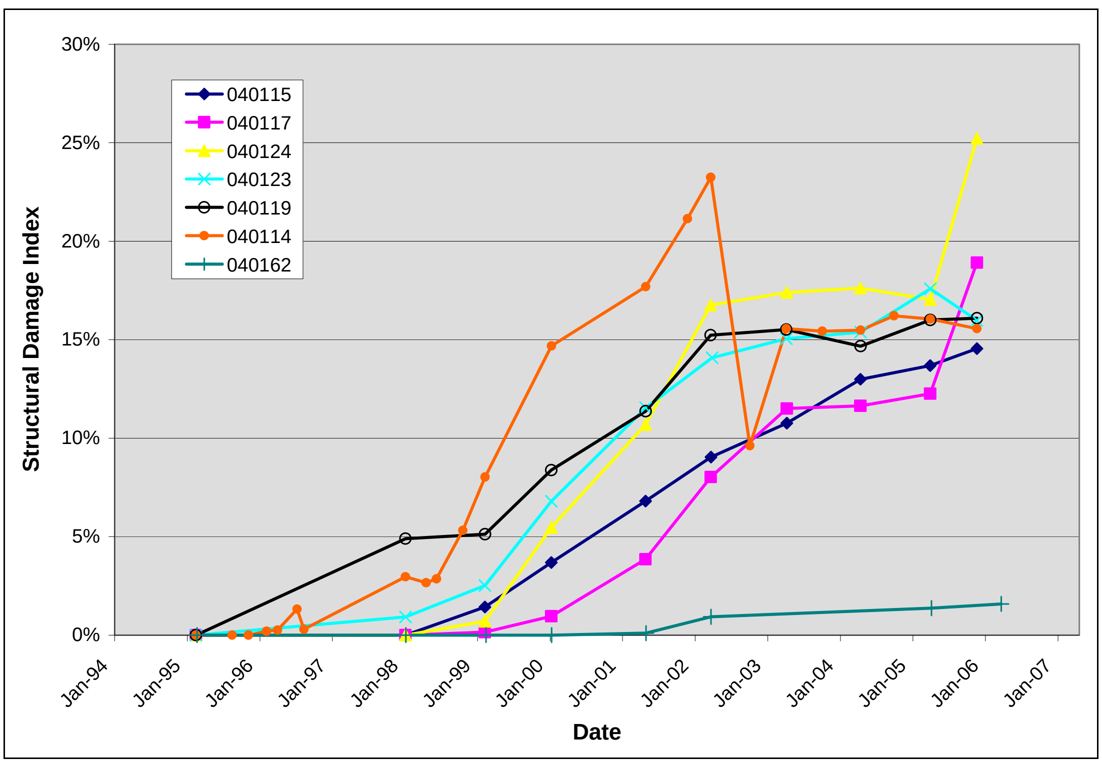

Figure 12. Structural damage trends for SPS-1 test sections with 7 inches or more of AC.

The overall environmental damage trends for each section can be found in Figures 13 and 14. The performance trends are relatively consistent and within the expected range of variation. Although slight decreases were somewhat discernible for surveys within a year of the slurry seal, environmental distresses clearly increased in magnitude approximately 10 years after construction, and there is not a clear indication that the slurry seal provided any abatement to environmental distress. In fact, environmental damage was observed reflecting through the slurry seal on some sections approximately seven months after placement.

The slurry seal did improve the surface characteristics of the road and eliminated the raveling surface. However, the seal was applied after cracking was present, which was too late to be effectively used as a preventative maintenance treatment. The purpose of such application is to slow crack initiation by reducing oxidation and weathering. Oxidation of the asphalt binder increases the brittleness of the binder and promotes raveling and cracking. Slurry seals do not increase the structural capacity of the pavement and are not thick enough to prevent existing cracks from reflecting through the treatment. If cracks are present in the existing pavement, a slurry seal will quickly reflect this cracking, thereby diminishing the expected resistance to oxidation and weathering.

Timing of surface applications is critical to the effectiveness of the treatments. Figures 4 through 7 indicate that the majority of sections had very little cracking in 1998 and the cracking that was present was likely to be of low severity. Applying the slurry seal in 1998 may have resulted in slower deterioration and improved effectiveness of the treatment.

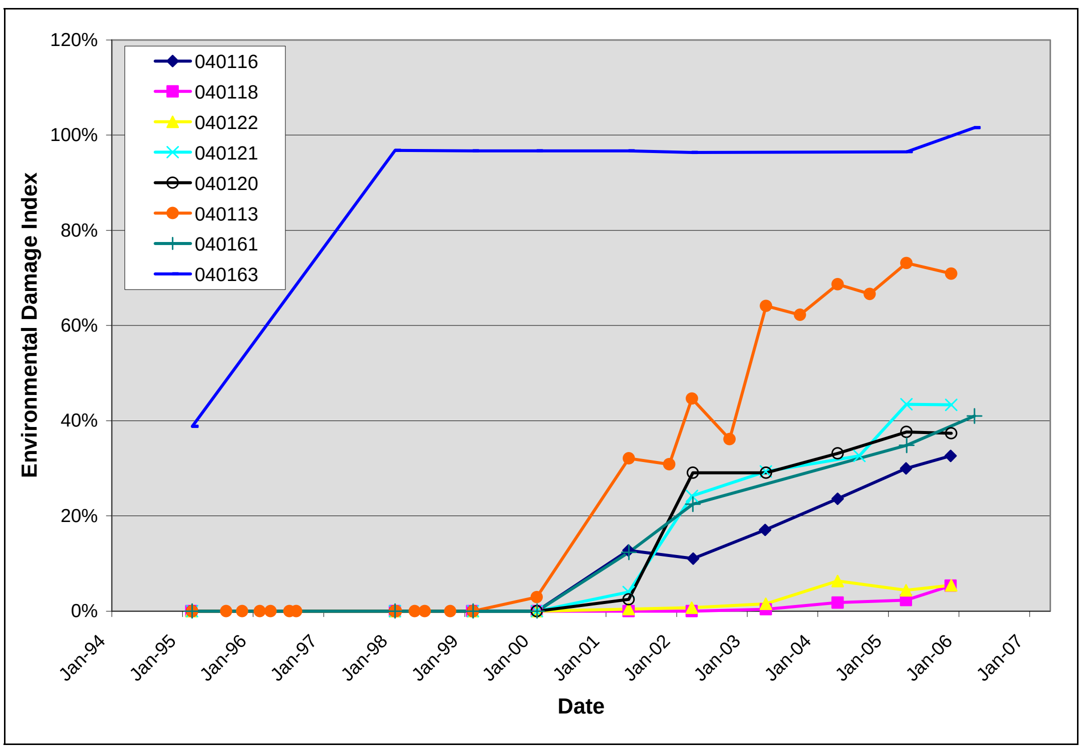

Figure 13. Environmental damage trends for SPS-1 test sections with 5 inches or less of AC.

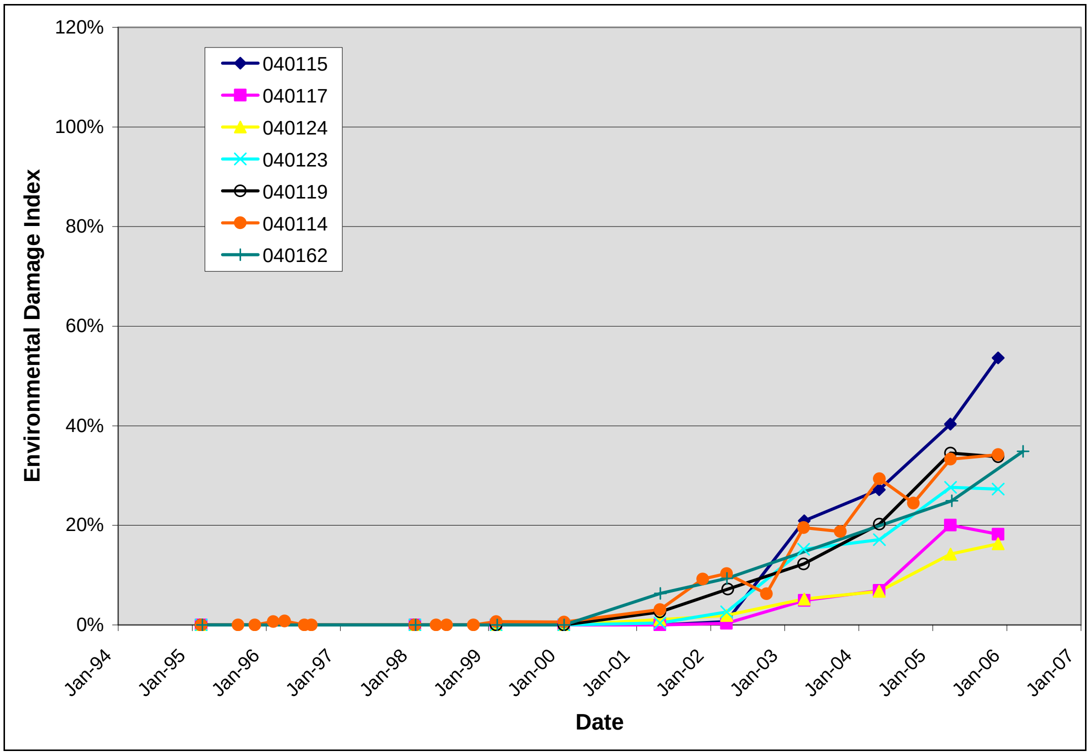

Figure 14. Environmental damage trends for SPS-1 test sections with 7 inches or more of AC.

PERFORMANCE COMPARISONS

In-depth analyses and comparisons were conducted for all of the SPS-1 test sections. Figure 15 provides a summary of the structural damage index and pavement structure for each section while a summary of the environmental damage index and pavement structure can be found in Figure 16. Both damage indices reported are based on the data collected in March/April 2002 (just prior to the slurry seal).

Figure 17 provides a summary of rutting and pavement structure for each section. Significant variation in rutting performance between the sections did not exist. All sections exhibited less than 7 mm of rutting after more than seven years in service, which is well below the level required to trigger improvements in most pavement management systems. Therefore, rutting was not the driving factor in the overall condition of the pavement.

Following is a synopsis on the findings and performance of each section in terms of structural deterioration, environmental deterioration, rutting, and any unique circumstances to be considered.

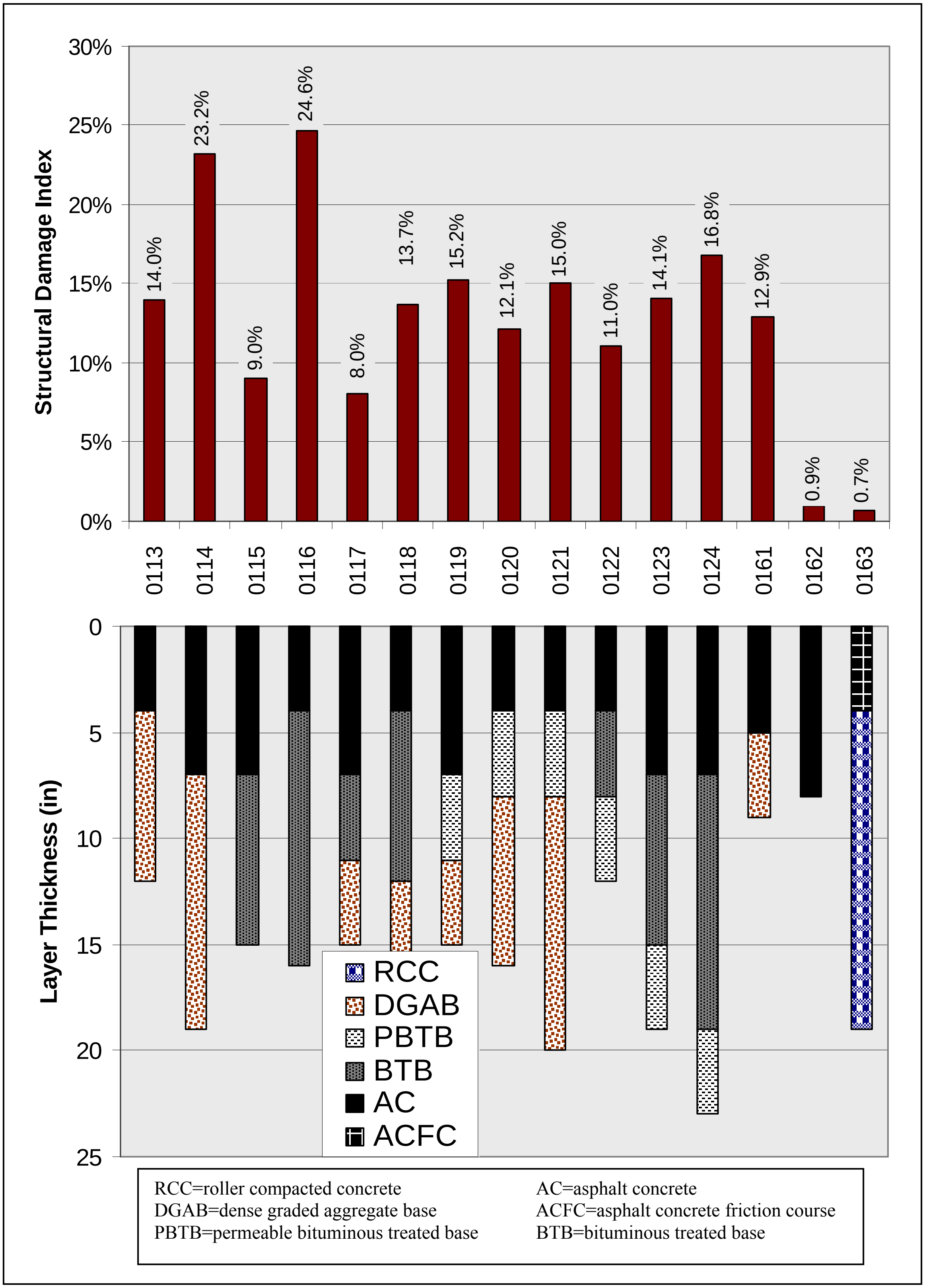

Figure 15. Structural Damage Index and pavement structure summary.

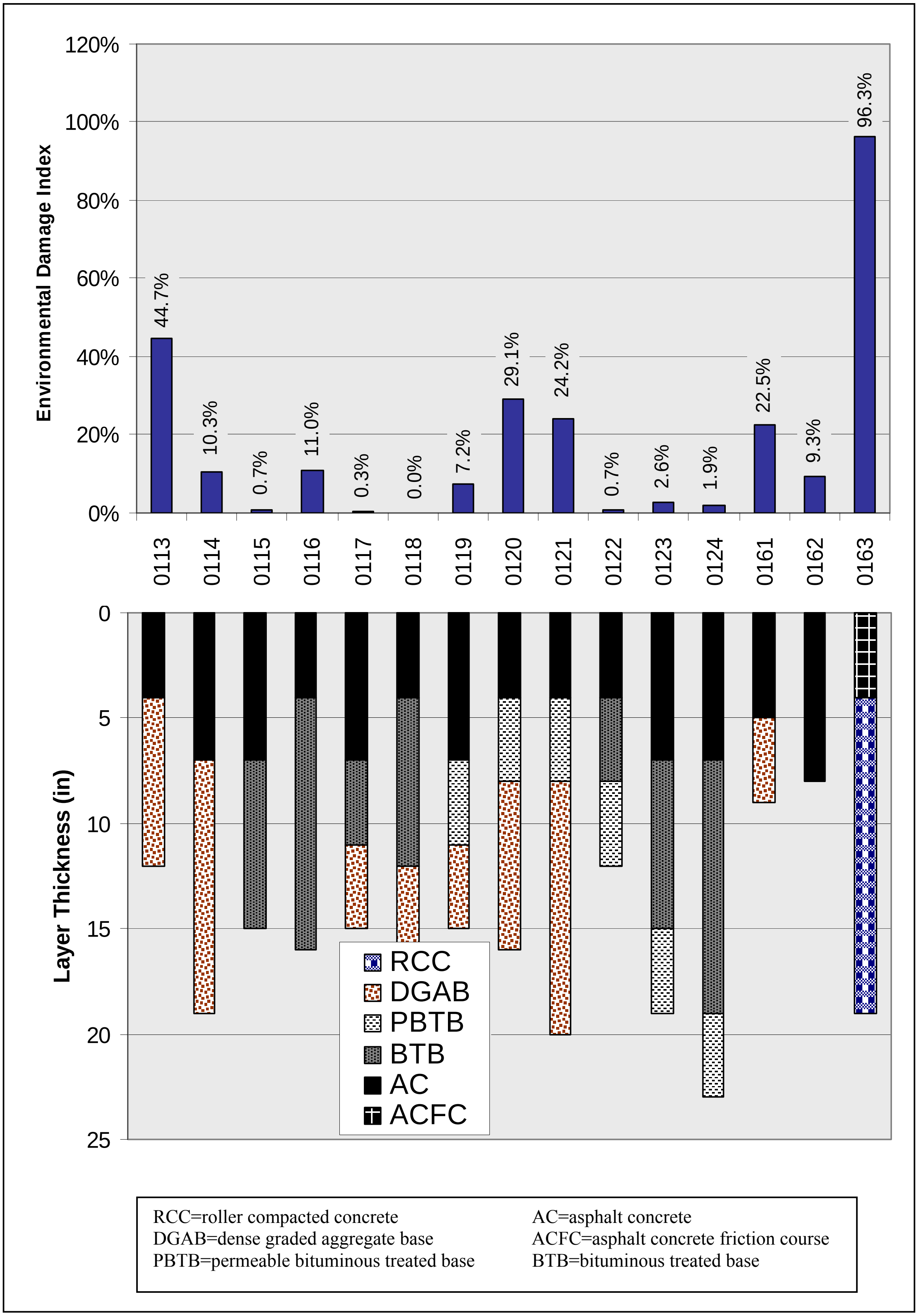

Figure 16. Environmental Damage Index and pavement structure summary.

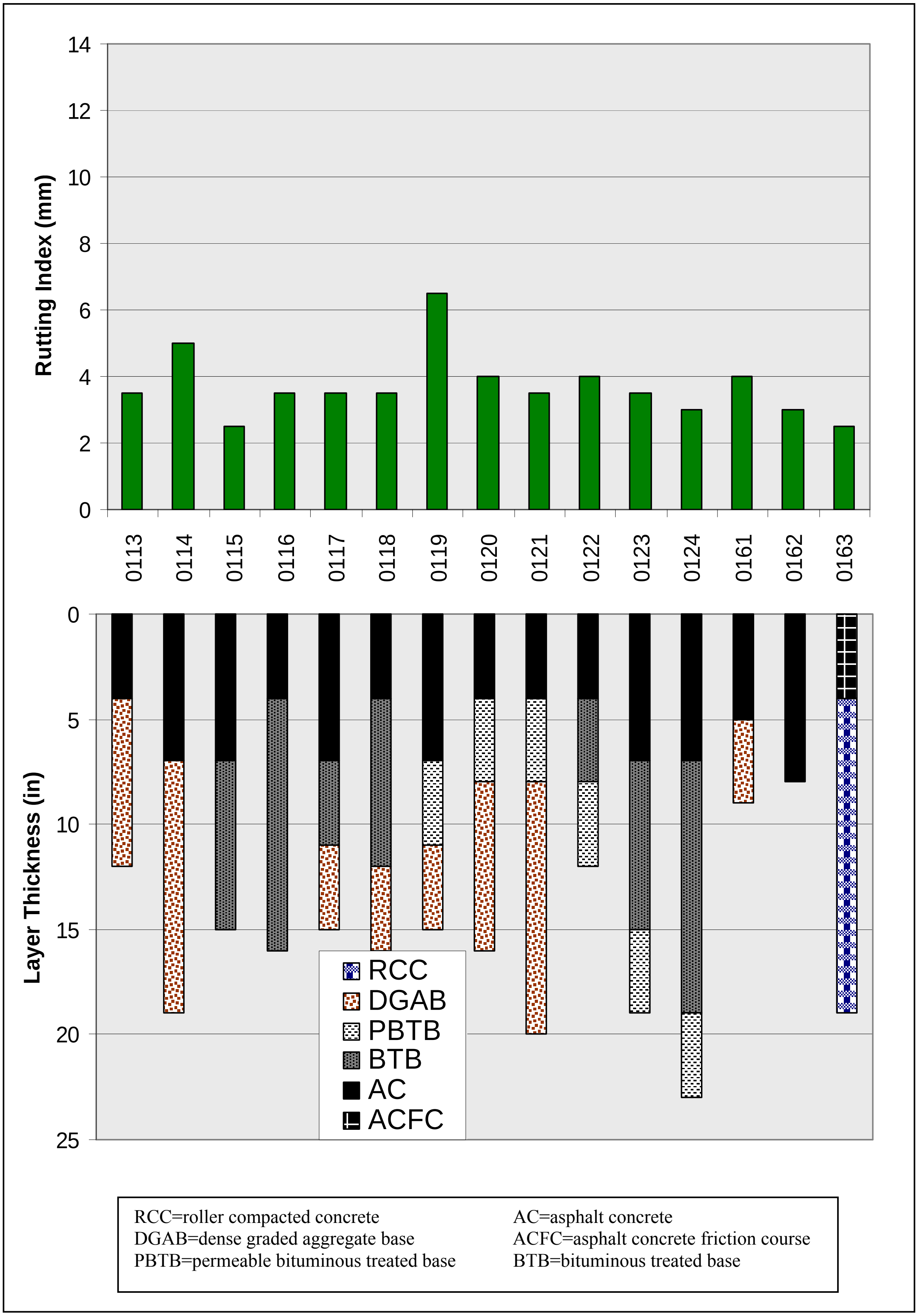

Figure 17. Rutting Index and pavement structure summary.

There is a debate in the paving community between top-down and bottom-up cracking. The classic fatigue cracking model looks at bottom-up cracking resulting from repeated tensile stresses at the bottom of the AC pavement. In the last 20 years there has been a growing awareness that some of the cracking seen in the wheel paths can initiate at the surface of the pavement and progress downward. Top-down cracking is particularly evident in thicker pavement sections. [6, 7]

Most of the pavement test sections on this project appear to have experienced early top-down cracking. When one looks at the deflection analysis work noted in the previous section, the plate deflection values (D_0) are quite low for most of the pavement sections and the SN_{eff} values are quite high and have not deteriorated much over 10 years. Since the cracks were not cored in the test sections, it is impossible to confirm that the cracking started at the pavement surface. To confirm if the cracking indicates full structural deterioration or only deterioration of the surface course, the best information is from the deflection analysis. That information tends to indicate that most pavement sections remained structurally competent through the 10-year observation period. The surface deterioration seems to have been made significantly worse by the placement of a longitudinal joint in the right wheel path of the wearing course. Much of the pavement cracking that is normally associated with structural deterioration occurred in the right wheel path. Very little cracking is evident in the left wheel path, which further indicates the large impact that construction joint had on the cracking experienced on the test sections.

Because the standard measure of pavement performance –"fatigue cracking" – seems to have been driven primarily by a construction abnormality rather than the structural layers, assessment of the relative value of the various test sections is better done looking at the deflection information.

<u>0113-AC/DGAB</u>

This section exhibited average cracking performance; however, it accumulated the second largest quantity of environmental damage. Section 0161 is similar to 0113 in that both structures consist of AC over DGAB. Section 0161 has 4 inches more AC and 4 inches less DGAB. Since they both have shown similar SN_{eff} values, they may be structurally equivalent and the added 1 inch of AC may be comparable to 4 inches of DGAB.

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6. Jeff Uhlmeyer, et al., "Top-Down Cracking in Washington State Asphalt Concrete Wearing Course." (Paper No. 00-0405, Transportation Research Board Annual Meeting, Washington, D.C., January 9-13, 2000).

7. Imad Al-Qadi, et. al.,"Dynamic Analysis and In-Situ Validation of Perpetual Pavement Response to Vehicular Loading" (paper presented at the Transportation Research Board Annual Meeting, Washington, D.C., January 13-17, 2008.

0114-AC/DGAB
Section 0114 had above-average fatigue and longitudinal cracking (second highest) and average environmental performance. One would expect that the structural deterioration of this section would be less than that of 0113 when consideration is given to the pavement structure of each. Looking at the SN_{eff} values computed for both sections, section 0114 is about 50 percent greater than 0113, which fits with the added layer thickness.

0115-AC/BTB
Both structural and environmental deterioration on this section were well below the average for the SPS-1 project. The section consisted of 7 inches AC over 8 inches of bituminous treated base (BTB). It should be noted that there does not seem to be much difference in terms of SN_{eff} values when compared to 0116, which consists of 4 inches AC over 12 inches of BTB. Therefore, exchanging 3 inches of AC for 4 inches of BTB did not result in a significant difference as far as load-carrying ability is concerned.

0116-AC/BTB
This section exhibited the largest amount of fatigue and longitudinal cracking of the entire SPS-1 project. Environmental deterioration for the section was just above average. As noted above, the SN_{eff} values were comparable to those of section 0115. Compared to the amount of apparent surface cracking that occurred on this test section, the SN_{eff} values deteriorated about the least of any of the test sections. With no real change in the structural capacity as measured by SN_{eff} values over 10 years, this section may provide a very long service life, provided the wearing course is removed and replaced on a regular basis.

0117-AC/BTB/DGAB
Section 0117 developed less than average fatigue and longitudinal cracking and very little environmental damage. The load-carrying capacity of this section in terms of SN_{eff} values is very close to section 0118's, which has roughly the same total thickness of AC and BTB, but the AC and BTB thickness ratios vary between the two sections.

0118-AC/BTB/DGAB
This section had essentially no environmental deterioration, but the structural deterioration was above average. It can be compared with 0117 because of similarities in the pavement structures and SN_{eff} values. Both sections developed relatively small quantities of environmental damage. There is no clear explanation as to why this occurred.

0119-AC/PBTB/DGAB
0120-AC/PBTB/DGAB
0121-AC/PBTB/DGAB
All three test sections have similar combinations of permeable bituminous treated base (PBTB), AC, and DGAB with varying thickness. The relative load-carrying ability of all three sections was similar when measured by SN_{eff} values. The difference between these sections may not be discernible over a 10-year monitoring period.

0122-AC/BTB/PBTB

This section developed environmental and structural deterioration that was below average as compared with the rest of the SPS-1 project. Relatively minor patching was performed on this section in 2001 to fill a small pothole that developed in an area of fatigue. The SN_{eff} values were comparable to those found for the three sections noted above. However, the center plate deflection D_0 was about half that measured for sections 0119, 0120, and 0121. This stiffer response might indicate the presence of the BTB between the AC and PBTB layers. Like the sections noted above, the differences between these sections may not be discernible over a short 10-year period. As far as pavement deflections go, there did not seem to be any particular advantage to adding a layer of PBTB in the last four pavement sections.

0123-AC/BTB/PBTB

The AC and BTB layers of section 0123 are identical to those of 0115. Section 0123 has an additional PBTB layer that is 4 inches thick. In comparing the two sections, the addition of the PBTB layer did not result in an improvement in cracking performance. The SN_{eff} values for 0123 and 0115 are comparable. There was a small advantage in SN_{eff} values for 0123 initially, but that seems to have been lost over the 10-year period.

0124-AC/BTB/PBTB

This section consists of an additional 4 inches of BTB as compared with 0123, yet it experienced more accumulation of structural distress (again this may be due more to surface cracking than actual structural deterioration of the full section). Section 0124 has the highest load-carrying capacity of all the test sections as measured by SN_{eff} values, which is due to the added BTB thickness.

0161-AC/DGAB

As mentioned above, this section exhibited similar structural performance as section 0113, indicating 1 inch of AC is approximately equivalent to 4 inches of DGAB. The SN_{eff} values were also about the same for both sections, further indicating that 1 inch of AC in 0161 was similar structurally to 4 more inches of DGAB in section 0113.

0162-AC

The performance of this section is unique. The section was constructed with 8 inches of AC on natural subgrade and exhibited significantly less distress than all other sections. This may be more the result of improved construction quality than any structural feature in that it was one of the last sections paved. The SN_{eff} values measured for the pavement section were a bit better than those for 0113 and 0161, which had the thinnest AC depths but not as large as the rest of the pavement sections. A thorough review of the construction records may be warranted to determine what was different between the wearing course on this section and the other sections which experienced more cracking.

0163-ACFC/RCC

While section 0163 exhibited excellent structural performance, the accumulation of reflection crack damage was significant. Within five years of construction, the section was rated with almost 100 percent block cracking due to the reflection of cracks in the roller compacted concrete beneath the friction course. The solid structural performance of this section came with a trade-off in environmental deterioration. Consideration should be given to retarding the propagation of reflective cracking, if ACFC is constructed over RCC in the future: this is one option that is particularly viable given Arizona's experience with asphalt rubber friction courses.

Relatively minor patching was performed on this section in 2001 to fill a small pothole that developed in a fatigued area. The size of the patching did not have an effect on the structural or environmental damage indices.

<u>0160-PCC</u>

Section 0160 was constructed with jointed Portland cement concrete pavement and was built primarily as a stable, flat platform for Weigh-In-Motion (WIM) and traffic classification equipment. The section also served a secondary purpose as an alternative pavement type to the asphalt concrete pavement designs for the region of the Arizona SPS-1. As Portland cement concrete pavements have different performance characteristics and distress phenomena, it was not possible to use the same analysis technique for the characterization of the pavement distress. As such, this section was not included in Figures 4 through 7, but had reasonably good distress performance over the life of the project. The most significant cracking distress to develop was three transverse cracks. The section received diamond grinding to enhance smoothness for the WIM system shortly after the section was built. Although the transverse joints had very little faulting (none exceeding 1 mm) that would have indicated poor load transfer, many of the joints did have minor fraying and spalling. Joint sealant failure was rated at almost all transverse joints, and the longitudinal joints had some portions where joint sealant failure had also occurred. The pavement on this section exhibited map cracking soon after the segment was constructed.

While the Arizona SPS-1 has reached the end of its service life, the Portland cement concrete slabs used for 0160 will continue to serve as the platform for the WIM equipment installed at this location.

Paving Seam Analysis

As mentioned previously, the paving seam present throughout the SPS-1 project has contributed to the damage accumulated; however, the extent of the seam's influence on performance cannot be completely determined and isolated from deterioration that would have occurred naturally due to environment and traffic. To provide a complete picture of the deterioration, Figure 18 provides structural damage index values for each wheel path. Figure 18 does not isolate construction issues from natural deterioration, but it is expected that the paving seam will have a greater influence on the deterioration of the outer wheel path as compared to the inner wheel path, due to the proximity of the outer wheel path and the paving seam.

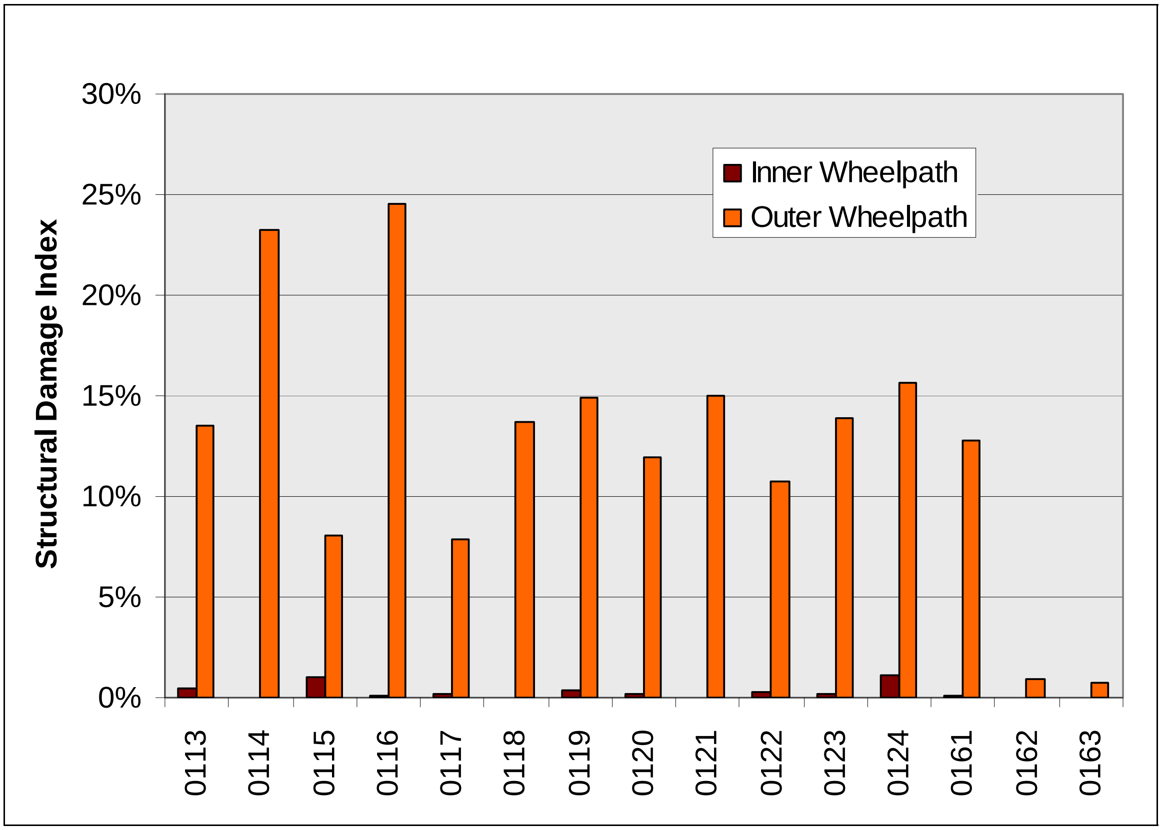

Figure 18. Structural Damage Index separated by wheel path.

From Figure 18, it is apparent that the outer wheel path—largely governed by the paving seam—has driven the overall structural damage. The outer wheel path of every section contains significantly more deterioration as compared to the inner wheel path.

Performance comparisons based solely on the inner wheel path would minimize the effect of the paving seam on the findings. However, the structural deterioration of the inner wheel path was very minimal (1 percent or less) and did not accumulate sufficient distress to distinguish robust performance comparisons between test sections.

DISTRESS KEY FINDINGS

The distress data captured at the project provides valuable insight into pavement performance, design, management, and construction. The following list provides highlights from the SPS-1 distress analysis.

- The longitudinal construction joint was located in the outer wheel path. Over time, this became a longitudinal crack and eventually a heavily fatigued area throughout the project. The importance of keeping longitudinal joints out of the areas of heaviest loading cannot be overstated.

- Nine of the sections received a slurry seal coat in 2002. This masked the raveling that started in 1999, but did not otherwise provide a significant improvement in environmental cracking. The sections not receiving the slurry seal had a very poor surface condition at the end of their service lives.

- Normal structurally-related distresses were greatly influenced by the longitudinal construction joint. The report developed during construction predicted the likelihood of distress propagation from this seam.

- Almost every section (except 0162 and 0163) showed significant growth in fatigue and longitudinal cracking 9 to 10 years after construction, with the rate of growth then slowing until the sections were placed out-of-study. It is surmised that the cracking experienced on this project was primarily top-down cracking, but there is no confirmation that it was the case. Deflection analysis indicates that there was no significant deterioration in SN_{eff} values over the life of the project for any of the sections, so there was no measured change in load-carrying ability.

- Construction quality can play a major role in performance. It is thought that section 0162, where the AC layer was placed directly on the subgrade, performed better due to the construction practices for this section.

- All sections, save 0163, had reasonable patterns of environmental distress growth, with a clear increase in magnitude approximately 10 years after construction.

- Sections constructed with 4 inches of AC over DGAB or PBTP exhibited some of the largest accumulations of environmental deterioration.

- From a structural performance perspective, 1 inch of AC is equivalent to 4 inches of DGAB.

- Exchanging 4 inches of BTB for 4 inches of DGAB does not appear to affect performance, based on limited observations at the SPS-1 project.

- There is no evidence that PBTB layers provide improved resistance to structural or environmental degradation in the Arizona climate (i.e., dry, no-freeze).

- The roller-compacted concrete section (0163) had almost 100 percent block cracking within five years of construction and also had significant water bleeding and pumping issues.

- All sections performed well with regard to rut resistance. Rutting would not have triggered a rehabilitation event for any section.

- With no replicate sections, there is limited ability to assess potential variability independent of actual performance.

- Four sections (0116, 0122, 0161, and 0163) received patching at some point.

SPS-1 ROUGHNESS ANALYSIS

This chapter characterizes the surface roughness of these sections throughout their service life and links the observations to records of pavement distress and its development. Road profile measurements were collected on this site about once per year starting with the winter after it was opened to traffic. This study analyzed the profiles in detail by calculating their roughness values, examining the spatial distribution of roughness within them, viewing them with post-processing filters, and examining their spectral properties. These analyses provided details about the roughness characteristics of the road and provided a basis for quantifying and explaining the changes in roughness with time.

PROFILE DATA SYNCHRONIZATION

Profile data were collected over the entire Arizona SPS-1 site on the 13 dates listed in Table 10. Raw profile data were available for all 13 visits. In each visit, a minimum of seven repeat profile measurements were made.

Table 10. Profile measurement visits of the SPS-1 Site.

Visit	Date	Time	Repeats	Sections
01	27-Jan-1994	13:44	7	0113-0124, 0160-0163
02	27-Feb-1995	12:45	9	0113-0124, 0160-0163
03	23-Jan-1997	09:54-11:47	9	0113-0124, 0160-0163
04	08-Apr-1998	13:50-15:02	7	0113-0124, 0160-0163
05	04-Dec-1998	10:40-11:46	7	0113-0124, 0160-0163
06	17-Nov-1999	09:26-10:32	7	0113-0124, 0160-0163
07	19-Dec-2000	11:26-12:54	9	0113-0124, 0160-0163
08	06-Nov-2001	11:25-12:44	9	0113-0124, 0160-0163
09	20-Feb-2002	10:41-12:21	9	0113-0124, 0160-0163
10	02-Mar-2003	14:30-16:25	9	0113-0124, 0160-0163
11	10-Mar-2004	11:29-13:34	9	0113-0124, 0160-0163
12	15-Mar-2005	13:42-16:02	9	0113-0124, 0160-0163
13	27-Mar-2006	12:43-15:02	9	0113-0124, 0160-0163

Profile data were also collected on 16 additional dates over sections 0113 and 0114 as part of the seasonal monitoring program. Table 11 lists the dates and times of these visits. These visits cover four seasons in 1998 and 12 seasons in a row starting in the winter of 2001. Visits S01 and S02 included section 0114 only. The rest covered both sections. Note that visits S02 and S10 occurred on dates that were very close to conventional visits 04 and 10, respectively.

DATA EXTRACTION

Profiles of individual test sections were extracted directly from the raw measurements. This was done for two reasons. First, profiles were collected in visits 03 through 09 and S01 through S07 at a 0.98 in sample interval and in visits 10 through 13 and S08 through S14 at a sample interval of about 0.77 inches. These data appeared in the database after the application of an 11.8-inch moving average and decimation to a sample interval of 5.91 inches. The raw data contained the more detailed profiles. Second, this study depended on consistency of the profile starting and ending points with the construction layout and consistency of the section limits with time. In particular, a previous quality check revealed that some profiles were shifted.[8]

Table 11. Seasonal visits of Sections 0113 and 0114.

Visit	Date	Repeats	Time	
			Section 0113	Section 0114
S01	14-Jan-1998	7	—	16:37-16:57
S02	07-Apr-1998	7	—	14:43-15:20
S03	08-Jul-1998	7	09:31-10:02	09:31-10:02
S04	01-Oct-1998	7	09:28-10:02	09:28-10:02
S05	10-Dec-2001	9	14:18-14:55	14:18-14:55
S06	23-Jan-2002	9	11:46-12:47	11:44-12:40
S07	14-Mar-2002	9	11:45-12:39	11:43-12:37
S08	11-Oct-2002	9	15:51-16:24	14:56-15:41
S09	18-Dec-2002	9	13:39-14:08	13:16-13:37
S10	10-Mar-2003	9	12:55-13:16	12:35-12:53
S11	09-Aug-2003	9	22:53-23:19	22:25-22:45
S12	23-Nov-2003	9	13:38-14:29	13:43-14:27
S13	17-Dec-2003	9	15:11-15:58	15:08-15:56
S14	22-Apr-2004	9	15:52-16:36	15:51-16:34
S15	15-Jul-2004	9	21:37-22:25	21:35-22:23
S16	08-Sep-2004	9	08:49-09:31	08:47-09:29

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) automated searching for the longitudinal offset between repeat measurements.

CROSS CORRELATION

Searching for the longitudinal offset between repeat profile measurements that provides the best agreement between them is a helpful way to refine their synchronization. This

8. L. D. Evans and A. Eltahan, *LTPP Profile Variability*, FHWA-RD-00-113 (Washington, DC: Federal Highway Administration, 2000).

can be done by inspecting filtered profile plots, but it is very time consuming. Visual assessment is also somewhat subjective when two profiles do not agree well, which is often the case when measurements are made several years apart. An automated procedure, rather than visual inspection, was used for finding the longitudinal offset between measurements.

The procedure is based on a customized version of cross correlation.[9] 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 to the basis measurement. A high level of cross correlation requires a good match of profile shape, the location of isolated rough spots, and overall roughness level. Therefore, the correlation level is often only high when the two 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 after the International Roughness Index (IRI) filter was applied to the profiles, rather than using the unfiltered 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 able to leverage profile features at isolated rough spots to fine tune the positioning.

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 visit 08.

   This was done using the event markers from a raw measurement. The fifth repeat measurement was used for this purpose. Event markers appeared at the start and end of every section. The locations of the event markers were compared to the layout provided in the construction report.[10] No inconsistencies were found between the event markers and the construction report.

   All of the sections were assumed to begin at the appropriate event marker and continue for 500 ft.

2. Automatically synchronize the other eight repeats from visit 08 to the basis set.

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9. Steve Karamihas, "Development of Cross Correlation for Objective Comparison of Profiles," *International Journal of Vehicle Design* 36, no. 2/3 (2004): 173-193.

10. Nichols Consulting Engineers, "Construction Report on Site 040100," 2.

3. Automatically synchronize the measurements from the previous visit to the current basis set.
4. Designate the previous 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 visit 01 is complete.

Data for visits 09 through 13 were provided after visits 01 through 08 were synchronized. Visits 09 through 13 were synchronized using steps 3 through 6, but going forward in time.

Some seasonal measurements appeared in a profile that only covered the section of interest. In these cases, automated synchronization was used simply as a way of verifying that the proper road segment was contained within each profile. These measurements were consistently lined up with a high degree of precision. Other seasonal measurements included some additional profiles upstream of the segment of interest or covered a large test length that included both sections 0113 and 0114. In these cases, the seasonal measurements were synchronized to a basis measurement from a regular visit of the same year.

LONGITUDINAL DISTANCE MEASUREMENT

The basis set of profile measurements for visit 08, established in step 1, above, was set using the event markers in one raw profile measurement (the fifth repeat). The other eight repeats from visit 08 were automatically synchronized to the basis set. When the longitudinal placement of the individual sections within each measurement were compared to the layout within the basis set, the slope of the linear fit ranged from 1.0000 to 1.0004. Thus, the longitudinal distance measurement for the nine profile measurements of visit 08 was consistent within 0.04 percent. This is a very high level of agreement in longitudinal distance measurement.

Figure 1 shows the disagreement in longitudinal distance measurement for each visit using the original basis set as a reference. In the figure, a range of disagreement for each visit exists because up to nine repeat profile measurements were made. The variation between repeat measurements within a visit appears as the width of each bar in the figure. Note that two separate bars are presented for visits 11 and 13. This is because the profile measurements from those visits covered the site in two parts. This included the first seven sections in a leading (L) set of measurements and the other nine in a trailing (T) set of measurements.

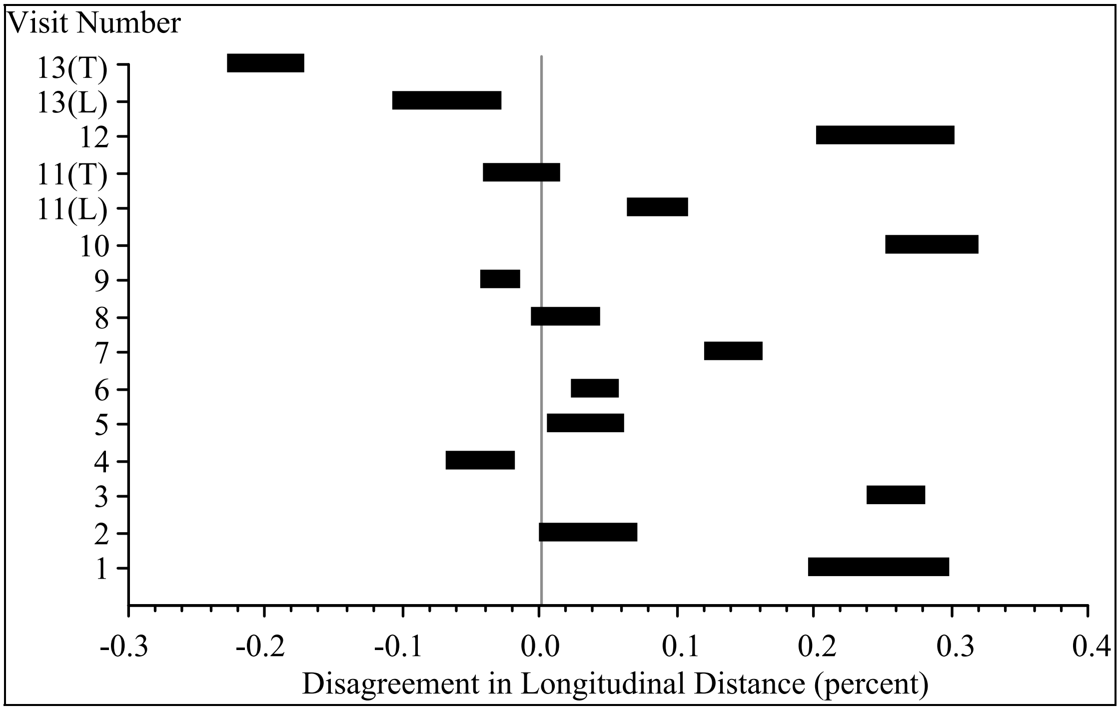

Figure 19. Consistency in longitudinal distance measurement.

Since the longitudinal distance measurement was based on the rotation of a drive wheel, the variations were most likely caused by variations in speed, lateral wander, and tire inflation pressure.[11] If tire inflation pressure were the dominant cause, the disagreement would grow more positive with each successive repeat measurement as the tire heated up and tire pressure increased. This is because the tire rolling radius would increase, and the profiler would register less wheel rotation for the same travel distance. This appeared to be the case for visits 03 through 08, but the effect was never greater than 0.05 percent of the overall distance. Note that the field procedures require the operator to warm up the tire prior to the measurements. That accounts for the high level of agreement among visits 03 through 13.

The variation between visits in Figure 19 is caused by differences in distance measurement instrument calibration. The longitudinal distance measured by a profiler is not true horizontal distance. It always includes some additional component because the profiler must travel up and down the undulations in the road. This component can be minimized by calibrating the profiler to true horizontal distance. However, if a profiler operates on a road with grade changes and roughness that are not similar to the site used for longitudinal distance measurement calibration, some error will exist. Tire inflation

11. Steve Karamihas, et. al., *Guidelines for Longitudinal Pavement Profile Measurement*, National Cooperative Highway Research Program Report 454 (Washington, DC: Transportation Research Board, 1999).

pressure and tread wear must also be close to the level that existed during calibration for consistent results.

Modest inconsistency in longitudinal distance measurement between visits is not critical as long as the profiles of individual sections are extracted using event markers rather than longitudinal distance from the start of each profile measurement. A high level of inconsistency, however, could interfere with comparisons between profile features and distress surveys. Errors in profile index values, such as the IRI, are also roughly of the same order as errors in longitudinal distance measurement. Figure 1 shows the longitudinal distance that was measured with a high level of agreement throughout all 13 visits.

DATA QUALITY SCREENING

Data quality screening was performed to select five repeat profile measurements from each visit of each section. The five measurements among the group of available runs which were selected had exhibited the best agreement with each other. In this case, agreement between any two profile measurements was judged by cross correlating them after applying the IRI filter. Correlation quantifies the association among variables. Karamihas described the details of this method.[12] In this method, the IRI filter is applied to the profiles, then the output signals are compared rather than the overall index. High correlation by this method requires that the overall roughness is 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 IRI filter output emphasizes profile features in (approximate) proportion to their effect on the overall roughness.
- Correlation of IRI filter output provides a good trade-off between emphasizing localized rough features at distressed areas in the pavement 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 IRI filter output and the expected agreement in overall IRI. [13]

Note that this method was performed with a special provision for correcting modest longitudinal distance measurement errors.

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12. Karamihas, "Development of Cross Correlation for Objective Comparison of Profiles," 181.

13. Karamihas, "Development of Cross Correlation for Objective Comparison of Profiles," 184.

Each comparison between profiles produced a single value that summarized its level of agreement. When nine repeat profile measurements were available, they produced a total of 36 correlation values. Any subgroup of five measurements could be summarized by averaging the relevant 10 correlation values. 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 ranged from six to nine, the number of measurements that were excluded ranged from one to four. Tables 12 through 27 list the selected repeats for each visit of each section and the composite correlation level produced by them.

Table 12. Selected Repeats, Section 0113.

Visit	Repeat Numbers					Composite Correlation
01	2	4	5	6	7	0.958
02	2	3	4	6	8	0.962
03	3	4	5	6	9	0.969
04	1	2	3	4	6	0.931
05	2	3	4	5	6	0.959
06	1	2	3	4	6	0.960
07	1	3	4	8	9	0.963
08	3	4	6	7	9	0.950
09	2	3	5	6	7	0.942
10	1	3	4	5	6	0.925
11	1	2	3	5	7	0.975
12	1	2	4	7	9	0.952
13	3	4	5	6	9	0.954
S03	2	3	4	5	6	0.959
S04	1	2	4	6	7	0.967
S05	1	3	4	5	9	0.950
S06	1	5	6	8	9	0.951
S07	3	4	5	8	9	0.976
S08	5	6	7	8	9	0.966
S09	3	4	6	8	9	0.955
S10	1	3	5	7	8	0.946
S11	1	3	4	6	7	0.975
S12	2	3	4	8	9	0.969
S13	2	3	4	8	9	0.968
S14	4	5	6	7	8	0.969
S15	3	5	6	7	8	0.972
S16	3	4	7	8	9	0.980

Table 13. Selected Repeats, Section 0114.

Visit	Repeat Numbers					Composite Correlation
01	1	2	3	4	5	0.864
02	2	3	4	6	7	0.943
03	1	2	4	7	9	0.920
04	1	2	4	6	7	0.841
05	2	3	4	6	7	0.890
06	2	3	4	6	7	0.925
07	1	2	5	6	9	0.927
08	2	4	5	6	9	0.909
09	2	3	4	7	9	0.911
10	1	2	3	4	5	0.911
11	1	2	4	5	6	0.946
12	3	4	5	8	9	0.945
13	1	2	4	5	7	0.941
S01	2	3	4	5	7	0.850
S02	1	2	4	6	7	0.874
S03	1	2	5	6	7	0.901
S04	1	2	4	5	6	0.896
S05	2	3	4	5	6	0.941
S06	2	4	5	6	8	0.946
S07	1	2	4	7	8	0.940
S08	2	3	5	7	9	0.934
S09	3	5	6	7	9	0.889
S10	1	3	6	8	9	0.917
S11	3	4	6	8	9	0.962
S12	1	2	3	5	6	0.936
S13	1	2	6	8	9	0.957
S14	1	2	4	5	9	0.938
S15	3	4	5	6	7	0.950
S16	3	4	5	7	8	0.970

Table 14. Selected Repeats, Section 0115.

Visit	Repeat Numbers					Composite Correlation
01	1	3	5	6	7	0.824
02	1	3	5	6	7	0.953
03	4	5	6	7	8	0.890
04	1	2	4	5	6	0.890
05	1	4	5	6	7	0.917
06	2	3	4	5	7	0.923
07	2	3	4	5	8	0.934
08	3	4	5	7	9	0.898
09	1	2	5	7	9	0.917
10	1	2	4	5	8	0.696
11	4	5	6	7	8	0.736
12	1	2	3	7	8	0.561
13	2	3	6	8	9	0.791

Table 15. Selected Repeats, Section 0116.

Visit	Repeat Numbers					Composite Correlation
01	1	2	3	4	7	0.881
02	2	3	4	5	8	0.915
03	1	2	3	6	7	0.907
04	2	3	5	6	7	0.868
05	1	2	3	6	7	0.896
06	1	3	4	6	7	0.911
07	1	2	3	5	8	0.911
08	2	3	4	5	7	0.794
09	2	5	6	7	9	0.949
10	1	2	3	6	7	0.911
11	3	5	6	7	9	0.949
12	3	5	6	8	9	0.960
13	5	6	7	8	9	0.970

Table 16. Selected Repeats, Section 0117.

Visit	Repeat Numbers					Composite Correlation
01	1	3	4	5	6	0.815
02	1	2	3	8	9	0.921
03	5	6	7	8	9	0.889
04	2	3	5	6	7	0.898
05	1	2	3	5	7	0.909
06	1	3	4	5	7	0.915
07	2	3	4	6	7	0.934
08	4	5	6	7	9	0.898
09	1	2	3	5	9	0.894
10	1	2	3	4	5	0.705
11	2	3	5	8	9	0.787
12	3	5	7	8	9	0.616
13	3	4	6	8	9	0.754

Table 17. Selected Repeats, Section 0118.

Visit	Repeat Numbers					Composite Correlation
01	1	4	5	6	7	0.712
02	2	5	7	8	9	0.930
03	2	3	5	7	8	0.911
04	1	3	5	6	7	0.890
05	1	2	3	4	6	0.902
06	2	3	5	6	7	0.865
07	2	4	5	7	9	0.892
08	1	2	5	7	9	0.757
09	1	2	4	5	9	0.748
10	2	3	4	6	7	0.944
11	2	4	5	7	8	0.920
12	2	5	6	7	9	0.930
13	1	4	6	7	9	0.950

Table 18. Selected Repeats, Section 0119.

Visit	Repeat Numbers					Composite Correlation
01	1	3	4	5	7	0.870
02	2	4	7	8	9	0.924
03	2	3	5	6	9	0.923
04	1	2	3	5	6	0.733
05	2	3	4	5	6	0.769
06	2	3	5	6	7	0.861
07	1	4	6	7	9	0.820
08	2	3	4	5	6	0.850
09	2	3	5	6	9	0.868
10	2	3	5	7	8	0.819
11	1	3	5	6	7	0.674
12	1	3	5	6	7	0.687
13	1	4	6	7	9	0.585

Table 19. Selected Repeats, Section 0120.

Visit	Repeat Numbers					Composite Correlation
01	2	3	4	5	6	0.904
02	2	3	7	8	9	0.958
03	2	5	6	7	8	0.937
04	1	2	3	4	7	0.922
05	1	2	3	5	7	0.943
06	1	2	4	5	7	0.921
07	1	3	6	7	8	0.964
08	2	5	6	7	9	0.964
09	1	3	4	7	9	0.960
10	1	2	5	8	9	0.961
11	1	2	4	6	8	0.960
12	3	4	5	6	8	0.945
13	5	6	7	8	9	0.956

Table 20. Selected Repeats, Section 0121.

Visit	Repeat Numbers					Composite Correlation
01	1	3	4	5	6	0.930
02	4	5	6	7	8	0.951
03	1	2	3	5	9	0.922
04	2	3	4	6	7	0.900
05	2	4	5	6	7	0.927
06	1	2	4	5	7	0.940
07	1	2	4	5	7	0.926
08	4	5	6	7	9	0.938
09	1	3	4	6	7	0.893
10	3	5	6	7	9	0.951
11	5	6	7	8	9	0.936
12	1	5	7	8	9	0.895
13	1	4	6	7	9	0.954

Table 21. Selected Repeats, Section 0122.

Visit	Repeat Numbers					Composite Correlation
01	2	3	4	5	7	0.936
02	2	3	4	6	7	0.955
03	2	4	6	8	9	0.948
04	1	2	3	4	6	0.911
05	2	3	5	6	7	0.945
06	1	2	3	5	7	0.941
07	1	3	5	7	8	0.962
08	3	4	5	6	9	0.958
09	2	4	5	6	7	0.965
10	1	4	6	8	9	0.948
11	2	4	6	7	8	0.941
12	3	5	7	8	9	0.920
13	1	3	5	6	9	0.961

Table 22. Selected Repeats, Section 0123.

Visit	Repeat Numbers					Composite Correlation
01	1	3	4	5	7	0.885
02	2	3	5	6	8	0.942
03	3	4	5	7	8	0.899
04	2	4	5	6	7	0.894
05	1	2	3	5	7	0.926
06	2	3	4	6	7	0.888
07	4	6	7	8	9	0.850
08	3	4	5	6	9	0.842
09	2	5	6	7	9	0.911
10	1	2	3	7	8	0.810
11	1	2	3	5	8	0.632
12	1	4	7	8	9	0.646
13	1	2	5	8	9	0.650

Table 23. Selected Repeats, Section 0124.

Visit	Repeat Numbers					Composite Correlation
01	1	3	4	5	6	0.833
02	1	3	4	7	9	0.928
03	2	4	5	8	9	0.884
04	1	2	3	6	7	0.809
05	1	3	4	5	7	0.908
06	1	2	4	5	7	0.894
07	2	4	5	7	8	0.855
08	1	2	7	8	9	0.812
09	1	3	4	5	9	0.833
10	1	5	7	8	9	0.758
11	1	4	6	7	9	0.720
12	1	2	3	8	9	0.430
13	1	2	4	5	8	0.656

Table 24. Selected Repeats, Section 0160.

Visit	Repeat Numbers					Composite Correlation
01	3	4	5	6	7	0.624
02	1	2	4	6	7	0.955
03	2	3	5	6	8	0.976
04	2	3	4	5	6	0.953
05	1	2	3	4	6	0.966
06	1	2	3	4	7	0.977
07	3	5	6	8	9	0.986
08	4	5	6	7	8	0.985
09	2	3	5	6	9	0.978
10	1	2	4	6	7	0.965
11	3	4	5	6	8	0.968
12	2	4	6	7	9	0.969
13	1	2	3	4	6	0.981

Table 25. Selected Repeats, Section 0161.

Visit	Repeat Numbers					Composite Correlation
01	2	3	4	5	7	0.947
02	1	2	7	8	9	0.954
03	1	3	5	7	8	0.968
04	1	2	3	5	7	0.932
05	1	2	4	6	7	0.963
06	1	4	5	6	7	0.969
07	3	4	5	8	9	0.976
08	1	2	3	4	9	0.962
09	1	2	3	5	6	0.971
10	1	2	4	6	8	0.954
11	1	4	5	7	8	0.962
12	1	6	7	8	9	0.958
13	1	3	4	5	7	0.974

Table 26. Selected Repeats, Section 0162.

Visit	Repeat Numbers					Composite Correlation
01	1	3	4	5	7	0.958
02	1	2	3	6	9	0.971
03	1	2	3	7	8	0.974
04	1	2	3	4	6	0.966
05	2	3	4	5	6	0.971
06	1	2	5	6	7	0.973
07	1	2	3	4	6	0.980
08	1	4	5	6	9	0.981
09	1	3	4	5	9	0.986
10	3	4	6	7	9	0.963
11	1	4	5	6	9	0.962
12	3	4	6	7	8	0.957
13	2	3	4	6	7	0.955

Table 27. Selected Repeats, Section 0163.

Visit	Repeat Numbers					Composite Correlation
01	2	3	4	6	7	0.839
02	1	2	3	4	5	0.966
03	4	5	7	8	9	0.968
04	1	2	4	6	7	0.958
05	1	3	4	5	7	0.971
06	1	2	4	5	7	0.975
07	1	5	7	8	9	0.977
08	2	4	5	8	9	0.978
09	1	2	3	4	5	0.969
10	2	5	7	8	9	0.949
11	2	5	6	7	9	0.918
12	2	4	5	7	9	0.906
13	3	5	7	8	9	0.902

The process described above for selecting five repeat measurements from a larger group is similar to the practice within LTPP, except that it is based on composite agreement in profile, rather than the overall index value. The correlation levels listed in Tables 12 through 27 provide an appraisal of the agreement between profile measurements for each visit of 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 this threshold, 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, they are expected to agree within 5 percent most of the time. Above this threshold, the agreement between profiles is good. Correlation above 0.92 often depends on consistent lateral tracking of the profile, 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.

Overall, the majority of the groups of measurements listed in Tables 12 through 27 exhibited excellent correlation, and most of them exhibited good correlation. Any group of repeat measurements that produced a composite correlation level below 0.82 was investigated using filtered plots: they are discussed here.

> Section 0114, Visit 04: Spikes (downward then upward) appeared in some repeat measurements of the right side profiles with a regular spacing of 25 ft over some of the second half of the section. They did not correspond to anything recorded in the distress surveys.
>
> Section 0115, Visit 01: Correlation was diminished by disagreement in the severity of roughness at a distressed area between 280 ft and 295 ft from the section start.
>
> Section 0115, Visits 10 through 13: Upward and downward spikes that were scattered throughout the profiles and did not appear in the same locations in

multiple repeats diminished the correlation. Correlation was severely diminished in the right side profiles by longitudinal cracking.

Section 0116, Visit 08: Correlation was diminished by disagreement in the severity and placement of very deep narrow dips about 138 ft and 170 ft from the start of the section and bumps about 237 ft from the start of the section.

Section 0117, Visit 01: Correlation was diminished by short wavelength “chatter.”

Section 0117, Visits 10 through 13: Correlation was poor because of gross disagreement in the short wavelength content of the right side profiles over longitudinal cracks (many sealed) and raveling on the right side.

Section 0118, Visit 01: Several of the measurements appeared to have included erroneous content caused by lost lock.[14]

Section 0118, Visit 08 and 09: Correlation was diminished by the appearance of dense patches of narrow dips in the right side profile, particularly from 205 ft to 280 ft into the section. It is likely that these are areas where the profile was not measured consistently over longitudinal cracks. Correlation was also diminished by disagreement in the measurement of narrow bumps within the left profile of the section.

Section 0119, Visits 04, 05, and 07: Measurements from these visits include dense patches of downward spikes. In each visit, the contaminated areas are the same, but the content within them is not correlated. It is likely that these are areas where the profile was not measured consistently over longitudinal cracks.

Section 0119, Visit 10 through 13: Correlation was diminished by uncorrelated short wavelength content, particularly on the right side, and small upward spikes in the profiles. This content was most likely caused by inconsistent measurement of profile over sealed longitudinal cracks.

Section 0123, Visit 10 through 13: Correlation was diminished by uncorrelated short wavelength content on the right side, including dense areas of narrow bumps and dips. This content was most likely caused by inconsistent measurement of profile over sealed longitudinal cracks.

Section 0124, Visits 04 and 08: Correlation was diminished by short wavelength “chatter” in the right side profiles.

14. L. D. Evans and A. Eltahan, *LTPP Profile Variability*, 2000.

Section 0124, Visit 09: Correlation was diminished by disagreement in short wavelength content in the right side profiles and some narrow downward spikes in the left side profiles.

Section 0124, Visits 10 through 13: Correlation was diminished by gross disagreement in short wavelength content in the right side profiles, including large extraneous narrow bumps throughout some of the repeats. This content was most likely caused by inconsistent measurement of the profile over sealed longitudinal cracks.

Section 0160, Visit 01: Correlation was critically low because of extremely large upward spikes in the profiles of the right side.

SUMMARY ROUGHNESS VALUES

Figures 20 through 35 show the left and right IRI values for each pavement section over their monitoring period. For most of the sections, this includes 26 summary IRI values; two per visit over 13 visits. Sections 0113 and 0114 include several extra IRI values from the seasonal visits (See Table 11). The figures show the IRI values versus time in years. In this case, "years" refers from the number of years between the measurement date and the date that the site was opened to traffic, which was August 1, 1993. Fractions of a year are estimated to the nearest day.

To supplement the plots, Appendix A lists the IRI, Half-car Roughness Index (HRI), and Ride Number (RN) of each section for each visit. These roughness values are the average of the five repeat measurements selected in the data quality screening. Keep in mind that these are not necessarily the same five repeat measurements selected for the LTPP database. Appendix A also provides the standard deviation of 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.

Figures 20 through 35 provide a snapshot of the roughness history of each pavement section. The remainder of this chapter is devoted to characterizing the profile content that made up the roughness, and explaining the profile features that contributed to roughness progression.

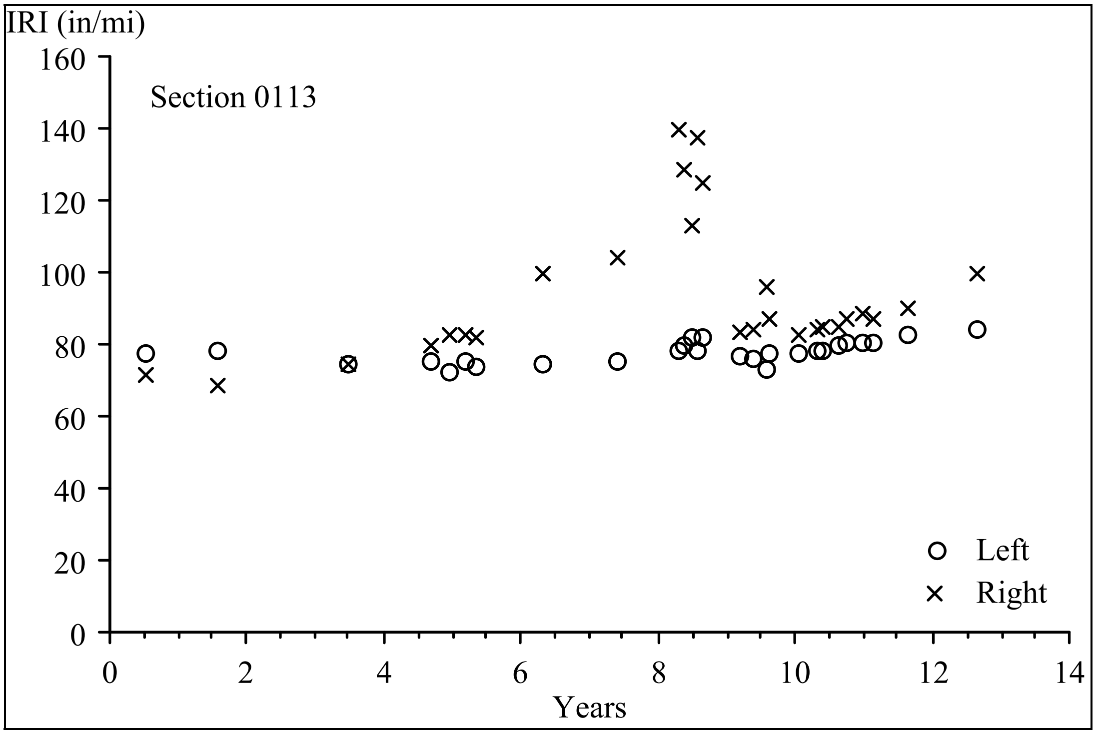

Figure 20. IRI progression, section 0113.

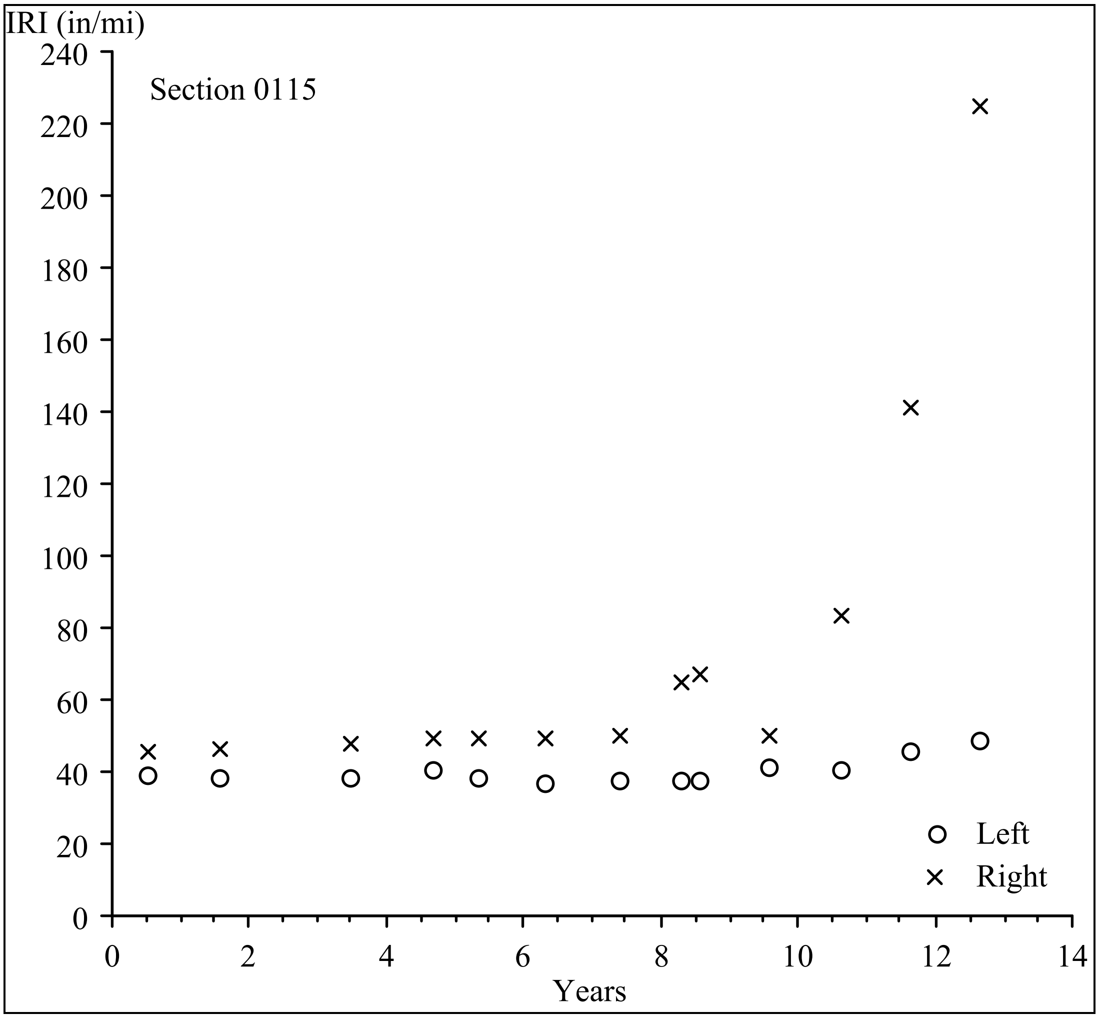

Figure 21. IRI progression, section 0115.

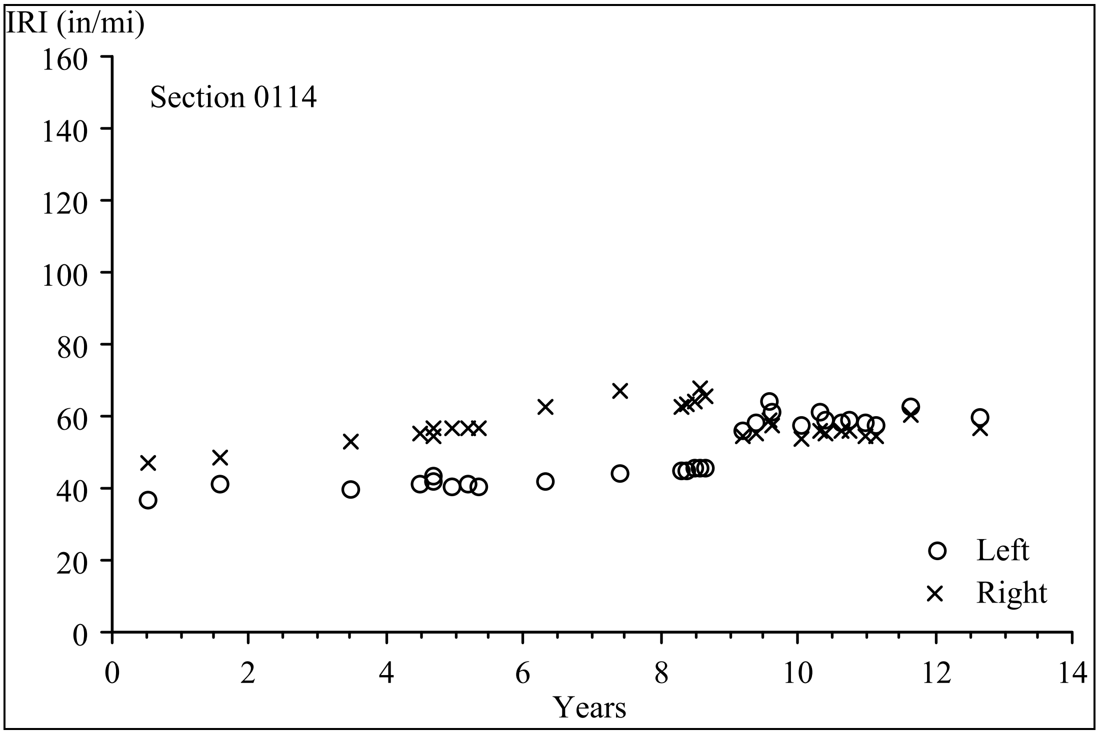

Figure 22. IRI progression, section 0114.

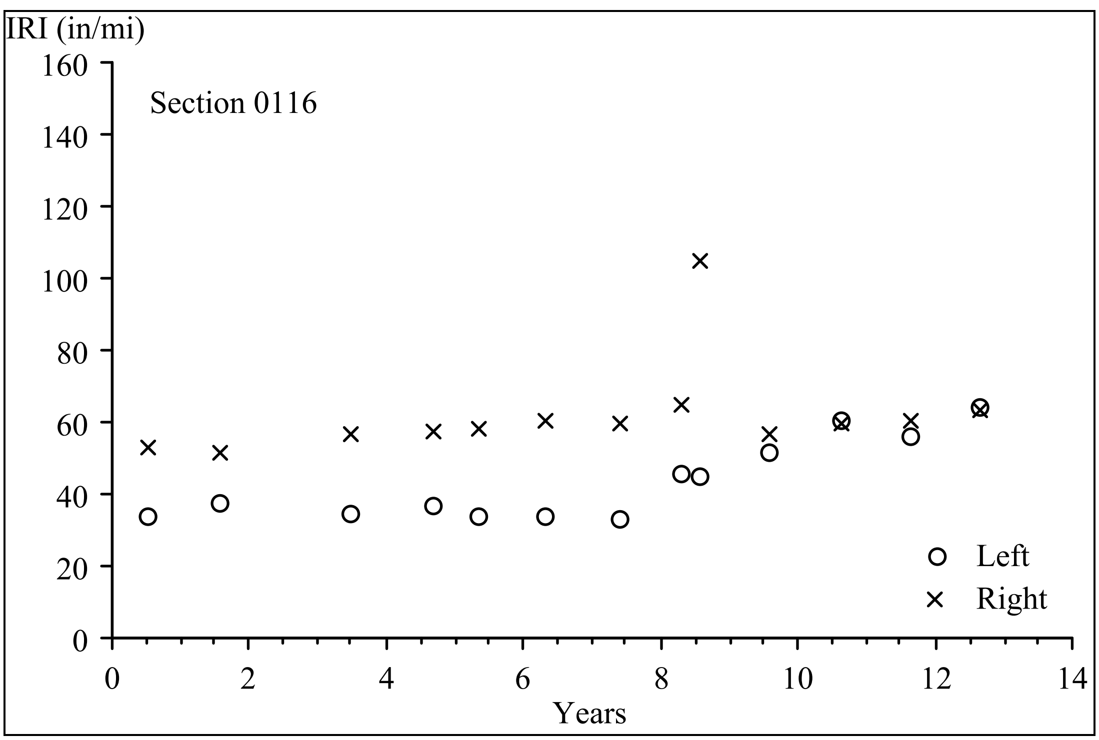

Figure 23. IRI progression, section 0116.

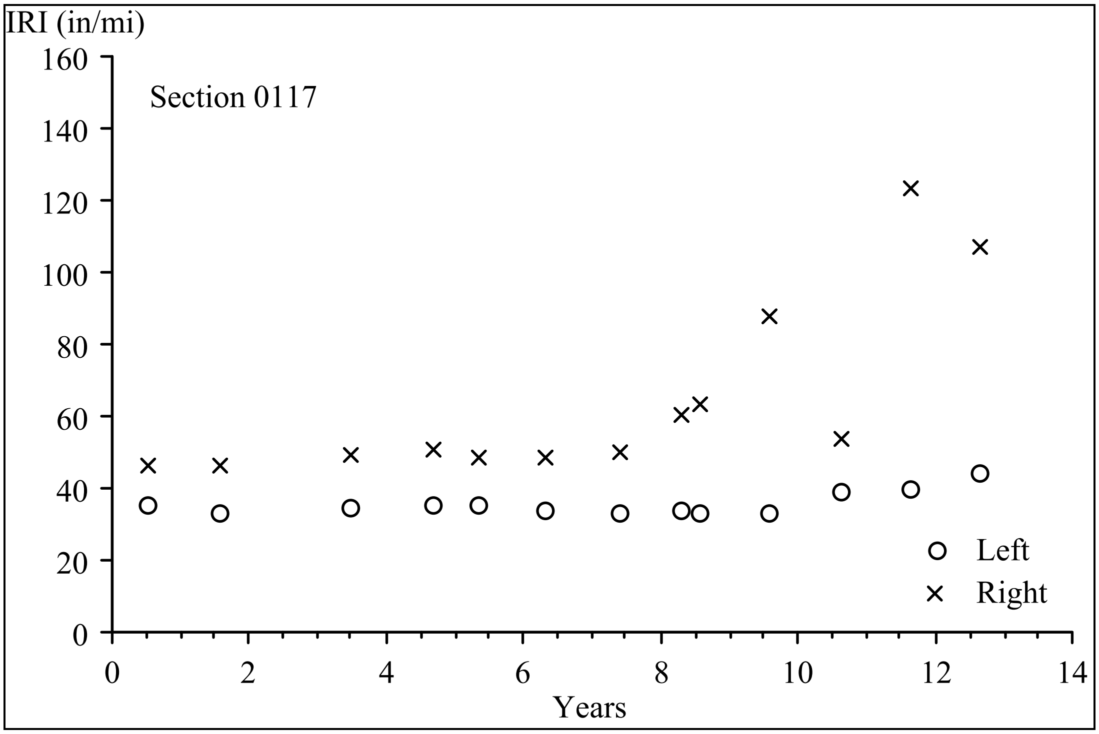

Figure 24. IRI progression, section 0117.

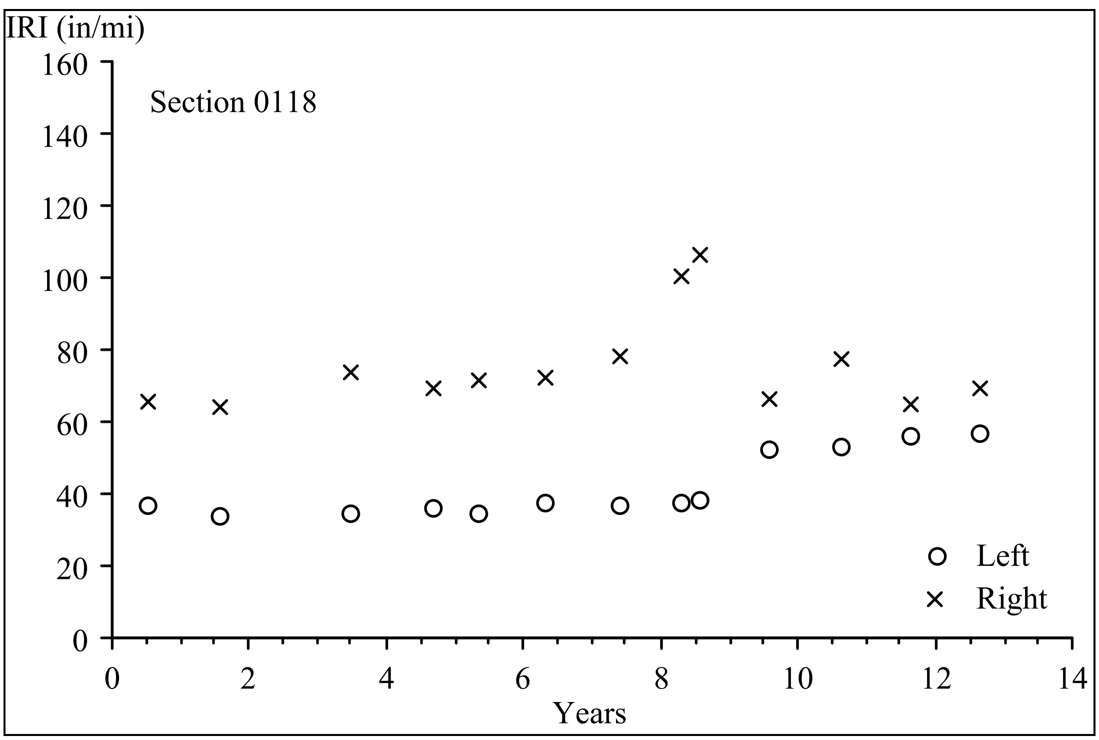

Figure 25. IRI progression, section 0118.

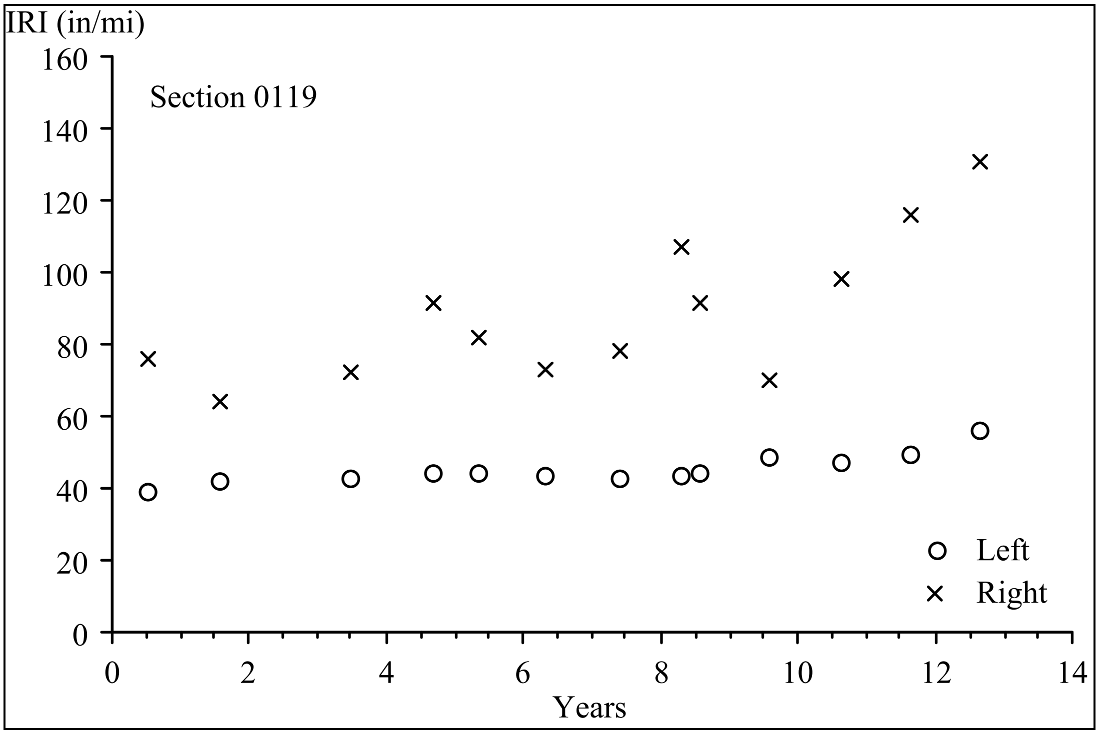

Figure 26. IRI progression, section 0119.

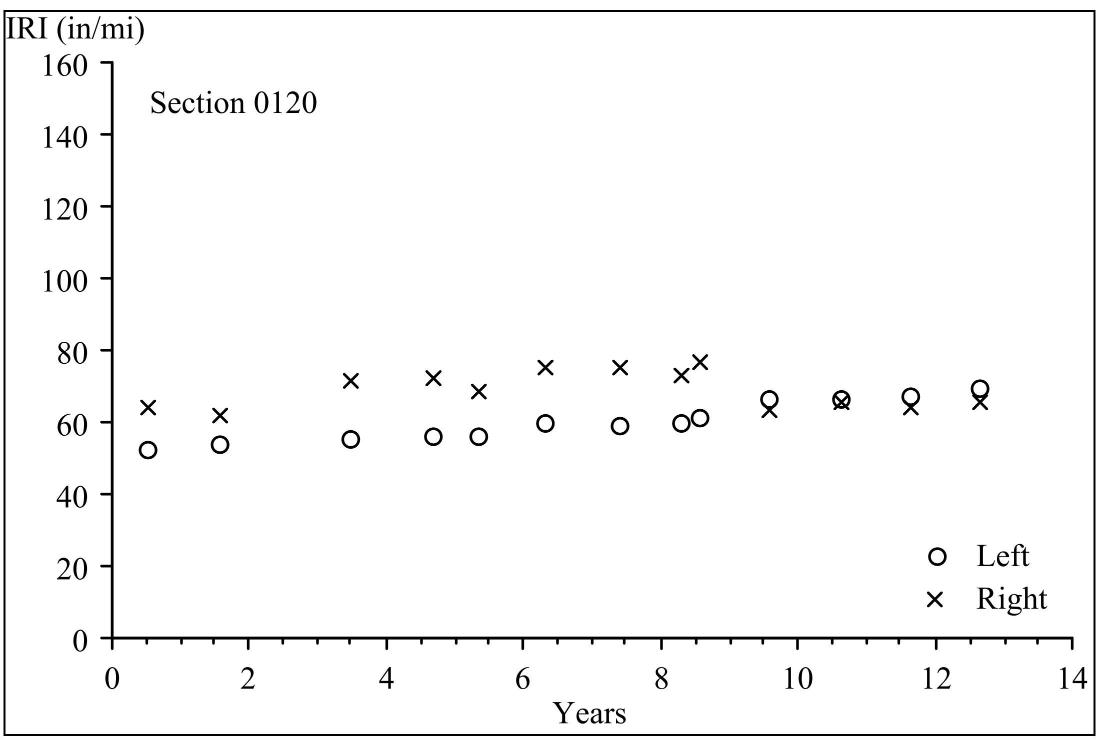

Figure 27. IRI progression, section 0120.

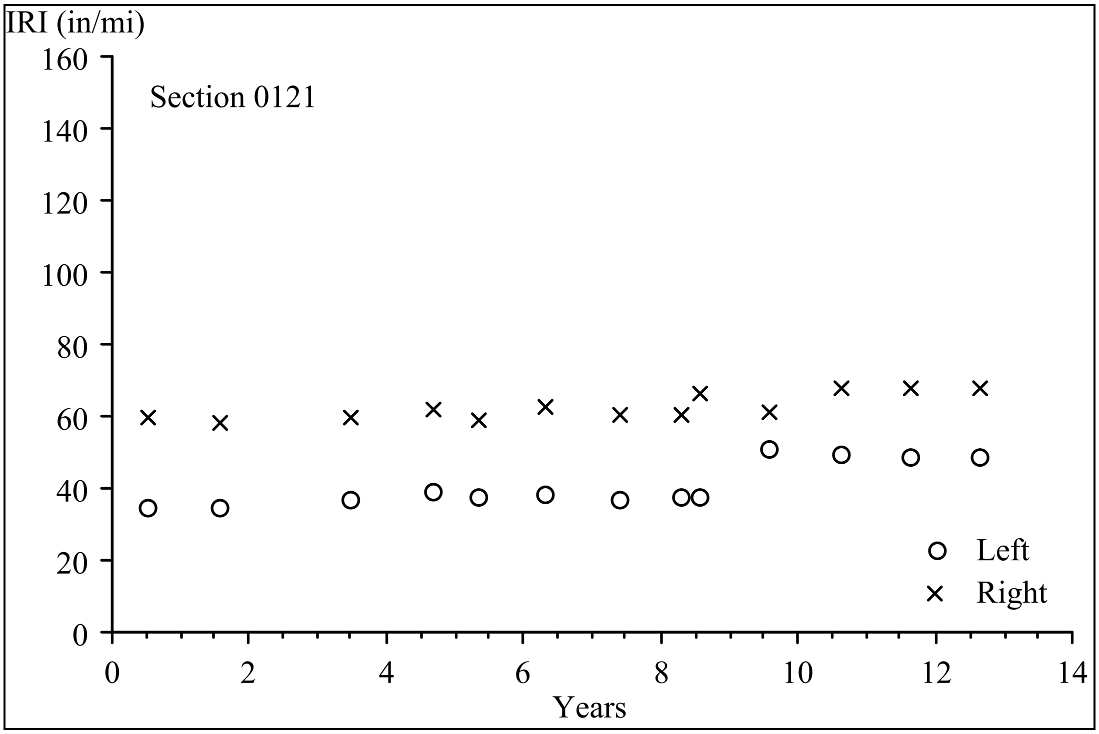

Figure 28. IRI progression, section 0121.

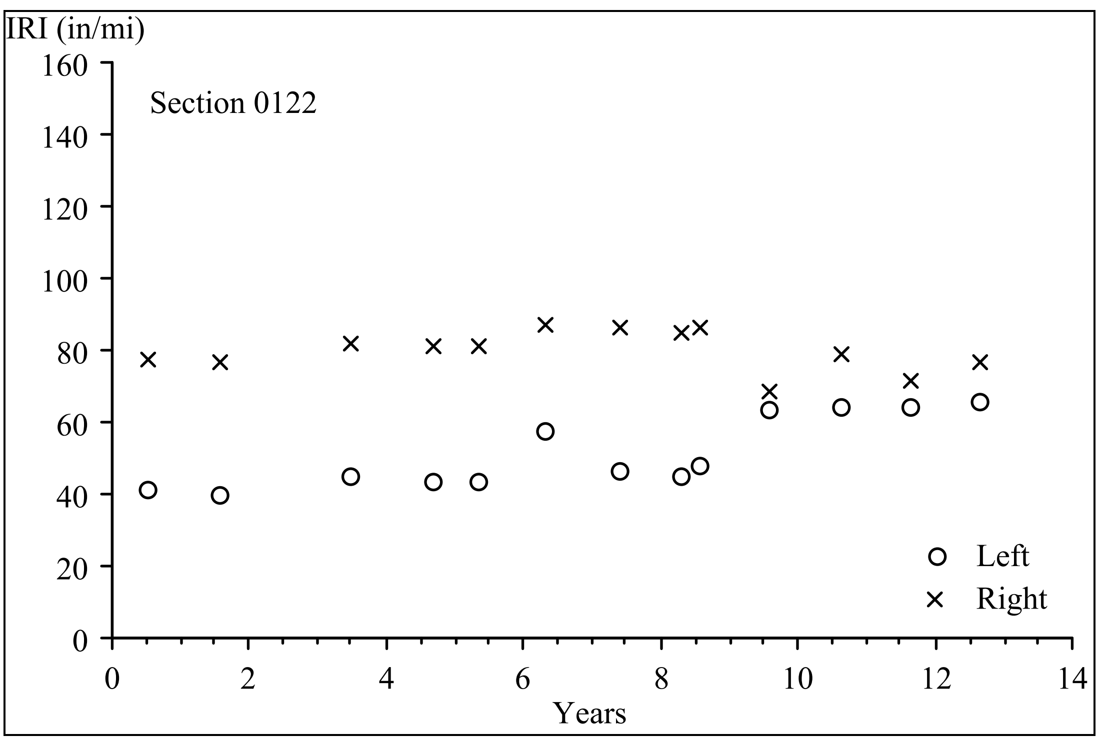

Figure 29. IRI progression, section 0122.

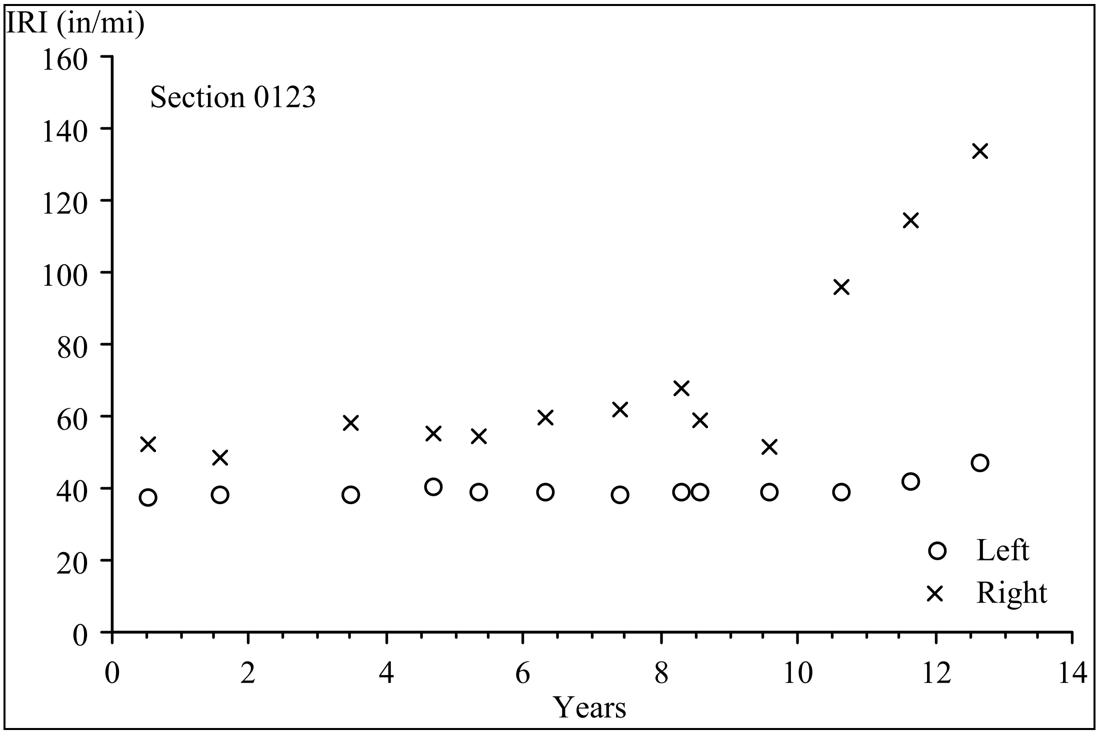

Figure 30. IRI progression, section 0123.

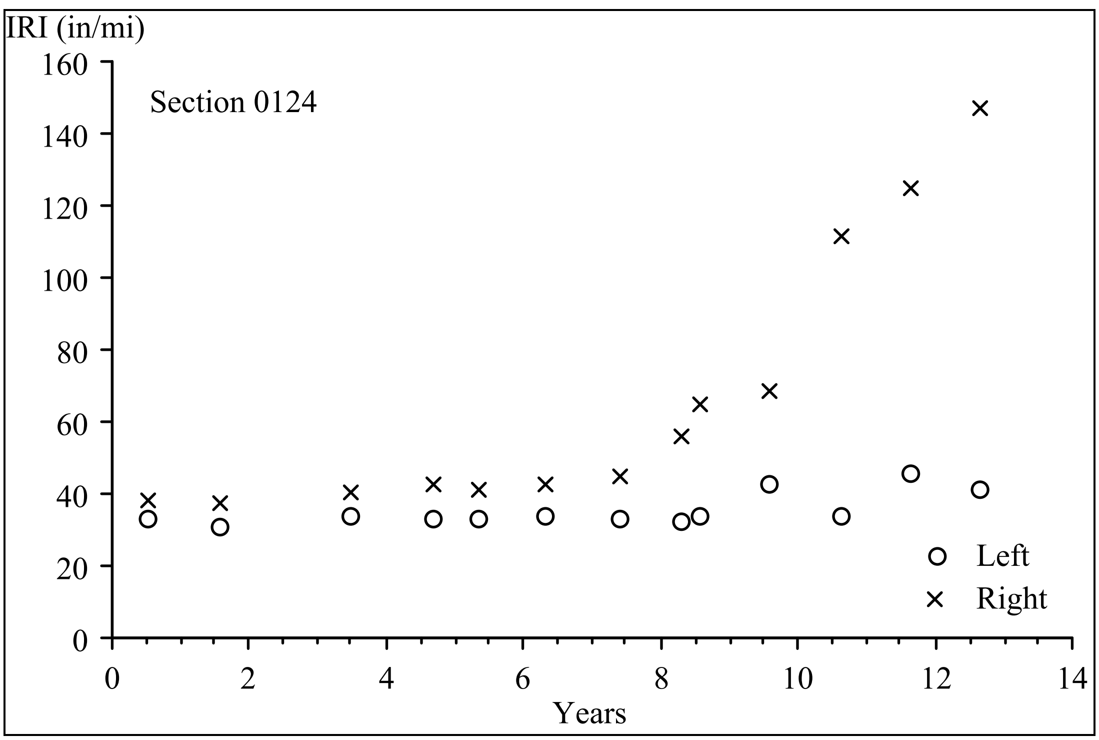

Figure 31. IRI progression, section 0124.

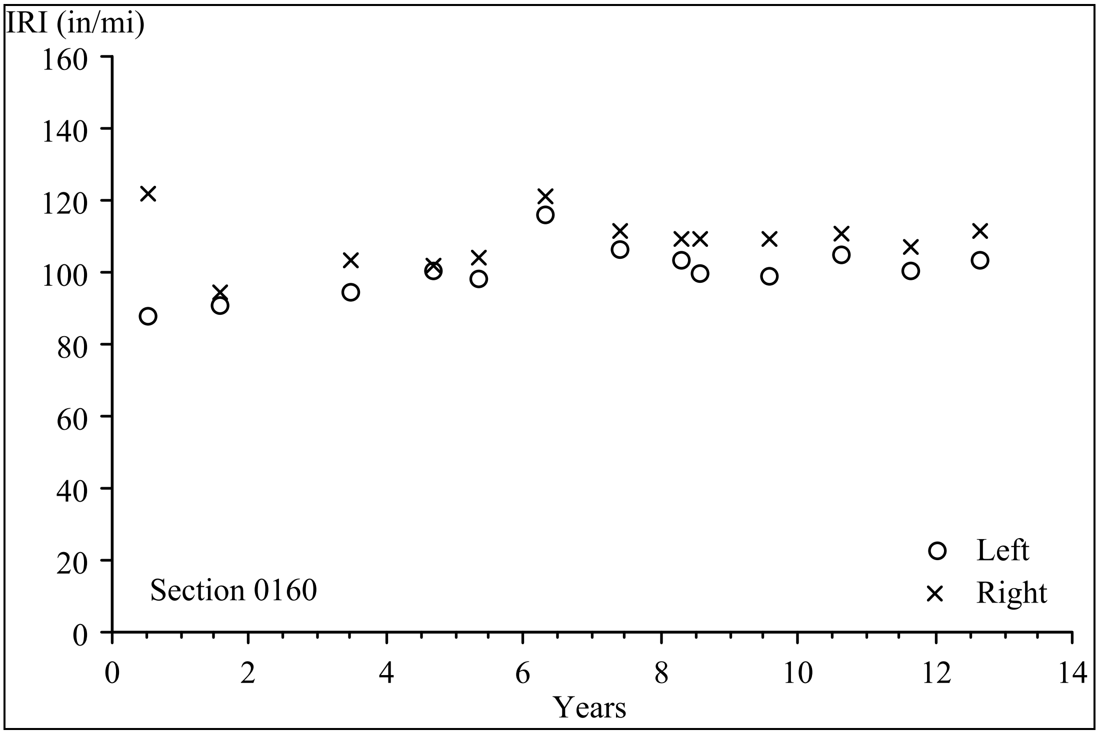

Figure 32. IRI progression, section 0160.

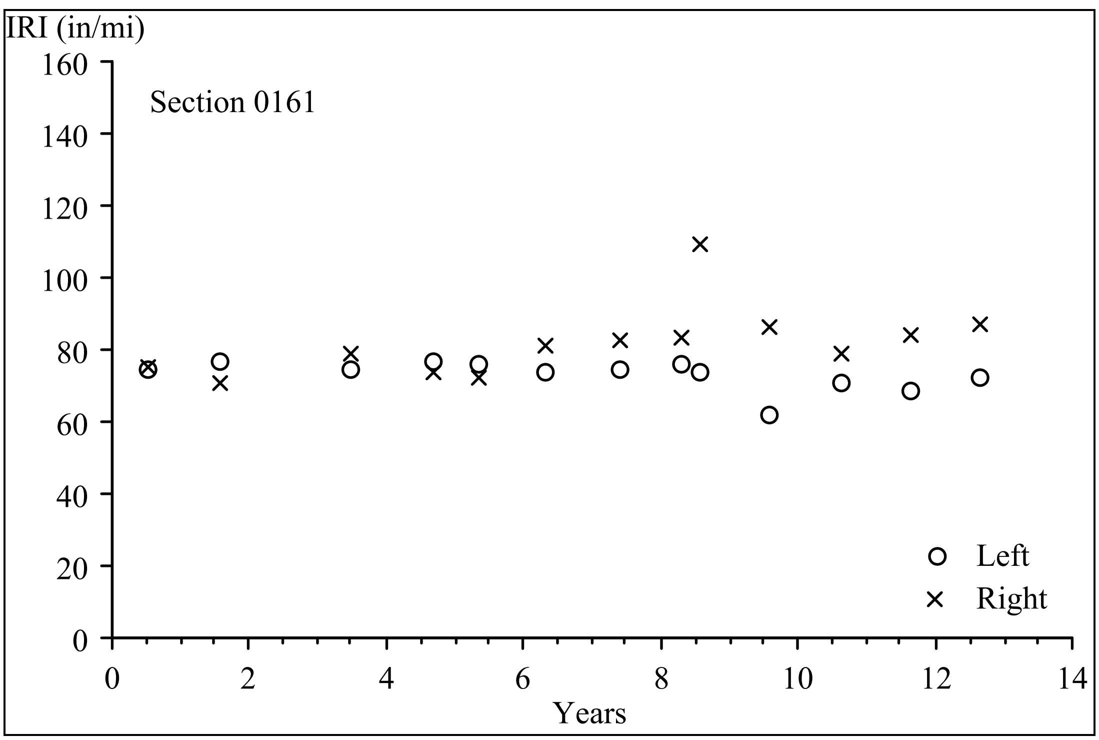

Figure 33. IRI progression, section 0161.

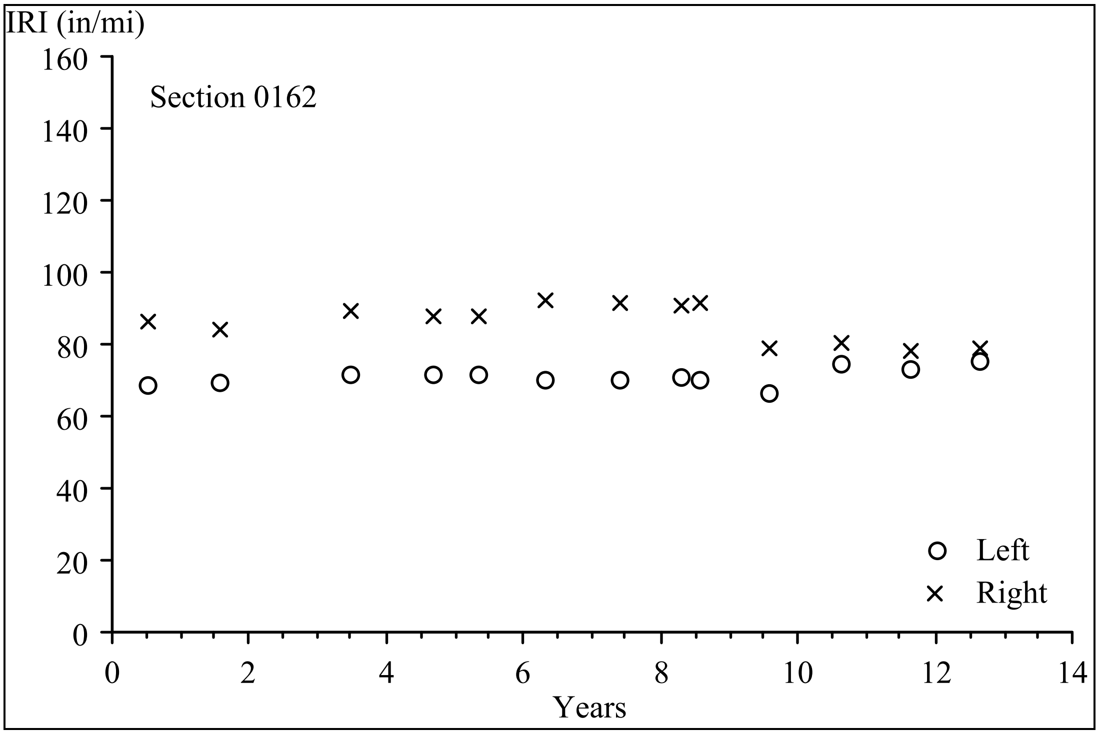

Figure 34. IRI progression, section 0162.

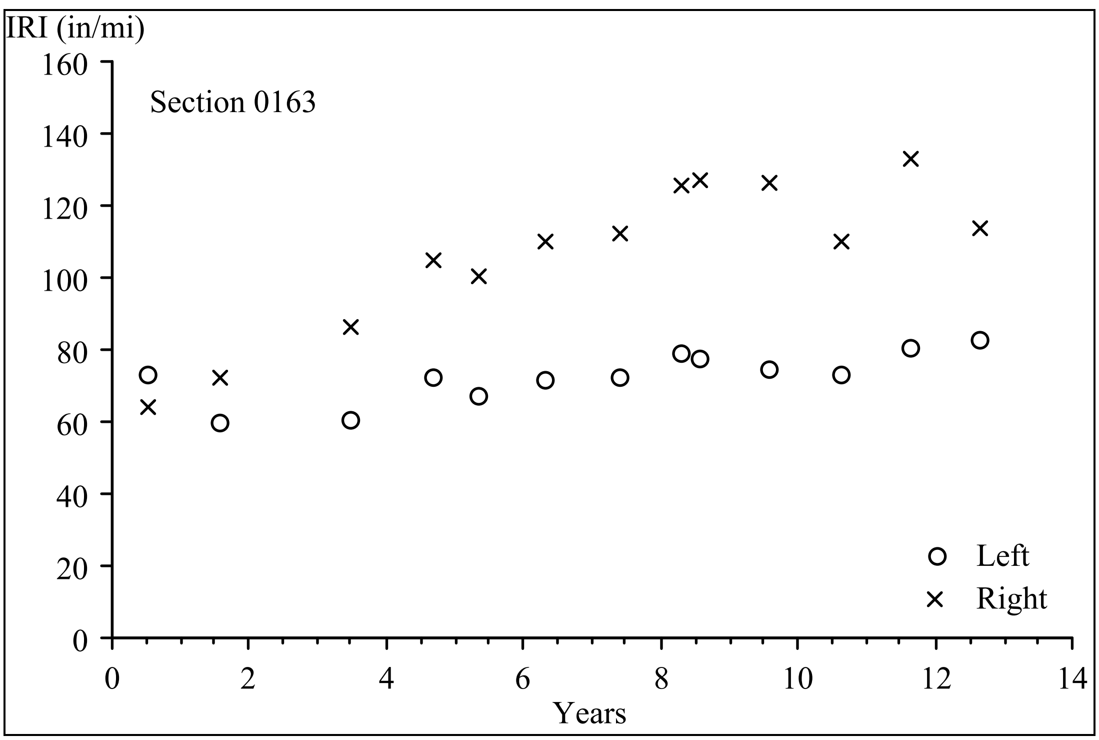

Figure 35. IRI progression, section 0163.

PROFILE ANALYSIS TOOLS

This section of the report describes analysis techniques that were used to study the profile characteristics of each pavement section and their change with time. These tools help study roughness, roughness distribution, and roughness progression of each section, including concentrated roughness that may be linked to pavement distress. The discussion of each analysis and plotting method is rather brief. However, some examples are provided, and all of the methods listed here are described in detail in other publications as referenced.[15]

Summary Roughness Values

Left IRI, right IRI, Mean Roughness Index (MRI), HRI, and RN values were calculated. Appendix A reports the average value of each index for each visit of each section. The discussion of roughness in this report emphasizes the left and right IRI. Nevertheless, comparing the progression of HRI and RN to that of the MRI provides additional information about the type of roughness that is changing. For example, a low HRI value relative to MRI indicates roughness that exists on only one side of the lane. Further, aggressive degradation of RN without a commensurate growth in MRI signifies that the developing roughness is biased toward short wavelength content.

Power Spectral Density Plots

A Power Spectral Density (PSD) plot of an elevation profile shows the distribution of its content within each waveband. An elevation profile PSD is displayed as mean square elevation versus wave number, which is the inverse of wavelength. A profile PSD plot is generated by performing a Fourier transform on a profile. The value of the PSD in each waveband is derived from the Fourier coefficients, and represents the contribution to the overall mean square of the profile in that band.

Often, the wavebands used in a PSD plot are given a uniform spacing on a log scale. In this research, PSD plots were typically displayed using 12 bands per octave. In other words, the center of each waveband was a factor of $2^{1/12}$ larger than the waveband to its left on the plot and a factor of $2^{1/12}$ smaller than the waveband to its right. This spacing provided enough detail to search for roughness that was isolated at a given wavelength, but enough averaging to eliminate spurious content that is common when PSD plots are displayed using a linear wave-number scale. PSD plots were also calculated from the slope profile, rather than the elevation profile. This aided in the interpretation of the plots, because the content of a slope PSD plot typically covers fewer orders of magnitude than an elevation PSD plot.

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15. M. W. Sayers and S. M. Karamihas, *Interpretation of Road Roughness Profile Data*, FHWA/RD-96/101 (Ann Arbor, MI: Univ. of Michigan Transportation Research Institute, 1996.)

The PSD plots provided a very useful breakdown of the content within a profile. In particular, the plots reveal: (1) cases in which significant roughness is concentrated within a given waveband, (2) the type of content that dominates the profile (e.g., long, medium, or short wavelength), (3) the effectiveness of maintenance in eliminating roughness over each waveband, (4) the type of roughness that increases with time, and (5) the type of roughness that is stable with time. Figure 36 shows the PSD plot of the right profile for section 0124 during visits 03 and 08.

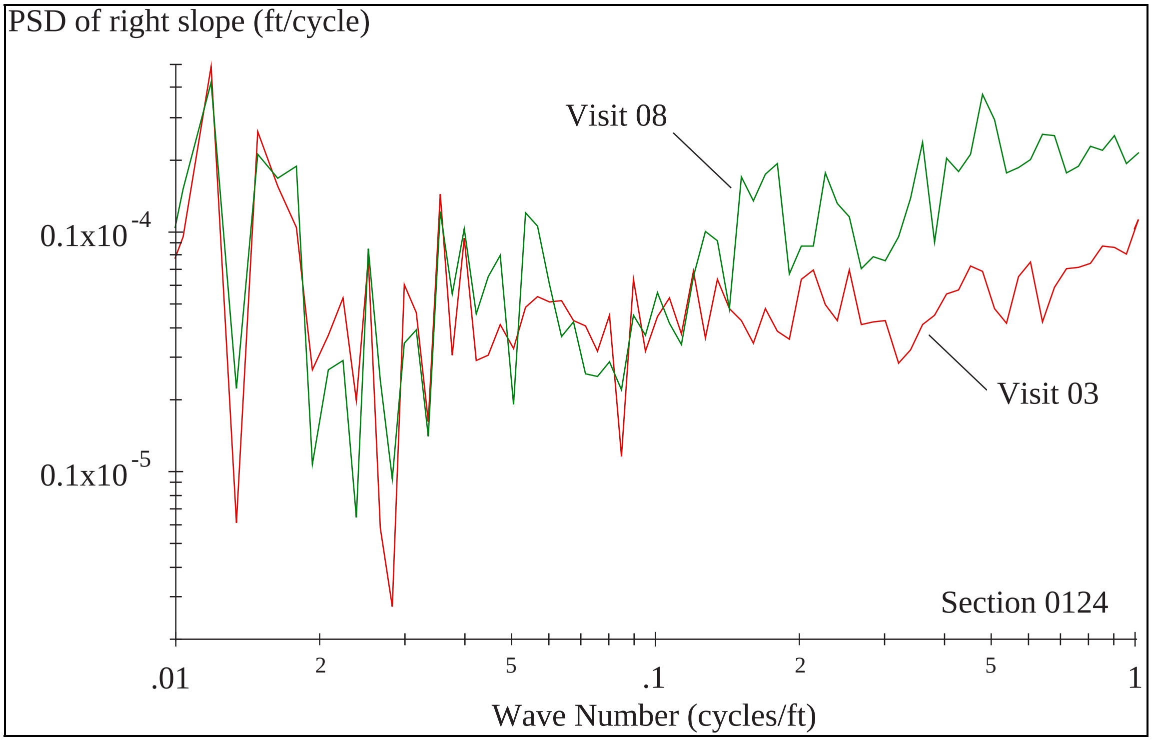

Figure 36. PSD plot of section 0124 profile, right side.

This plot includes several noteworthy features:

- The plot shows the PSD of slope, rather than elevation. Thus, the vertical axis has units of slope^2/(cycles/ft), as opposed to elevation^2/(cycles/ft).
- The plot covers a range of wave numbers from 0.01 cycles/ft to 1 cycles/ft. This is the range that affects IRI most.
- The spectral content within the profiles for wavelengths longer than 10 ft (i.e., wave numbers below 0.1 cycles/ft) did not change significantly with time between visit 03 and 08.

- The spectral content for wavelengths shorter than 10 ft increased between visits 03 and 08. In this case, the increase was caused by the presence of cracking in several areas of the section in visit 08. Several of the pavement sections behaved this way, and an increase in spectral content for shorter wavelengths often accompanied an increase in cracking.
- The spectral content of the profiles in both visits was biased toward longer wavelengths (i.e., lower wave numbers) in visit 03. Note that without the logarithmic vertical scaling, the long wavelength content would appear even more dominant. A skew in content toward longer wavelengths is a common property of smooth full-depth asphalt pavement.

Each of the final three observations listed above provide important information about the nature of the roughness on section 0124 and its progression. However, the PSD plot provides no information about where the roughness exists within a section. Further, if the roughness within a profile is concentrated in a single location, the PSD plot may provide misleading information. The filtered profile plots and the roughness profiles, discussed below, provide a more complete assessment of the roughness on a given pavement.

The PSD plot also provides insight into the filtering practices of the profiler that made the measurements. Figure 37 shows the PSD plot of the left profile for section 0117 during visits 09 and 10 over the maximum range allowed by the section length and sample interval. This plot includes several noteworthy features:

- The spectral content differs for very long wavelengths (low wave numbers). This is not caused by a change in the shape of the section. Rather, it is the result of a change in profiler, and an associated change in the high-pass filtering methods.[16]
- The spectral content shows a decreasing trend at very short wavelengths (high wave numbers). This is an artifact of the low-pass filtering applied at the time of the measurement, which is a combination of digital filtering and height sensor footprint.[17]
- The PSD plot for visit 09 includes a spike at a wave number of about 2.2 cycles/ft, and at double that value. This is also an artifact of the measurement process, but the source is not clear. The spikes were present in all of the measurements made by this profiler, which includes all of the measurements made in visits 03 through 09. However, the spikes did not occur at the same wave number in each visit, or in each repeat measurement within a given visit.

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16. R. W. Perera and S. D. Kohn, *Quantification of Smoothness Index Differences Related to Long-Term Pavement Performance Equipment Type*. FHWA-HRT-05-054. (McLean, VA: Federal Highway Administration, 2005).

17. Steve Karamihas, *Critical Profiler Accuracy Requirements.* UMTRI-2005-24. (Ann Arbor, MI: University of Michigan Transportation Research Institute, 2005).

The wave number where the left-most spike occurred ranged from about 1.62 cycles/ft to 2.80 cycles/ft. A similar effect was present in the profile used in visits 01 and 02, and the spikes occurred from about 0.40 cycles/ft to 0.42 cycles/ft.

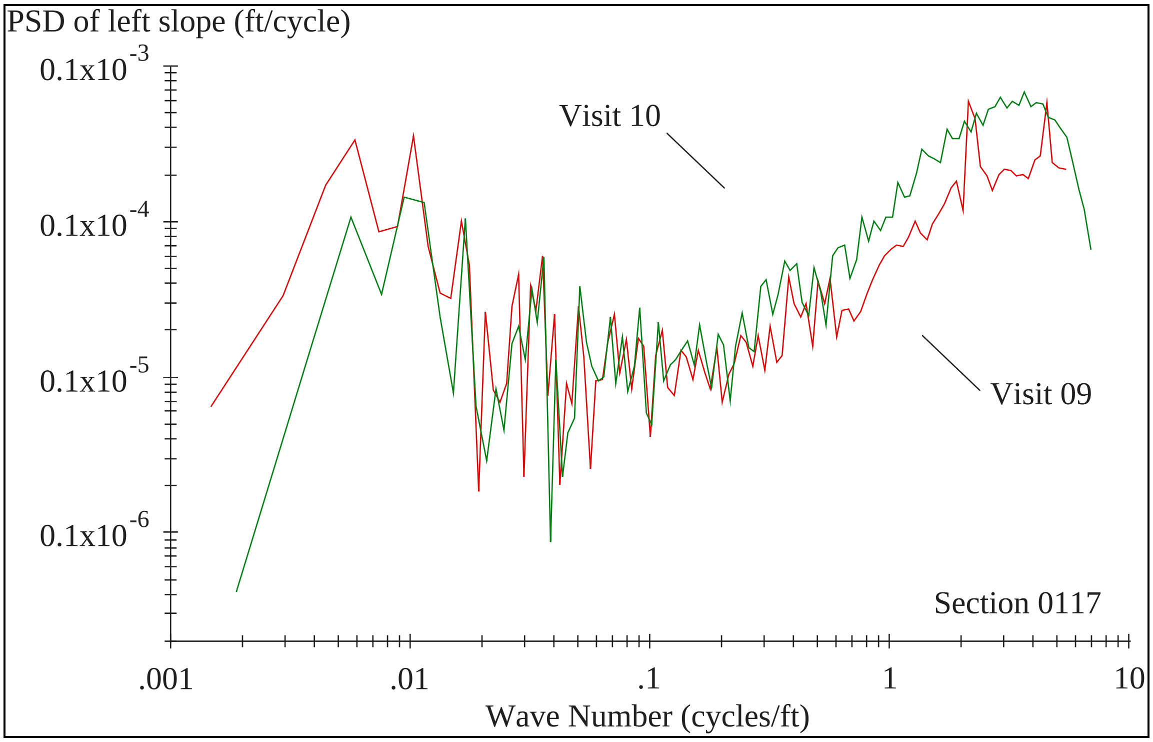

Figure 37. PSD plot of section 0117 profile, left side.

Filtered Profile Plots

A simple way to learn about the type of roughness that exists within a profile is to view the trace. However, certain key details of the profile are often not as obvious in a raw profile trace as they may be after the profile is filtered. For example, Figure 38 shows the left raw profile trace for three visits of section 0122. The plot shows that the long wavelength content, or the trend, in each plot is quite consistent with time. However, a narrow dip appears about 309 ft from the start of the section which is much more severe in visit 06 because the profile tracked directly over it.

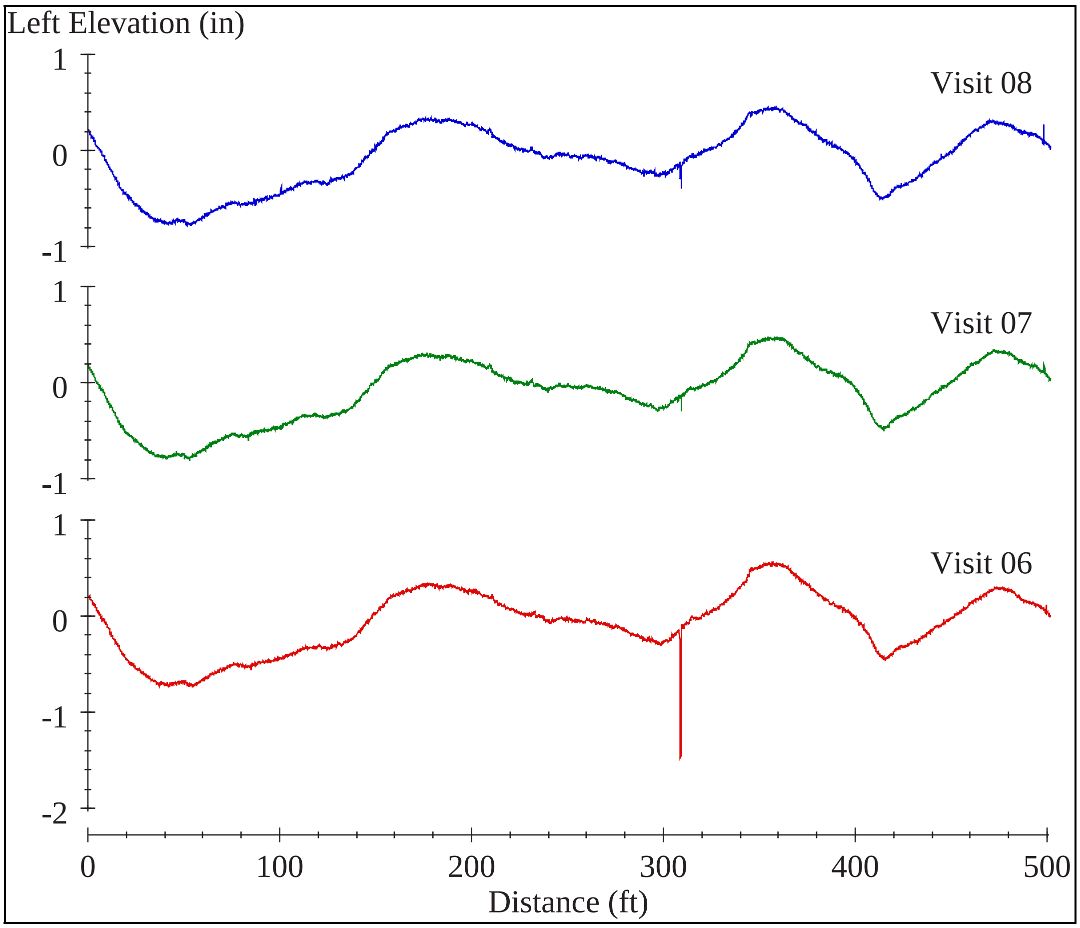

Figure 38. Raw profiles of section 0122.

Although the raw profile plots in Figure 20 provide very useful information about the nature of the roughness on section 0122, a filtered plot may provide a more detailed look at short-duration features of interest, such as the dip at 309 ft. Figure 39 shows a small segment of the profile after it has been high-pass filtered. In this case, a moving average (smoothing) filter with a base length of 20 ft was applied to the profile, and the result was subtracted from the raw profile. Without the filter, the large changes in elevation along the profile may have masked the dip in visits 07 and 08, such that they may have been ignored. When the profile is filtered, the dip and its shape are much easier to evaluate.

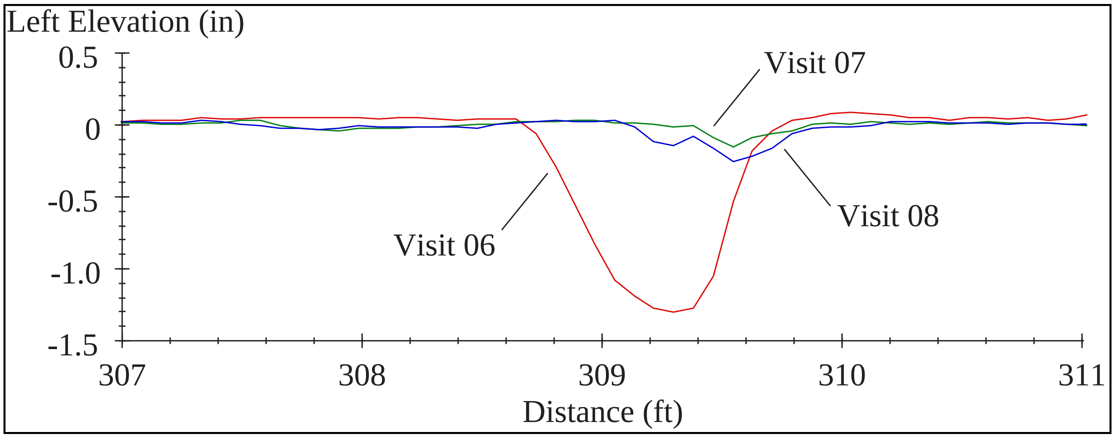

Figure 39. Filtered profile of section 0122.

Three types of filtered plots were inspected for every visit of every section:

Long Wavelength: This is a plot of profile smoothed with a baselength of 25 ft and anti-smoothed with a baselength of 125 ft.

Medium Wavelength: This is a plot of profile smoothed with a baselength of 5 ft and anti-smoothed with a baselength of 25 ft.

Short Wavelength: This is a plot of profile smoothed with a baselength of 1 ft and anti-smoothed with a baselength of 5 ft.

These filters were used to screen the profiles for changes with time and special features of interest. The terms “long”, “medium”, and “short” are relative, and in this case pertain to the relevant portions of the waveband that affects the IRI. The long wavelength portion of the profile was typically very stable with time. However, the long wavelength profile plots of every section changed somewhat between visit 09 and 10. This was not caused by a change in the surface characteristics of the section. Rather, it was caused by a change in profiler make and the associated change in filtering practices.

The medium wavelength plots provided a view of the features in a profile that were likely to have a strong effect on the IRI, and may change with time. The short wavelength elevation plots also typically progressed with time, but only affected the IRI through localized roughness or major changes in content with time. However, the short wavelength elevation plots helped identify and track the progression of narrow dips and other short-duration features that may have been linked to distress.

Most of the features of interest within the SPS-1 project were narrow bumps and dips. Thus, after their location was identified using the short wavelength plots, the progression in their size and shape was evaluated using an anti-smoothing filter with a base length of 20 ft, as shown in Figure 21.

Filtered profile plots also helped to characterize the effects of maintenance operations. For example, a slurry seal was applied to nine of the sections on the SPS-1 site in May 2002 (between visit 09 and 10). In most cases, this caused a complete change to the short wavelength profile plots and a significant change to the medium wavelength profile plots. Figure 40 shows an example of the change in the medium wavelength content on section 0122. Local peaks and troughs occur in roughly the same place before and after the slurry seal, but the shape and severity of bumps and dips are heavily altered. This, and the submerging of narrow dips at cracks under the seal, is the source of the change in roughness that occurred after the slurry seal.

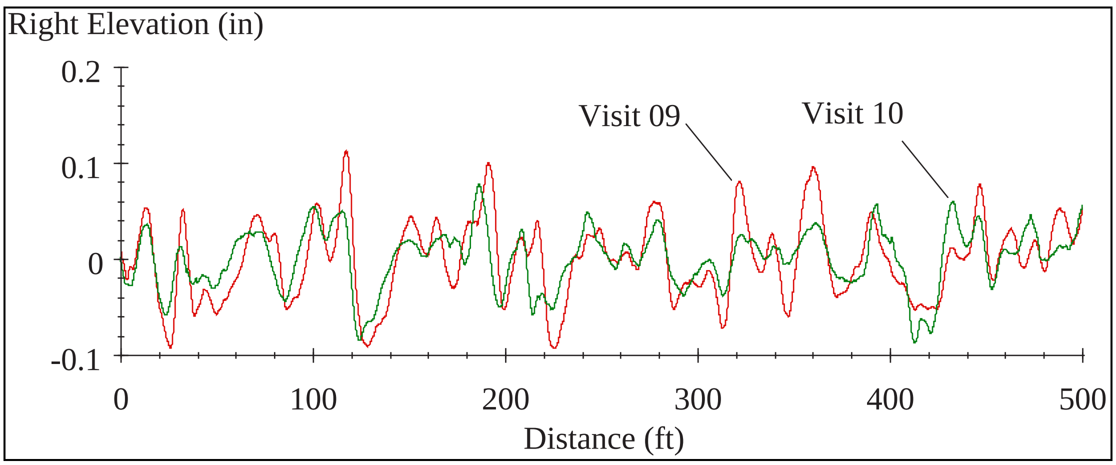

Figure 40. Medium wavelength profiles of section 0122.

Roughness Profile

A roughness profile provides a continuous report of road roughness using a given segment length.[18] Instead of summarizing the roughness by providing the IRI for an entire pavement section, the roughness profile shows the details of how IRI varies with distance along the section. It does this by displaying the IRI of every possible segment of given base length along the pavement, using a sliding window.

A roughness profile displays the spatial distribution of roughness within a profile. As such, it can be used to distinguish road sections with uniform roughness from sections

18. M. W. Sayers, "Profiles of Roughness," *Transportation Research Record* 1260 (1990): 106-111.

with roughness levels that change over their length. Further, the roughness profile can pinpoint locations with concentrated roughness and provide an estimate of the contribution of a given road disturbance to the overall IRI.

Figure 41 shows an example of a roughness profile for visit 08 of section 0160. The roughness profile was generated using a base length of 25 ft. That means that every point in the plot shows the IRI of a 25-ft long segment of road, starting 12.5 ft upstream and ending 12.5 ft downstream. The plot shows several areas of elevated roughness over the first 400 ft. The smoothest 100 ft segment appears from 400 ft to 500 ft from the start of the section, but it is no smoother than the areas between isolated rough spots over the first 400 ft. Note that isolated roughness is absent over the last 100 ft of the section because it was diamond-ground to smooth the section for an approach to a weigh-in-motion scale just downstream of the section.

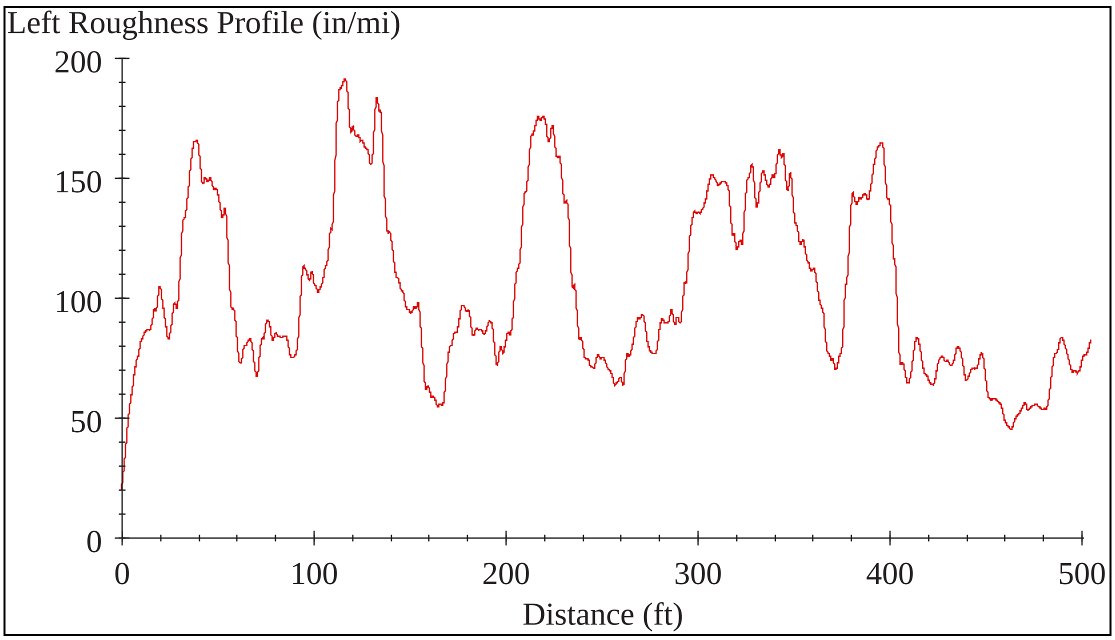

Figure 41. Roughness profile of section 0160, 25-ft base length.

Figure 42 shows how a roughness profile can help find and quantify isolated roughness. The figure shows the roughness profile of section 0122 using a 10 ft base length for visits 06, 07 and 08. With a 10 ft base length, isolated roughness is easy to identify. In visit 06, the peak roughness at the dip is about 755 in/mi. In the same location, the roughness is 88 in/mi. This is a difference of 667 in/mi over 10 ft. Since that value represents the roughness over just one fiftieth of the segment, it suggests that the single dip contributes about 13 in/mi to the overall IRI of the section. This is most of the difference between the IRI in visits 06 and 07.

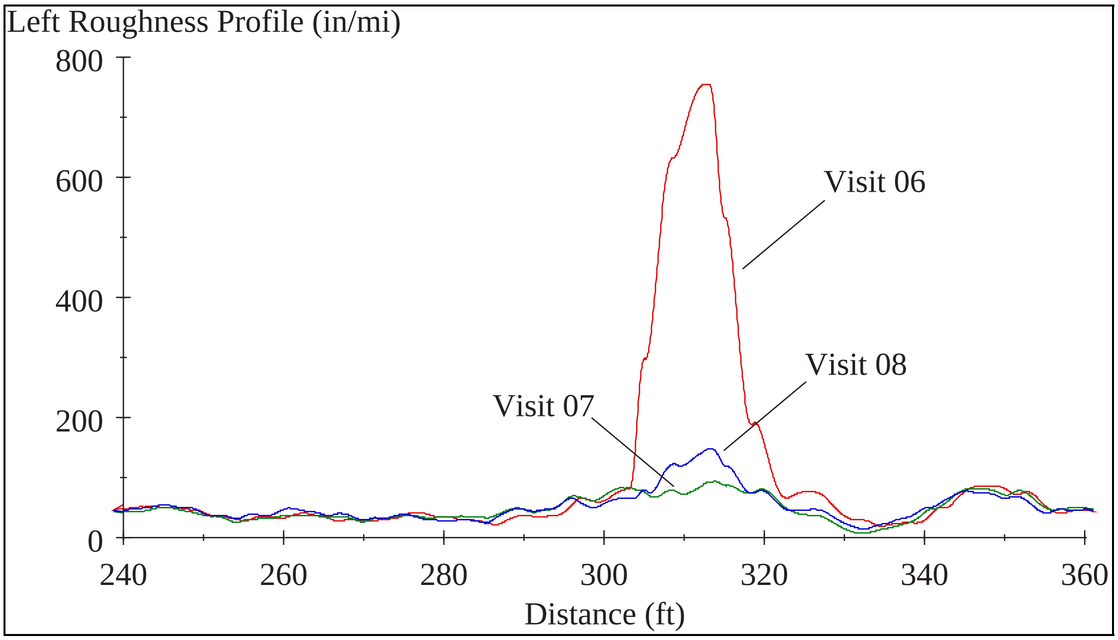

Figure 42. Roughness profile of section 0122, 10-ft base length.

Distress Surveys and Maintenance Records

Once the analysis and plotting described above were completed, all of the observations were compared to the manual distress surveys performed on each section. Manual distress surveys were available for each section starting in 1994, and covering a visit nearly every year for the rest of the monitoring history. These were performed using LTPP protocols by technicians certified to perform distress surveys. The surveys provided a means of relating profile features to known distresses.

For this SPS-1 project, two observations were common. First, narrow dips did not always increase in severity with time over portions of the wheel path with longitudinal cracking. The “hit or miss” nature of profiling a narrow track over longitudinal cracks often meant that the roughness was not measured consistently among consecutive visits. Many of the dips were much wider than the crack itself, which indicated sunken pavement near the cracks. Second, narrow bumps appeared over sealed longitudinal cracks that added to roughness. In a few cases, roughness was also found at transverse cracks.

Observations of changes in profile properties were also compared to maintenance records. In particular, sealing of cracks affected the presence and shape of narrow dips on some sections, and the application of a slurry seal affected the short and medium content within the profiles as described above, as well as the overall roughness.

DETAILED OBSERVATIONS

Appendix B reports key observations from the roughness index progression, PSD plots, filtered profile plots, roughness profiles, and distress surveys. In many cases, similar results were noted for multiple sections. Those observations are repeated under the heading of every section where it is appropriate. However, changes in profile properties with time that were caused by changes in profiler make or model are not discussed in Appendix B.

SUMMARY

This section provides a summary of important observations from each section within the Arizona SPS-1 site. Several observations within this report were common to more than one pavement section, as described below. This section of the report, in conjunction with the roughness progression plots (Figures 20 through 35), provides the essential information about each pavement section.

A slurry seal coat was applied to sections 0113, 0114, 0116, 0118, 0120, 0121, 0122, 0161 and 0162 in May 2002. The seal coat modified the short wavelength content of the profiles significantly on all of these sections. Often, the net result was temporary smoothing of narrow dips that appeared at transverse and longitudinal cracks. On many of the sections, the medium wavelength content of the profiles was also altered. This usually meant that high and low points within the medium wavelength profile plots occurred in roughly the same places, but with altered shape and severity.

On most of the sections where a seal coat was placed, the IRI changed significantly. Usually, the left side profiles were very smooth before the seal coat and became slightly rougher afterward. However, in many cases the right side profiles became smoother after the seal coat. This is because the right side profiles often included a higher level of narrow dips caused by cracking that was submerged after the seal coat was placed.

Placement of the seal coat also improved the relationship between the right and left profiles by eliminating narrow dips and uncorrelated short wavelength content. This is demonstrated by the fact that the difference between the HRI and MRI always diminished after the seal coat was placed. On average, the percentage difference between HRI and MRI went down by 6.6 percent after the seal coat was placed.

On sections 0113, 0118, 0122 and 0162 a bump appeared in the location where the seal coat operation had stopped and restarted. This usually was rough enough to register as localized roughness in the left side of the lane.

A seam existed at a longitudinal construction joint along the right side of the lane over the entire project. Longitudinal cracking developed there on many of the test sections. However, with the exception of section 0119, the cracking usually did not contribute aggressively to the roughness until after the application of sealant in either May 2001 or April 2002. Sections 0115, 0117, 0118, 0119, 0123 and 0124 were affected most by the sealed longitudinal cracks. (Note that most of these sections did not receive a slurry seal coat.)

The additional roughness caused by sealed longitudinal cracks usually appeared as narrow bumps and dips that were not consistent in size, shape, or location between repeat measurements. The “hit or miss” nature of the roughness was caused by slight changes in lateral positioning of the profiler in each measurement, and some lateral wandering of the cracks themselves. In most cases, the bumps and dips caused the roughness of the right side profiles to increase aggressively during the last three profiling visits. In section 0117 and 0124, raveling also contributed to roughness in the right side of the lane. An important feature of the increase in roughness with these causes is that it overestimates the probable degradation in ride quality felt by the user, since much of the influence of raveling and longitudinal cracking is masked by vehicle tires.

Many other profile features were found that affected the roughness of these test sections, such as transverse cracking (sections 0113, 0121, 0161 and 0163), potholes (0163), and rough patching (0116). The end of this report describes the most noteworthy features of each test section that affected the roughness or the roughness progression.

The change in profiler make in late 2002 affected the long wavelength content of the profiles on every test section. This is because the newer profiler used a high-pass filter that eliminated a little more of the profile content than the previous device. This probably had no effect on the measurement of localized roughness or the study of narrow bumps and dips caused by distresses. However, it did confound the study of the true effect caused by the slurry seal coat, since the device change and application of the seal coat both occurred between visits 09 and 10.

One other minor device effect within the profiles was peaks in the PSD plots with no pavement-related explanation. In visits 01 and 02 (measured by the K.J. Law DNC 690) most PSD plots from the left side included a strong peak at a wavelength of 2.5 ft. In visits 03 through 09 (K.J. Law T-6600) all profiles from the left and right side included a peak in their spectral content at a wavelength somewhere between 0.35 and 0.7 ft and another at a wavelength of double the first.

The rest of this report provides a summary of the most important observations made about each test section. The summaries are extracted from Appendix B, which provides detailed notes about each section. To help provide context for the summary statements below, Figure 43 shows the range of left and right IRI for each section. Note that the highest IRI value for some of the sections did not occur in the final visit. (See Appendix A or Figures 20 through 35.)

Section 0113: A bump appeared 157 ft from the start of the section on the left side throughout the profile monitoring history, but it did not correspond to any observed distress. After the application of a slurry seal in May 2002, the bump was much longer. A severe bump appeared on the left side at a seam between slurry seal applications 175 ft from the start of the section. This was detected in all visits after May 2002. The right side of section 0113 was significantly rougher between November 2001 and March 2002 than it was over the rest of the profile monitoring history. The most significant contributors to this were two sunken areas of pavement between 350 ft and 400 ft from the start of the section that had several narrow dips among them. Photographs of the surface show slightly sunken pavement and alligator cracking in these areas. Secondary contributions came from several narrow dips at transverse cracks. All of these features were much less rough after the application of a slurry seal coat.

Section 0114: The left side of this section was extremely smooth until the application of a slurry seal coat in May 2002. Afterward, the roughness had increased in the wavelength range from 2 to 10 ft, but the overall roughness was still low. The right side of the section included some localized roughness at a narrow dip 456 ft from the start of the section that was about 1 ft wide and up to 0.6 in deep. This appeared in only two of the visits before the slurry seal coat was applied. Afterward, only a minor disturbance was found there. All distress surveys after 1996 show significant cracking there.

Sections 0113 and 0114: The profiles from visit S16 underestimated longitudinal distance by about 1 percent.

Section 0115: This section was very smooth on the left side throughout the entire monitoring period and was smooth on the right side through the first 10 visits. The roughness increased very aggressively on the right side over the last three visits because of longitudinal cracking. By the final visit the average IRI was 225 in/mi. However, the profile measurements of the right side were not very consistent with each other in the last three visits. This was because the profiler used height sensors with a narrow footprint and wandered above the cracks.

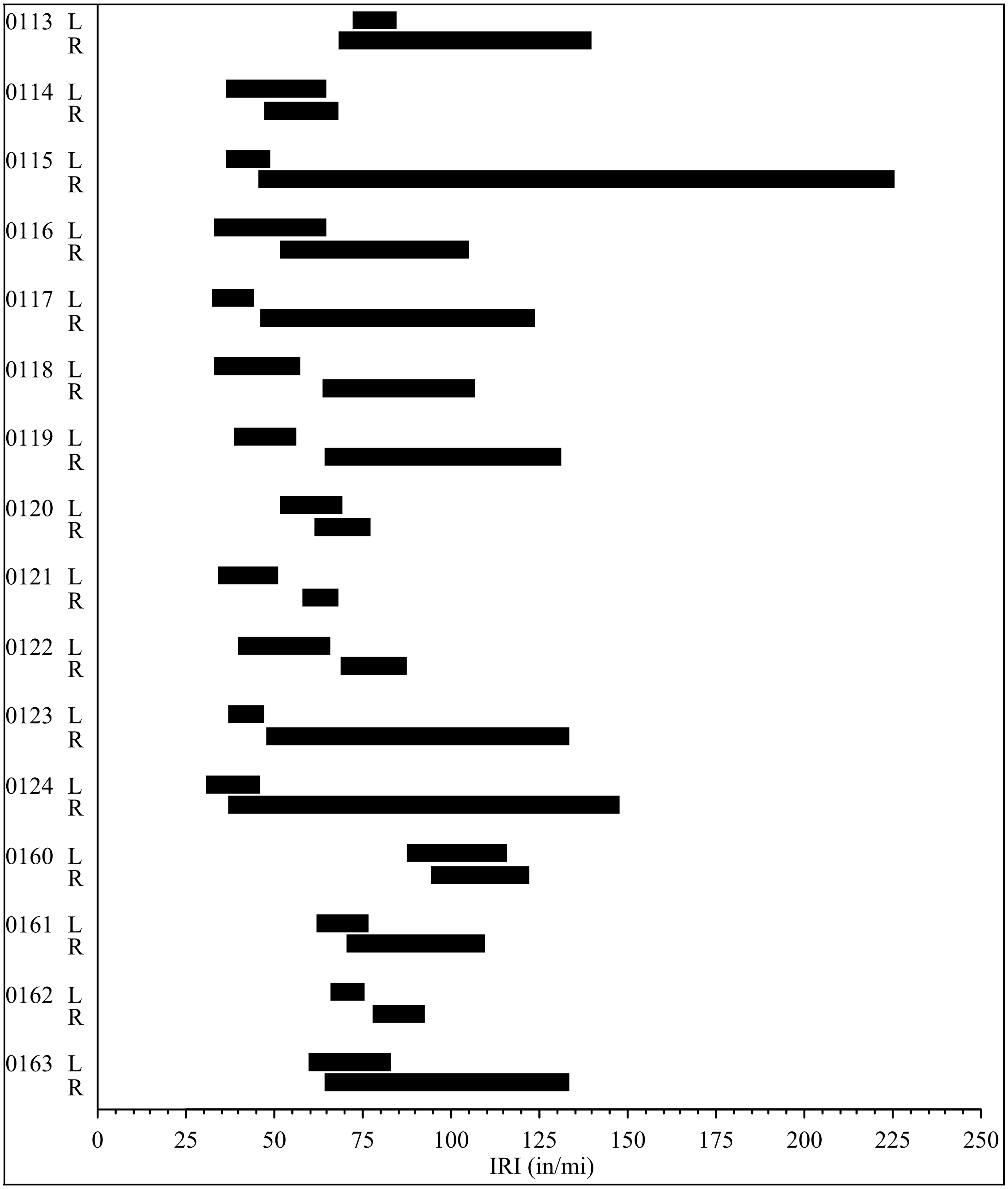

Figure 43. Summary of IRI ranges.

Section 0116: This section remained smooth over the entire monitoring period, with the exception of three small areas. In all three cases, deep dips appeared in the profiles that added significant roughness to the section. In August 2001 patches were placed over all three dips, but the patches were often at least as rough as the dips they replaced. One patch on the right side of the lane from 150 to 170 ft from the start of the section was so rough that it temporarily added more than 25 in/mi to the roughness of the entire section.

Section 0117: The roughness of this section was affected most by longitudinal cracking and raveling along the right side of the lane, which usually appeared as poorly correlated areas of narrow dips. Crack sealing in both May 2001 and April 2002 actually increased the roughness by introducing narrow bumps to the profile. In the visits after crack sealing, the right side profiles included long areas of high short-wavelength roughness that was not always well repeated between measurements. This content was most prevalent in the last third of the section.

Section 0118: The right side profiles from this section included significant roughness caused by erratic measurement of longitudinal cracking in two visits just after crack sealing was performed in May 2001. The left side profiles included two areas of localized roughness after the placement of the slurry seal. One of them is a bump in the location where the seal coat operation had stopped and restarted.

Section 0119: The left side profiles remained smooth overall during the monitoring period, although the effect of longitudinal cracking began to appear in the later visits. The right side of the lane included significant longitudinal cracking that eventually extended along the entire section. The right side profiles were often poorly repeated and grew in roughness erratically because of "hit or miss" detection of dips along the cracks. The profile measurements taken after the crack sealing was performed in April 2002 were even rougher and included dense areas of both bumps and dips that were not well repeated.

Section 0120: The profiles of this section were not affected directly by distress. However, they did include two areas of localized roughness. The first was caused by a dip nearly 0.5 in deep extended from 10 ft ahead of the start of the section to 40 ft after the start of the section on both sides of the lane. The second was caused by a slope break on the left side about 380 ft from the start of the section.

Section 0121: This section included several narrow bumps in the left and right side profiles starting in March 2003 that corresponded to locations where transverse cracks were recorded. Before the application of a slurry seal in May 2002, the right side profiles included a bump about 0.25 in high from 330 to 350 ft from the start of the section that added about 3 in/mi to its roughness.

Section 0122: A deep, narrow dip was detected in the left side profiles in some visits (06, 08, and 09) at a pothole. In visit 06, it added up to 14 in/mi to the overall roughness of the section. It was patched in February 2001, and no localized roughness appeared there afterward. A bump appeared in the profiles 175 ft from the start of the section where the slurry seal operation was stopped then restarted in May 2002. The bump was severe enough to cause a peak in the roughness profile of 180 in/mi on the left side.

Section 0123: This section remained very smooth on the left side. On the right side, an erratic trend in roughness was caused throughout the earlier visits by inconsistent measurement of a long dip about 320 ft from the start of the section. Erratic profile measurement and aggressive development of roughness on the right side was caused in the later visits by sealed longitudinal cracking that extended over most of the section. The effect was much more pronounced after crack sealing.

Section 0124: This section remained very smooth on the left side, although the roughness in the last 50 ft of the section increased in the later visits due to raveling. On the right side, erratic profile measurement and aggressive development of roughness on the right side was caused in the later visits by sealed longitudinal cracking that extended over most of the section. The effect seemed to be exacerbated by crack sealing.

Section 0160: A significant portion of the roughness was caused by slab curl, which was significantly more severe in November 1999 than in other visits. The last 100 ft of the section were much smoother than the rest because they were diamond ground.

Section 0161: Placement of a slurry seal between visits 09 and 10 smoothed the short and medium wavelength content of the profiles somewhat over most of the section. The smoothing was most significant on the left side profile from 90 to 150 ft from the start of the section. On the right side, a patch was placed 485 ft from the start of the section in August 2001 (after visit 08). This caused an abrupt downward step at this location which contributed 15-18 in/mi to the overall roughness of the section in the later visits. Deep (0.1 to 0.4 in) narrow dips appeared at the locations of six transverse cracks on the left side in the later visits, and were most severe in the last profiling visit.

Section 0162: The profiles of this section did not contain any localized roughness and did not change much over the first nine visits. PSD plots of the left side profiles show significant content in the profiles isolated between wavelengths of 26 and 29 ft. The application of a slurry seal coat reduced the roughness significantly on both sides of the lane between visit 09 and 10. A bump 0.4 inches high appeared in the last 10 ft of the section on both sides in the last four profiling visits. Photographs of the section show that this was a seam at the end of the seal coat. The roughness there adds 5 to 11 in/mi to the overall IRI of the section.

Section 0163: This section included a long dip over the last 100 ft. The section was roughest over the last 50 ft, and the roughness there grew the most aggressively with time. This occurred because of several cracks that caused narrow dips in the profile on both sides. The most severe narrow dips appeared in the left side profiles 450 and 475 ft from the start of the section. These correspond to locations where a distress survey in May 2001 observed small potholes. Several other narrow dips were observed in the profile in the locations of transverse cracks. Together, these dips did increase roughness with time after visit 03, particularly on the right side.

CONCLUSIONS AND RECOMMENDATIONS

As part of the Long Term Pavement Performance (LTPP) Program, ADOT constructed 16 SPS-1 test sections on U.S. Route 93 near Kingman. The SPS-1 study was designed to study a variety of structural sections in new asphalt concrete construction. There were two sets of test sections on this project: 12 core sections to match similar projects constructed by other highway agencies and four supplemental sections to investigate alternative design characteristics as selected by ADOT. Construction of all 16 sections was completed in the summer of 1993, and the 15 AC sections were placed out-of-study in the spring of 2006, right before they received a mill-and-overlay.

ADOT initiated this project to study the relative performance of the various SPS-1 design alternatives (including supplemental sections), which will provide a foundation for future design decisions. Surface distress, deflection, and profile data were used as the basis for performance evaluation and were each analyzed as part of the study

The SPS-1 project offers a unique opportunity to directly compare performance of various pavement structures while reducing the confounding effect of other variables such as traffic loading, climate, and subgrade conditions. However, the findings drawn from this evaluation must be considered carefully. The experimental design did not offer replicate treatments to verify findings. Conclusions drawn from this comparison are based on one set of *in situ* conditions; observations from other climate or loading scenarios may differ from those noted within this report. Additionally, the paving seam issues encountered at the project significantly impacted performance and its contribution could not be fully isolated in the analysis. Therefore, findings reported may be unique to the conditions and construction of this site.

Even with these issues, the data captured at the project provides valuable insight into pavement performance, design, management, and construction. Following is a summary of lessons learned from the performance data collected at the SPS-1 sites:

- A longitudinal construction joint located in the outer wheel path became a longitudinal crack and eventually a heavily fatigued area throughout the site. The importance of keeping longitudinal joints out of the areas of heaviest loading cannot be overstated.

- Roughness and roughness progression alone cannot be used to represent the condition of a test section. Several test sections did not exhibit changes in roughness in proportion to the amount of fatigue cracking, and sections that had clearly reached the end of their service lives did not necessarily have roughness values that would trigger a rehabilitation event.

- Nine of the sections received a slurry seal coat in 2002, which significantly altered the profile features. This masked the raveling that started in 1999, but did not otherwise provide a significant reduction in environmental cracking. The sections not receiving the slurry seal had a very poor surface condition at the end of their service lives.

- Structurally related distresses were generally influenced by the longitudinal construction joint. The report developed during construction predicted the likelihood of distress propagation from this seam. Figure 1 summarizes distresses for each section. Please note that the structural index is comprised of load-related distresses (i.e., fatigue cracking) while the environmental index includes distresses associated with environmental factors (i.e., transverse cracking).

- Almost every section (except 0162 and 0163) showed significant growth in structurally related distresses by 9 to 10 years after construction, with the rate of growth then slowing until the sections were placed out-of-study.

- Section 0162 had the lowest quantity of structural distresses of any conventionally constructed section. Considering this was the only section where the paving was directly on top of the subgrade, it is possible that in some cases the construction of bound or unbound base layers does not always result in improved performance. Another possible reason for the improved performance is better construction quality as compared to the other test sections.

- There was no strong correlation between the structural thicknesses and the resistance to structural cracking, almost certainly because most fatigue cracking was associated with top-down cracking starting at the longitudinal construction joint.

- All sections, save 0163, had reasonable patterns of environmental distress growth, with a clear increase in magnitude approximately 10 years after construction.

- The roller-compacted concrete section (0163) had almost 100 percent block cracking within five years of construction and also had significant water bleeding and pumping issues. This is likely reflection cracking from the RCC layer.

- The best resistance to environmental cracking was in those sections where a bituminous-treated base was on either a permeable bituminous-treated base or a dense-graded aggregate base (0117, 0118, 0122, 0123 and 0124).

- All sections performed well with regard to rut resistance. Rutting would not have triggered rehabilitation for any section.

- Both the base and subgrade moduli decreased over time. For the base, this is likely due to traffic loading; it is less certain why the subgrade moduli would decline, although current conventional wisdom postulates it is related to a leveling off of subgrade moisture content at a level higher than observed during construction.

- While there was a reduction in structural capacity over time, no correlation was observed between the initial structural capacity and the decrease of structural capacity over time.

- Using data from all of the test sections, it was possible to develop an equation for asphalt concrete modulus as a function of temperature.

- With no replicate sections, there is limited ability to assess potential variability independent of actual performance.

- Four sections (0116, 0122, 0161, and 0163) received patching at some point.

Based on these findings, the following recommendations are provided by the research team for consideration by ADOT:

- Performance of AC placed directly on subgrade should be studied further to verify the findings from this study and to determine what conditions (i.e., subgrade type and moisture content, environment, and loading) are required to achieve good performance from a full-depth AC section. This could also be the basis for studying perpetual or long-life AC pavements.

- Specifications and plans should prevent pavement seams from being constructed in the wheel paths.

- Specifications should be modified to include density testing near pavement seams (regardless of their transverse location in the roadway).

- The timing of maintenance treatments such as slurry seals should be studied further to determine the optimum timing to slow environmental deterioration of the pavement.

- Most of the pavement test sections appeared to have experienced top-down cracking; however, this could not be confirmed. It is recommended that forensic analysis be performed at other locations throughout Arizona to learn about the factors contributing to top-down cracking.

Appendix A: Roughness Values

This appendix lists the left International Roughness Index (IRI), right IRI, Mean Roughness Index (MRI), Half-car Roughness Index (HRI), and Ride Number (RN) values for each visit of each section. The roughness values are the average for 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. Values of standard deviation are also provided for left and right IRI to reveal cases of high variability among the five measurements. However, the screening procedure used to select 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. MRI is simply the average of the left and right IRI value. HRI is calculated by converting the IRI filter into a half-car model.[19] This is done by collapsing the left and right profile 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 value provides a crude indication of the significance of roll (i.e., side-by-side variation in profile) to the overall roughness. When HRI is low compared to MRI, roll is significant. This is common among asphalt pavements.[20] Certain types of pavement distress, such as longitudinal cracking, may also cause significant differences between HRI and MRI.

Figure A-1 compares the HRI to MRI for all of the profile measurements that are covered in this appendix. This includes 1,190 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 0.849. This is typical for asphalt pavement.

RN has shown a closer relationship to road user opinion than the other indexes.[21] As such, it may help distinguish the segments from each other by ride quality. Further, the effect on RN may help quantify the impact of that distress on ride when a particular type of distress dominates the roughness of a section. In particular, a very low RN value coupled with moderate IRI values indicates a high level of short wavelength roughness,

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19. M. W. Sayers, "Two Quarter-Car Models for Defining Road Roughness: IRI and HRI," *Transportation Research Record* 1215 (1989): 165-172.

20. Steve Karamihas, T. D. Gillespie, and S.M. Riley, "Axle Tramp Contribution to the Dynamic Wheel Loads of a Heavy Truck," in *Proceedings of the 4th International Symposium on Heavy Vehicle Weights and Dimensions*, dd. C. B. Winkler, 425-434 (Ann Arbor, Michigan, 1995)..

21. M. W. Sayers and S. M. Karamihas, "Estimation of Rideability by Analyzing Road Profile," *Transportation Research Record* 1536 (1996): 110-116.

and potential sensitivity to narrow dips and measurement errors caused by coarse surface texture.

Table 28 provides the roughness values. The tables also list the date of each measurement and the time in years since the site was opened to traffic.

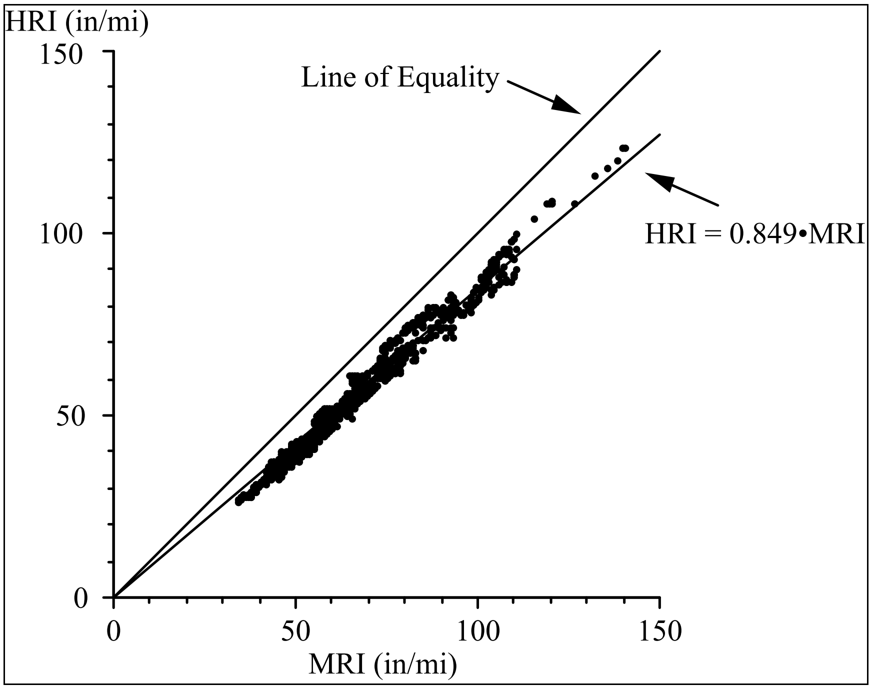

Figure 44. Comparison of HRI to MRI.

Table 28. Roughness Values.

Section	Date	Years	Left IRI (in/mi)		Right IRI (in/mi)		MRI (in/mi)	HRI (in/mi)	RN
			Ave	St Dev	Ave	St Dev			
0113	27-Jan-94	0.49	78	0.8	72	1.5	75	61	3.71
0113	27-Feb-95	1.57	79	0.7	69	0.4	74	61	3.77
0113	23-Jan-97	3.48	75	0.9	75	0.3	75	61	3.68
0113	08-Apr-98	4.68	76	1.9	80	1.8	78	63	3.52
0113	08-Jul-98	4.93	73	0.8	83	1.8	78	64	3.59
0113	01-Oct-98	5.17	75	0.4	83	0.9	79	66	3.57
0113	04-Dec-98	5.34	74	0.8	82	1.3	78	65	3.59
0113	17-Nov-99	6.29	75	0.7	100	1.7	87	72	3.58
0113	19-Dec-00	7.38	76	0.9	104	2.0	90	74	3.46
0113	06-Nov-01	8.27	79	0.8	140	2.3	109	89	2.85
0113	10-Dec-01	8.36	80	0.9	129	2.8	105	85	3.03
0113	23-Jan-02	8.48	82	0.6	113	3.1	98	80	3.15
0113	20-Feb-02	8.56	78	0.9	137	3.1	108	87	3.02
0113	14-Mar-02	8.62	82	1.0	125	1.5	104	84	3.08
0113	11-Oct-02	9.19	77	1.2	84	0.5	81	74	3.51
0113	18-Dec-02	9.38	77	1.0	84	0.6	80	74	3.49
0113	02-Mar-03	9.58	74	0.9	97	4.8	85	78	3.36
0113	10-Mar-03	9.60	78	0.6	88	3.5	83	75	3.42
0113	09-Aug-03	10.02	78	0.4	83	0.6	80	74	3.44

Table 28. Roughness Values, cont.

Section	Date	Years	Left IRI (in/mi)		Right IRI (in/mi)		MRI (in/mi)	HRI (in/mi)	RN
			Ave	St Dev	Ave	St Dev			
0113	23-Nov-03	10.31	79	0.8	85	0.8	82	75	3.41
0113	17-Dec-03	10.38	78	0.9	85	1.2	82	75	3.38
0113	10-Mar-04	10.61	80	0.6	86	0.4	83	76	3.37
0113	22-Apr-04	10.72	80	1.1	88	1.3	84	77	3.39
0113	15-Jul-04	10.95	81	0.9	89	1.2	85	77	3.37
0113	08-Sep-04	11.10	81	0.4	87	0.5	84	77	3.37
0113	15-Mar-05	11.62	83	0.3	91	1.2	87	78	3.30
0113	27-Mar-06	12.65	84	1.0	100	0.7	92	82	3.06
0114	27-Jan-94	0.49	37	1.8	48	1.1	42	34	4.19
0114	27-Feb-95	1.57	41	0.3	49	0.7	45	36	4.20
0114	23-Jan-97	3.48	40	0.5	54	0.8	47	38	4.11
0114	14-Jan-98	4.45	42	0.8	55	1.4	49	38	3.79
0114	07-Apr-98	4.68	44	1.1	57	1.6	51	40	3.70
0114	08-Apr-98	4.68	43	1.4	55	0.8	49	39	3.76
0114	08-Jul-98	4.93	41	0.6	57	0.4	49	39	3.95
0114	01-Oct-98	5.17	41	0.7	57	0.6	49	39	3.96
0114	04-Dec-98	5.34	41	0.7	57	1.2	49	39	3.93
0114	17-Nov-99	6.29	42	0.5	63	1.1	53	44	3.93
0114	19-Dec-00	7.38	45	0.5	67	0.7	56	47	3.62
0114	06-Nov-01	8.27	45	0.5	63	0.8	54	45	3.93
0114	10-Dec-01	8.36	45	0.5	64	0.6	54	45	3.96
0114	23-Jan-02	8.48	46	0.5	64	0.6	55	45	3.95
0114	20-Feb-02	8.56	46	0.5	68	1.8	57	47	3.75
0114	14-Mar-02	8.62	46	0.6	66	1.4	56	46	3.92
0114	11-Oct-02	9.19	57	0.6	55	0.7	56	49	3.85
0114	18-Dec-02	9.38	59	2.1	55	1.0	57	49	3.83
0114	02-Mar-03	9.58	65	0.7	59	0.9	62	53	3.68
0114	10-Mar-03	9.60	62	0.6	58	1.2	60	51	3.76
0114	09-Aug-03	10.02	58	0.5	54	0.4	56	50	3.89
0114	23-Nov-03	10.31	62	0.4	56	0.9	59	51	3.82
0114	17-Dec-03	10.38	59	0.4	56	0.8	57	51	3.87
0114	10-Mar-04	10.61	59	0.5	56	0.4	58	52	3.85
0114	22-Apr-04	10.72	60	0.7	57	0.3	58	51	3.86
0114	15-Jul-04	10.95	59	1.1	55	0.5	57	50	3.87
0114	08-Sep-04	11.10	58	0.1	55	0.6	56	51	3.87
0114	15-Mar-05	11.62	63	1.1	61	0.9	62	53	3.72
0114	27-Mar-06	12.65	60	0.3	57	0.8	58	52	3.74
0115	27-Jan-94	0.49	39	0.4	46	2.1	43	36	4.22
0115	27-Feb-95	1.57	38	0.2	47	0.6	42	36	4.28
0115	23-Jan-97	3.48	39	1.0	48	0.9	43	36	4.19
0115	08-Apr-98	4.68	41	0.5	50	0.9	45	38	4.00
0115	04-Dec-98	5.34	39	0.4	49	0.6	44	37	4.09
0115	17-Nov-99	6.29	37	0.5	50	0.8	44	37	4.18
0115	19-Dec-00	7.38	38	0.5	51	0.6	44	37	4.18
0115	06-Nov-01	8.27	38	0.5	65	1.2	51	42	3.89
0115	20-Feb-02	8.56	38	0.7	67	2.0	53	43	3.84
0115	02-Mar-03	9.58	41	3.3	50	4.0	46	39	3.88
0115	10-Mar-04	10.61	41	0.4	84	12.1	62	51	3.41
0115	15-Mar-05	11.62	46	1.0	142	40.5	94	80	2.86
0115	27-Mar-06	12.65	49	0.2	225	6.7	137	120	2.37
0116	27-Jan-94	0.49	34	0.5	53	0.9	44	34	4.13

Table 28. Roughness Values, cont.

Section	Date	Years	Left IRI (in/mi)		Right IRI (in/mi)		MRI (in/mi)	HRI (in/mi)	RN
			Ave	St Dev	Ave	St Dev			
0116	27-Feb-95	1.57	38	0.9	52	0.5	45	33	4.15
0116	23-Jan-97	3.48	35	0.4	57	0.9	46	34	4.08
0116	08-Apr-98	4.68	37	0.3	58	1.9	47	36	3.82
0116	04-Dec-98	5.34	34	1.0	59	1.6	46	35	3.93
0116	17-Nov-99	6.29	34	0.5	61	0.8	48	37	4.07
0116	19-Dec-00	7.38	34	0.3	60	1.8	47	36	4.06
0116	06-Nov-01	8.27	46	4.5	65	1.3	55	44	3.18
0116	20-Feb-02	8.56	45	0.9	105	0.9	75	62	2.99
0116	02-Mar-03	9.58	52	1.2	57	2.0	55	43	3.85
0116	10-Mar-04	10.61	61	0.4	60	0.7	60	47	3.73
0116	15-Mar-05	11.62	57	0.9	61	0.4	59	46	3.79
0116	27-Mar-06	12.65	65	0.5	64	0.6	64	50	3.59
0117	27-Jan-94	0.49	35	1.6	47	2.1	41	33	4.16
0117	27-Feb-95	1.57	33	0.5	47	0.9	40	31	4.18
0117	23-Jan-97	3.48	35	1.2	50	0.1	42	33	4.06
0117	08-Apr-98	4.68	36	0.7	51	0.7	43	34	3.93
0117	04-Dec-98	5.34	36	0.8	49	0.7	42	33	4.00
0117	17-Nov-99	6.29	34	0.6	49	0.7	41	32	4.11
0117	19-Dec-00	7.38	34	0.4	50	0.5	42	33	4.11
0117	06-Nov-01	8.27	34	0.3	61	2.3	47	38	4.00
0117	20-Feb-02	8.56	34	0.8	64	0.8	49	39	3.97
0117	02-Mar-03	9.58	34	0.9	89	7.2	61	50	3.49
0117	10-Mar-04	10.61	39	0.9	54	2.1	47	38	3.78
0117	15-Mar-05	11.62	40	0.7	124	19.6	82	69	2.92
0117	27-Mar-06	12.65	44	0.5	107	5.3	76	63	2.94
0118	27-Jan-94	0.49	37	1.4	66	2.1	51	40	4.03
0118	27-Feb-95	1.57	34	0.6	64	0.6	49	38	4.12
0118	23-Jan-97	3.48	35	0.6	74	0.4	54	42	3.93
0118	08-Apr-98	4.68	37	0.9	70	1.3	53	40	3.87
0118	04-Dec-98	5.34	35	0.8	72	1.6	53	41	3.93
0118	17-Nov-99	6.29	38	1.0	73	2.4	55	43	3.85
0118	19-Dec-00	7.38	37	0.8	78	1.7	58	45	3.71
0118	06-Nov-01	8.27	38	0.9	101	3.4	69	55	3.35
0118	20-Feb-02	8.56	38	0.5	107	5.9	73	59	3.20
0118	02-Mar-03	9.58	52	1.0	67	0.6	60	51	3.77
0118	10-Mar-04	10.61	53	0.7	78	3.1	65	58	3.67
0118	15-Mar-05	11.62	56	1.6	65	1.4	61	52	3.78
0118	27-Mar-06	12.65	57	1.0	69	1.1	63	55	3.75
0119	27-Jan-94	0.49	39	0.6	77	2.4	58	47	3.96
0119	27-Feb-95	1.57	42	0.5	65	1.4	53	44	4.09
0119	23-Jan-97	3.48	43	0.4	72	1.9	58	46	3.96
0119	08-Apr-98	4.68	45	0.9	92	10.2	68	55	3.39
0119	04-Dec-98	5.34	44	0.4	82	5.1	63	51	3.59
0119	17-Nov-99	6.29	44	1.2	74	5.7	59	47	3.80
0119	19-Dec-00	7.38	43	0.6	78	3.8	61	49	3.64
0119	06-Nov-01	8.27	44	0.8	107	1.7	76	62	3.40
0119	20-Feb-02	8.56	45	0.9	92	6.6	68	55	3.58
0119	02-Mar-03	9.58	49	1.5	70	1.6	60	47	3.58
0119	10-Mar-04	10.61	47	1.0	98	13.1	73	58	3.22
0119	15-Mar-05	11.62	50	1.2	116	3.0	83	67	2.95

Table 28. Roughness Values, cont.

Section	Date	Years	Left IRI (in/mi)		Right IRI (in/mi)		MRI	HRI	RN
			Ave	St Dev	Ave	St Dev	(in/mi)	(in/mi)	
0118	27-Mar-06	12.65	57	1.0	69	1.1	63	55	3.75
0119	27-Jan-94	0.49	39	0.6	77	2.4	58	47	3.96
0119	27-Feb-95	1.57	42	0.5	65	1.4	53	44	4.09
0119	23-Jan-97	3.48	43	0.4	72	1.9	58	46	3.96
0119	08-Apr-98	4.68	45	0.9	92	10.2	68	55	3.39
0119	04-Dec-98	5.34	44	0.4	82	5.1	63	51	3.59
0119	17-Nov-99	6.29	44	1.2	74	5.7	59	47	3.80
0119	19-Dec-00	7.38	43	0.6	78	3.8	61	49	3.64
0119	06-Nov-01	8.27	44	0.8	107	1.7	76	62	3.40
0119	20-Feb-02	8.56	45	0.9	92	6.6	68	55	3.58
0119	02-Mar-03	9.58	49	1.5	70	1.6	60	47	3.58
0119	10-Mar-04	10.61	47	1.0	98	13.1	73	58	3.22
0119	15-Mar-05	11.62	50	1.2	116	3.0	83	67	2.95
0119	27-Mar-06	12.65	56	2.8	131	4.7	94	75	2.62
0120	27-Jan-94	0.49	52	0.8	64	1.1	58	48	4.04
0120	27-Feb-95	1.57	54	0.7	62	0.3	58	49	4.11
0120	23-Jan-97	3.48	55	1.1	72	0.8	64	53	3.96
0120	08-Apr-98	4.68	57	0.7	73	1.2	65	55	3.84
0120	04-Dec-98	5.34	57	0.4	69	0.8	63	54	3.93
0120	17-Nov-99	6.29	60	0.7	75	0.6	68	56	3.87
0120	19-Dec-00	7.38	59	0.1	76	0.7	68	56	3.93
0120	06-Nov-01	8.27	60	0.6	73	0.3	66	56	3.92
0120	20-Feb-02	8.56	62	0.7	77	0.5	69	58	3.88
0120	02-Mar-03	9.58	67	0.6	64	0.5	65	61	3.94
0120	10-Mar-04	10.61	67	0.8	66	0.8	66	60	3.92
0120	15-Mar-05	11.62	68	0.7	65	0.7	66	61	3.88
0120	27-Mar-06	12.65	69	0.6	66	0.8	68	61	3.83
0121	27-Jan-94	0.49	35	0.4	60	0.8	47	37	4.20
0121	27-Feb-95	1.57	35	0.2	58	0.8	47	37	4.24
0121	23-Jan-97	3.48	37	0.3	60	1.0	48	38	4.12
0121	08-Apr-98	4.68	39	1.3	62	1.0	51	39	3.93
0121	04-Dec-98	5.34	38	0.8	59	0.4	49	38	4.04
0121	17-Nov-99	6.29	39	0.3	63	0.5	51	40	4.09
0121	19-Dec-00	7.38	37	0.5	61	1.1	49	39	4.09
0121	06-Nov-01	8.27	38	0.5	61	0.3	49	39	4.06
0121	20-Feb-02	8.56	38	0.3	67	2.6	52	42	3.90
0121	02-Mar-03	9.58	51	0.7	62	0.8	56	49	3.81
0121	10-Mar-04	10.61	49	0.3	68	1.7	59	49	3.72
0121	15-Mar-05	11.62	49	0.8	68	1.6	58	50	3.72
0121	27-Mar-06	12.65	49	0.6	68	0.6	58	49	3.69
0122	27-Jan-94	0.49	41	0.4	78	0.6	60	49	4.09
0122	27-Feb-95	1.57	40	0.8	77	0.5	59	49	4.16
0122	23-Jan-97	3.48	45	0.7	82	0.5	64	52	4.03
0122	08-Apr-98	4.68	43	0.8	81	1.5	62	51	3.84
0122	04-Dec-98	5.34	44	0.5	81	0.9	63	51	3.93
0122	17-Nov-99	6.29	58	0.9	88	0.8	73	61	2.91
0122	19-Dec-00	7.38	47	0.6	87	0.5	67	54	4.01
0122	06-Nov-01	8.27	45	0.6	85	1.1	65	53	3.93
0122	20-Feb-02	8.56	48	0.7	87	0.4	67	54	3.78
0122	02-Mar-03	9.58	64	0.3	69	1.3	67	58	3.80

Table 28. Roughness Values, cont.

Section	Date	Years	Left IRI (in/mi)		Right IRI (in/mi)		MRI	HRI	RN
			Ave	St Dev	Ave	St Dev	(in/mi)	(in/mi)	
0122	10-Mar-04	10.61	65	0.4	79	2.0	72	63	3.74
0122	15-Mar-05	11.62	64	1.2	72	1.7	68	60	3.81
0122	27-Mar-06	12.65	66	0.6	77	0.9	71	63	3.76
0123	27-Jan-94	0.49	38	0.6	53	0.6	45	38	4.15
0123	27-Feb-95	1.57	38	0.8	49	0.6	43	37	4.21
0123	23-Jan-97	3.48	39	0.2	58	1.3	49	40	4.06
0123	08-Apr-98	4.68	40	1.0	55	0.8	48	40	3.90
0123	04-Dec-98	5.34	40	0.5	55	0.3	47	39	4.00
0123	17-Nov-99	6.29	39	0.7	60	1.5	50	43	4.03
0123	19-Dec-00	7.38	39	0.5	62	3.1	51	43	3.93
0123	06-Nov-01	8.27	39	0.2	68	7.9	54	45	3.89
0123	20-Feb-02	8.56	39	0.5	59	2.1	49	42	4.02
0123	02-Mar-03	9.58	39	0.6	52	2.5	46	37	3.90
0123	10-Mar-04	10.61	39	0.7	97	30.5	68	56	3.35
0123	15-Mar-05	11.62	42	0.8	115	19.0	79	65	3.08
0123	27-Mar-06	12.65	47	0.9	134	14.2	91	75	2.76
0124	27-Jan-94	0.49	33	0.9	38	0.5	36	28	4.25
0124	27-Feb-95	1.57	31	0.6	37	0.5	34	27	4.29
0124	23-Jan-97	3.48	34	0.8	41	0.3	37	28	4.23
0124	08-Apr-98	4.68	33	0.5	43	1.8	38	29	3.98
0124	04-Dec-98	5.34	33	0.5	42	1.0	37	29	4.07
0124	17-Nov-99	6.29	34	0.7	43	0.4	38	30	4.18
0124	19-Dec-00	7.38	33	0.6	45	1.6	39	31	4.16
0124	06-Nov-01	8.27	33	0.8	56	3.9	45	36	3.94
0124	20-Feb-02	8.56	34	0.3	66	1.5	50	38	3.75
0124	02-Mar-03	9.58	43	2.3	69	2.6	56	44	3.28
0124	10-Mar-04	10.61	34	0.4	112	15.5	73	62	3.25
0124	15-Mar-05	11.62	46	4.8	125	18.2	86	68	2.75
0124	27-Mar-06	12.65	42	0.9	148	14.7	95	79	2.88
0160	27-Jan-94	0.49	88	1.6	122	28.3	105	90	2.75
0160	27-Feb-95	1.57	91	1.3	95	0.9	93	78	3.47
0160	23-Jan-97	3.48	95	0.9	103	1.2	99	85	3.36
0160	08-Apr-98	4.68	101	1.9	102	1.2	102	86	3.36
0160	04-Dec-98	5.34	98	0.8	105	1.0	102	88	3.38
0160	17-Nov-99	6.29	116	2.3	121	1.4	119	108	3.28
0160	19-Dec-00	7.38	107	0.2	112	1.1	109	99	3.34
0160	06-Nov-01	8.27	103	1.1	110	0.7	107	95	3.36
0160	20-Feb-02	8.56	100	1.1	109	1.3	105	93	3.40
0160	02-Mar-03	9.58	99	0.7	110	1.1	104	91	3.24
0160	10-Mar-04	10.61	105	1.1	111	0.8	108	95	3.26
0160	15-Mar-05	11.62	101	0.7	108	0.7	104	92	3.28
0160	27-Mar-06	12.65	104	0.5	112	0.8	108	95	3.24
0161	27-Jan-94	0.49	75	0.7	75	2.4	75	65	3.83
0161	27-Feb-95	1.57	77	0.5	71	1.3	74	64	3.92
0161	23-Jan-97	3.48	75	0.8	80	0.5	77	67	3.78
0161	08-Apr-98	4.68	77	0.6	74	1.1	75	64	3.72
0161	04-Dec-98	5.34	76	0.7	72	1.3	74	63	3.76
0161	17-Nov-99	6.29	74	0.9	81	0.9	78	66	3.76
0161	19-Dec-00	7.38	75	0.5	83	0.4	79	68	3.77
0161	06-Nov-01	8.27	76	0.6	84	1.6	80	68	3.73

Table 28. Roughness Values, cont.

Section	Date	Years	Left IRI (in/mi)		Right IRI (in/mi)		MRI (in/mi)	HRI (in/mi)	RN
			Ave	St Dev	Ave	St Dev			
0161	20-Feb-02	8.56	74	0.6	110	0.5	92	79	3.18
0161	02-Mar-03	9.58	62	0.5	87	2.6	75	70	3.48
0161	10-Mar-04	10.61	71	0.7	79	1.3	75	69	3.49
0161	15-Mar-05	11.62	69	0.7	84	1.1	76	70	3.34
0161	27-Mar-06	12.65	72	0.7	87	0.2	80	73	3.17
0162	27-Jan-94	0.49	69	1.2	87	1.1	78	67	3.84
0162	27-Feb-95	1.57	69	0.4	84	0.7	77	66	3.90
0162	23-Jan-97	3.48	72	0.4	89	0.5	81	69	3.79
0162	08-Apr-98	4.68	72	0.5	88	0.6	80	69	3.71
0162	04-Dec-98	5.34	72	0.6	88	0.9	80	68	3.75
0162	17-Nov-99	6.29	71	0.6	92	0.8	82	69	3.75
0162	19-Dec-00	7.38	70	0.3	92	0.8	81	69	3.76
0162	06-Nov-01	8.27	71	0.4	91	0.5	81	70	3.78
0162	20-Feb-02	8.56	70	0.3	92	0.4	81	69	3.76
0162	02-Mar-03	9.58	66	0.7	79	0.7	73	65	3.72
0162	10-Mar-04	10.61	75	1.2	81	1.0	78	71	3.63
0162	15-Mar-05	11.62	73	1.1	78	0.9	76	69	3.66
0162	27-Mar-06	12.65	75	0.8	80	0.5	77	71	3.62
0163	27-Jan-94	0.49	74	2.3	65	1.1	69	61	4.11
0163	27-Feb-95	1.57	60	0.8	73	0.8	66	60	4.13
0163	23-Jan-97	3.48	61	0.7	86	1.4	74	65	3.68
0163	08-Apr-98	4.68	72	0.6	106	1.7	89	79	3.45
0163	04-Dec-98	5.34	67	0.6	101	1.2	84	74	3.38
0163	17-Nov-99	6.29	72	0.7	110	0.5	91	79	3.17
0163	19-Dec-00	7.38	72	0.3	113	1.2	93	80	3.11
0163	06-Nov-01	8.27	79	0.9	126	0.6	103	90	2.94
0163	20-Feb-02	8.56	78	1.2	127	0.7	103	89	2.84
0163	02-Mar-03	9.58	75	1.0	127	3.7	101	85	2.76
0163	10-Mar-04	10.61	74	1.2	110	3.3	92	78	3.01
0163	15-Mar-05	11.62	81	1.3	133	2.4	107	90	2.58
0163	27-Mar-06	12.65	83	2.2	114	3.4	98	81	2.79

Appendix B: Detailed Observations

This appendix provides detailed observations from the roughness trend, profiles and distress surveys of each section within the Arizona SPS-1 project. Observations regarding profile features are made using power spectral density (PSD) plots, filtered elevation profile plots, and roughness profiles. Each section is discussed individually. Sections 0113 and 0114 are discussed one side (left and right) at a time, since the high number of visits caused the discussions to be somewhat long.

Typically, roughness profiles provided the most information about the location of features that affected the IRI most, including areas of localized roughness. In this appendix, roughness profiles were made using a base length of 25 ft unless otherwise specified. An area is considered to have localized roughness when the roughness profile (with a base length of 25 ft) reaches a peak value that is greater than 2.5 times the average IRI for the whole section. This usually prompted more careful examination of the filtered elevation profiles.

The PSD plots were less informative, since none of the profiles were dominated by periodic content.

Section 0113

Roughness: The HRI was 17 to 19 percent lower than the MRI for visits 01 through 09 and seasonal visits S03 through S07. These earlier visits include all of those on or before May 2002. During the later visits, which include visits 10 through 13 and seasonal visits S08 through S16, the HRI was 8 to 11 percent lower than the MRI. This is an unusually low difference for the SPS-1 project. The similarity between the HRI and MRI indicates that more profile features exist on both sides along this section than is typical for an SPS-1 pavement section.

Section 0113, Left Side

Roughness: The IRI ranged from 73 to 84 in/mi over the monitoring period.

PSD Plots: The spectral content was fairly consistent over all of the visits and was similar to “white noise slope.” White noise slope is a common approximation of road profile spectral content in which the amplitude of each component of profile content is proportional to the wavelength. In addition, the PSD plots were very consistent over a group of visits including 01 through 09 and seasonal visits S03 through S07. The PSD plots were also consistent over seasonal visits S08 through S16. While profiles from the two groups of visits include roughly the same spectral distribution, the details of the plots in the earlier visits are not always similar to the later visits. This may be the result of a change in profiler make. Note that visit 10 was not as consistent with the later group of visits as they were with each other.

Long Wavelengths: The long wavelength content was consistent with time.

Medium Wavelengths: The medium wavelength profile plots were consistent over about half of the section. In the areas that were 170 to 280 ft and 340 to 450 ft from the start of the section, and particularly a bump 195 ft from the start of the section, the profile changed gradually. The change was greatest between visits 06 and 07.

Longitudinal distance measurement in seasonal visit S16 was not consistent with other visits, such that profiles in visit S16 estimated the longitudinal distance between features as about 1.1 percent shorter than in other visits.

Short Wavelengths: A bump appeared 157 ft from the start of the section that was about 3 ft long and 0.25 in high in visits 01 through 09 and S03 through S07. In the rest of the visits, the bump was approximately the same height, but more than 10 ft long. In visits 10 through 13 and seasonal visits S08 through S16, the profile rises up to 0.4 in over 2 ft of profile starting 170 ft from the start of the section then lowers about 0.2 in afterward. In all visits, an area of high short wavelength content appeared from 190 to 230 ft from the start of the section.

Roughness Profiles: A peak value of 156-173 in/mi appeared in the roughness profiles 157 ft from the start of the section in visits 01 through 09 and seasonal visits S03 through S07. An equally rough area appeared about 200 ft from the start of the section by visit 09, but its roughness had grown gradually with time. In visits 10 through 13 and seasonal visits S08 through S16, the areas of localized roughness from the earlier visits were gone. However, all of the roughness profiles from the later visits included a peak value of up to 300 in/mi about 165 ft from the start of the section.

Distress Surveys and Maintenance History: The bump 195 ft from the start of the section is near some transverse cracking that was present in March 2002 and February 2003, but not present in October 2002. The cracking there was probably temporarily obscured by a slurry seal that was applied in May 2002. The distress surveys do not explain the bump 157 ft from the start of the section, although a diagonal crack cuts across the left side of the lane near that location.

In the later visits, a seam appeared between seal coat applications 175 ft from the start of the section. This was most likely the cause of the severe localized roughness there. Note that the short and medium wavelength content changed significantly in shape (but not roughness) in the part of the section after the seam, but not before.

Section 0113, Right Side

Roughness: The IRI increased with time from 72 to 100 in/mi, with the exception of a set of values from 100 to 140 in/mi in the seven visits between November

1999 and March 2002. This included values that ranged from 113 to 149 in/mi over less than eight months.

PSD Plots: The spectral content showed that the changes in roughness with time typically took place in the short wavelength range and were most likely caused by the presence or absence of narrow bumps or dips in the profiles. The level of spectral content in the short wavelength range (< 5 ft) usually followed the same trend between visits as the IRI.

Filtered Profiles: Evaluation of filtered plots in the long, medium, and short wavelength ranges showed that the features of greatest interest were usually narrow dips. These were best inspected using a simple high-pass filter or by viewing plots of raw profile.

In visit 06, three dips about 2 ft long and 0.1 in deep appeared 354, 378, and 397.5 ft from the start of the section. By visit 07, these dips were deeper, and secondary dips appeared near them. In visits 08, 09, and S05 the areas from 354 to 367 ft and the range from 374 to 380.5 ft were about 0.2 in beneath the surrounding pavement, and included several narrow dips 0.1 in to more than 1 in deep. In addition, narrow dips greater than 0.1 in deep appeared 167, 186, 188, 238.5, 252, 269, 284, 303.5, 313, 317, 345.5, 393.5, 394, 397, 406.5, 413.5, 488, and 494 ft. Visits S06 and S07 included dips in the same locations, except the dips in the depressed areas were not as severe.

In visits S08 and later, dips were found in some of the same locations as in previous visits, but they were not nearly as deep or long, and were not measured as consistently among repeat measurements from the same visit. Two rough areas, including sharp changes in slope, appeared 162 to 173 ft and 373 to 378 ft from the start of the section. However, the sunken areas between 350 and 400 ft from the start of the section were much smoother than in the earlier visits, and did not include as many narrow dips.

At most locations, the shape and depth of the narrow dips was measured consistently within each set of repeats.

Roughness Profiles: Very short interval (10 ft) roughness profiles show that increases in roughness between visits usually correspond to the appearance of the narrow dips described above. The most severe localized roughness on the right side of this section was observed in visits 08, 09 and S05 from 355 to 386 ft from the start of the section. In visit 08, this area alone contributed 30 in/mi to the roughness of the entire section.

Roughness profiles show similarities between visits and are consistent in consecutive visits except where new dips appear in the elevation profiles, with one exception. The roughness profiles in seasonal visit S08 were significantly different than that of seasonal visit S07. In visit S08 all of the areas of localized roughness in visit S07 were eliminated or heavily modified. Two areas of localized roughness appeared in visit S08; 162 to 173 ft and 373 to 378 ft from the start of the section. These were not at narrow dips. Rather, they were in locations of transitions between broader bumps and dips that included large changes in elevation over short distances.

Distress Surveys and Maintenance History: The major change in roughness, roughness distribution, and the elimination of the narrow dip listed above for visits 08, 09, and S05 correspond to the placement of a slurry seal in May 2002. The dips listed for the visits prior to the slurry seal appear near locations where transverse cracks were noted in a distress survey in November 2001. In most cases, the dips correspond to transverse cracks that run from a longitudinal crack on the right side of the lane to the right edge of the lane. The "sunken" areas listed above correspond to large areas of cracking noted in the survey.

The reduction in IRI from 126 in/mi in visit S07 to 85 in/mi in visit S08 corresponds to the date of the slurry seal and to a reduction in cracking observed during distress surveys. However, the two areas of localized roughness in the group of visits after the slurry seal are in positions where cracking was noted, as were many of the narrow dips.

Section 0114

Roughness: The HRI was 15 to 21 percent lower than the MRI for visits 01 through 09 and seasonal visits S03 through S07. These earlier visits include all of those on or before May 2002. During the later visits, which include visits 10 through 13 and seasonal visits S08 through S16, the HRI was 10 to 15 percent lower than the MRI. This is an unusually low difference for the SPS-1 project. The similarity between the HRI and MRI indicates that most profile features along this section exist on both sides.

Section 0114, Left Side

Roughness: The IRI exhibited an increasing trend with time, and ranged from 37 to 46 in/mi in the earlier visits that led up to March 2002. In the visits after March 2002, the IRI ranged from 57 to 65 in/mi.

PSD Plots: The PSD plots were consistent in the earlier visits from 01 to seasonal visit S07. The PSD plots of most visits after S07 were also consistent with each other. The increase in roughness in the later visits occurred primarily in the wavelength range from 2 to 10 ft.

Filtered Profiles: Evaluation of filtered plots in the long, medium, and short wavelength ranges showed that the features of greatest interest were usually in the short wavelength range. These were studied using a simple high-pass filter with a base length of 20 ft.

No significantly rough features were found in the earlier visits (before seasonal visit S08).

A noteworthy property of the elevation profile plots was the change that occurred between visit S07 and S08. Profiles from the later visits had very little similarity to the earlier visits in the short wavelength range, and in the medium wavelength range local highs and lows often occurred in the same place, but individual features did not have the same shape or severity.

Roughness Profiles: No significant localized roughness was found in the visits before S08. The modest increase in roughness between visits 01 and visit S07 took place primarily between 70 and 140 ft from the start of the section.

In visits S08 and later, the first 170 ft of the section were rougher than the rest of the section. The roughness was caused primarily by localized features, usually narrow dips that were not reproduced completely between visits. An area of localized roughness also appeared in visit 12, only that was caused by a series of three dips from 105 to 120 ft from the start of the section.

Distress Surveys and Maintenance History: Very little distress appeared on the left side. In addition, the elevated roughness in the first third of the section is not explained by recorded distress. Further, transverse cracks that appeared in the distress surveys rarely had an obvious effect on the profiles.

The major change in profile features and changeover in the locations of rough spots between visits S07 and S08 corresponds to the application of a slurry seal in May 2002.

Section 0114, Right Side

Roughness: The IRI exhibited an increasing trend with time and ranged from 48 to 68 in/mi in the earlier visits. In the later visits the IRI held somewhat steady, with values that ranged from 54 to 61 in/mi.

PSD Plots: The PSD plots were consistent from visit S08 on. In the earlier visits, the PSD plots were consistent for wavelengths above 7 ft. For wavelengths shorter than 7 ft, the PSD plots were typically consistent within each visit, but not among visits. Further, the changes did not follow a consistent trend with time. For example, the plots for visits 04, S01, and S02 have higher content in the range of wavelengths below 3 ft than previous visits 01 through 03 and later visits 05, S03, and S04. The roughest visits, 07 and 09, included content higher than the other visits in the range of wavelengths from 1 to 10 ft.

Filtered Profiles: Evaluation of filtered plots in the long, medium, and short wavelength ranges showed that the features of greatest interest were usually in the short wavelength range. These were studied using a simple high-pass filter with a base length of 20 ft.

Very few rough features were found in the visits leading up to seasonal visit S07. The area 220 to 280 ft from the start of the section included rougher short wavelength “chatter” than in the rest of the section starting in visit 06. A dip first appeared 455 ft from the start of the section in visit 06 that was about 1 ft long and 0.15 in deep. It was very deep (0.4 to 0.6 in) in visits 07 and 09, but not in others. In visits 08, S05, and S06, a small bump appeared about 208 ft from the start of the section.

In visit 04 and seasonal visit S02, a narrow dip followed by a narrow bump, resulting in a graphical “spike,” appeared 299 ft from the start of the section, and every 25 ft through the end of the section. These “spikes” have roughly the same shape as the spikes that occur at the start and end of the section in some measurements, which are caused by pavement markings. Without the additional roughness caused by these spikes, the trend in roughness with time would have followed a more consistent pattern.

The later visits, starting with S08, included a narrow bump up to 0.1 in high and 91 ft from the start of the section. In some visits, a minor disturbance in the profile was found 455 ft from the start of the section. Several very narrow dips and some bumps also appeared 300 to 400 ft from the start of the section in later visits, but they were not measured very consistently.

The most noteworthy property of the elevation profile plots was the tremendous change that occurred between visits S07 and S08. Profiles from the later visits had very little similarity to the earlier visits in the short and medium wavelength range, and were less similar than expected in the long wavelength range.

<u>Roughness Profiles</u>: No significant localized roughness was found in the later visits (S08 and afterward). The most severe localized roughness occurred in visits 07 and 09. In visit 07 a dip 456 ft from the start of the section was severe enough to explain the increase in overall roughness compared to the previous visit. This is because the dip there was much deeper (> 0.4 in). In visit 09, the area from 240 to 260 ft from that start of the section was rougher than in other visits. Again, this accounted for much of the increase in roughness compared to the previous (and subsequent) visit.

<u>Distress Surveys and Maintenance History</u>: Nothing in the distress surveys accounts for the spikes that appeared 25 ft apart in some visits. The elevated roughness in the early visits from 220 to 280 ft from the start of the section corresponds to large areas of cracking noted in the distress surveys, particularly in November 2001 and March 2002. The cracking was absent in October 2002 and later.

Cracking was recorded on the right side of the lane near 456 ft from the start of the section in every distress survey taken in 1996 through 2005.

The major change in profile features and changeover in the locations of rough spots between visits S07 and S08 corresponds to the application of a slurry seal in May 2002.

Section 0115

Roughness: The IRI of the left side ranged from 37 to 41 in/mi over the first 11 visits, and rose to 49 in/mi by visit 13. The IRI of the right side ranged from 46 to 51 in/mi over the 10 visits, with the exception of elevated roughness (~70 in/mi) in visits 08 and 09. The IRI then increased very aggressively to 225 in/mi by visit 13. The HRI was 12 to 18 percent lower than the MRI.

PSD Plots: The roughness of this section was skewed toward long wavelength content. On the left side, the spectral content was very consistent throughout the monitoring period in the range of wavelengths from 2 to 100 ft. However, visits 10 through 13 included progressively higher content for wavelengths shorter than 5 ft. (This was caused by spikes in the profiles.) On the right side, the spectral content was also consistent with time in the first 10 visits, except for elevated content in the range shorter than 10 ft in visits 08 and 09. In visits 12 and 13, the spectral content was much higher than in previous visits over the entire range.

Long Wavelengths: With the exception of the device effect, the long wavelength content was very consistent with time.

Medium Wavelengths: The medium wavelength content was consistent over visits 01 through 10 on the left side, and no features stood out as very rough. Over visits 10 through 13 the peaks and valleys in the medium wavelength profiles became progressively more severe. On the right side, the medium wavelength content was fairly consistent over the first seven visits. Afterward, the medium wavelength roughness increased in the second half of the section. It did not begin to increase in the first half until visit 12.

Short Wavelengths: Narrow bumps, 1 to 1.5 ft long and 0 to 0.1 in high, appeared 233.5 and 245 ft from the start of the section on the left side in visit 10 only. Their shape and severity was not consistent throughout the repeat measurements. Repeat 1 from visit 10 also included a series of narrow bumps from 102 to 114 ft into the section. These were probably caused by sensor error. Several narrow dips appeared throughout the profiles from visits 10 through 13. These dips rarely appeared in more than one repeat measurement at a given location.

On the right side, a small bump appeared in visit 10 with a downward step of about 0.1 in. This was 264 ft from the start of the section. Bumps up to 0.15 in high also appeared at 292 and 346 ft. In visits 08 and 09, there was a significant increase in the short-wavelength roughness on the right side in the second half of the section. However, with the exception of the features cited above, the profiles from visit 10 were similar to those of visit 07. Since the repeat measurements in each of the visits are consistent with each other, this is not attributed to measurement error. Instead, the contrast between visits 08 through 09 and the others is attributed to differences in lateral tracking of the profiler.

Visits 11 through 13 all included areas of extreme short wavelength roughness. These usually appeared as a dense series of narrow dips that were not well correlated between repeat measurements. The most extreme content appeared in visit 13 in the ranges from 16 to 45 ft and 300 to 335 ft from the start of the section.

Roughness Profiles: On the left side, the roughness profile was very consistent with time over most of the section. Between visits 09 and 10 the roughness doubled in the range from 230 to 255 ft from the start of the section. On the right side, the transition into the section included some severe localized roughness. The roughness on the right side was consistent throughout the life of the section in the first half and much higher, but spread out fairly uniformly, in the second half for visits 08 and 09. The later visits (10 through 13) included severe localized roughness on the right side in some areas, including an area of the roughness profile from 300 to 350 ft from the start of the section with a peak value over 800 in/mi.

Distress Surveys and Maintenance History: On the left side, the localized roughness mentioned above appeared in locations where longitudinal cracks were found. However, longitudinal cracks appeared in other locations or in other visits without the same type of roughness. On the right side, significant longitudinal cracking first appeared in the second half of the section in visit 07 and became more significant in later visits. By visit 10, longitudinal cracking extended over most of the section. During all visits, most of the cracks were sealed. The elevated roughness in visits 08 and 09 was measured because the profiler passed directly over the longitudinal cracking, and the lack of elevated roughness in visits 07 and 10 was caused by the tracking of the profiler over a different lateral position.

Section 0116

Roughness: The IRI of the left side ranged from 35 to 38 in/mi in visits 01 through 07, increased to 46 in/mi by visit 08, then increased gradually to 65 in/mi by visit 13. The IRI of the right side followed a gradually increasing trend from 53 to 64 in/mi, with the exception of much higher roughness (105 in/mi) in visit 09. The HRI was 18 to 27 percent lower than the MRI. This range includes higher values than most of the other SPS-1 sections.

PSD Plots: The roughness of this section was skewed toward long wavelength content in the earlier visits. On both sides, the spectral content was very consistent from visits 01 through 07 for wavelengths greater than 4 ft. However, the content on the left side at wavelengths shorter than 15 ft was much higher in visits 08 and later than in the earlier visits. The content on the right side increased slightly for wavelengths shorter than 5 ft in visit 08, showed a major increase for wavelengths shorter than 100 ft in visit 09, and returned to content like that of visit 07 in visit 10.

Long Wavelengths: The long wavelength content was not very consistent in visits 07 though 10 on the left side, because of the influence of severe localized roughness. On the right side, the profile was consistent over time with the exception of a severe feature about one third of the way into the section in visit 09.

Inspection of profile plots in the long, medium, and short wavelength ranges helped locate features of interest, but they were characterized best using a simple anti-smoothing filter with a base length of 50 ft

Left Side: The profiles were consistent in shape and severity of roughness through visit 07. In visit 08, a severe dip (1.5 ft long and 0.8-1.0 in deep) appeared about 225 ft from the start of the section. In some of the repeat measurements, less severe dips were also present 228 and 231 ft from the start of the section. In visit 09, a very rough area appeared from 219 to 234 ft into the section. This area included an upward step more than 0.2 in high at the leading end and a downward step of more than 0.2 in at the trailing end. Visits 08 and 09 had profiles that were similar to older visits over the rest of the section. This rough area was still present in visits 10 through 13, but it had "sunk" to 0.25 in below the surrounding pavement.

Right Side: The profiles were consistent in shape and severity of roughness through visit 06. In visit 07 a dip (0.5 ft long and 0.10-0.35 in deep) appeared about 137 ft from the start of the section and a dip (about 0.05 in deep) appeared about 168 ft from the start of the section. In visit 08, the dip at 137 ft had increased in depth to about 0.4 in, and a new dip appeared at 170 ft that was up to 0.2 in deep. In visit 09 the dips were not present, but two areas of significant roughness appeared from 131 to 145 ft into the section and 149 to 172 ft into the section. The second rough area was elevated 0.75 in above the surrounding pavement. The profiles of visits 10 through 13 were similar to each other, but they were not very similar to those of previous visits in the medium and short wavelength ranges, and did not include the isolated rough areas from visits 07 though 09.

Roughness Profiles: On the left side, the roughness profile was very consistent through visit 07. In visit 08 the narrow dip caused extreme localized roughness that added 7 to 14 in/mi to its overall roughness. The narrow dip was not present in visit 09, but a rough area appeared at that location. An area of localized roughness also appears on both sides of the section that is centered 140 ft from the start of the section.

On the right side, the roughness level was fairly consistent through visit 07. In visit 08, the dip at 137 ft appeared to add 0-5 in/mi to the roughness of the whole section, depending on which repeat measurement was inspected. The area from

131 to 145 ft in visit 09 was equally rough. However, the area from 149 to 172 ft caused extreme roughness in visit 09, such that it was responsible for increasing the roughness of the whole section by more than 25 in/mi, with the most extreme roughness on the trailing edge. (This was the location of a 0.75-in downward step in the profile.) Visit 10 had very little relationship to previous visits. In visits 10 through 13, the area from 134 to 157 ft had much higher roughness than the rest of the section.

Distress Surveys and Maintenance History: On the left side, the deep dip found in visit 08 appeared in a location at which cracking was recorded during distress surveys on two prior dates. Photos of the section after visit 09 show that the localized roughness that replaced the dip is a patched area. The boundaries of the patched area listed in the distress survey roughly correspond to the boundaries of the rough area in the profile. On the right side, the dip found 137 ft into the section in visits 07 and 08 appeared in a location at which cracking was recorded in the distress survey between those visits. The rough areas found in visits 09 through 13 occur over ranges of the section at which the distress survey and photographs taken in April 2002 show patched pavement.

Section 0117

Roughness: The IRI of the left side ranged from 33 to 44 in/mi over the monitoring period and increased the most rapidly in the last three visits. The IRI of the right side ranged from 47 to 51 in/mi in visits 01 through 07, then increased erratically to a final value of 107 in/mi in visit 13. The peak value of 124 in/mi occurred in visit 12. The HRI was 15 to 23 percent lower than the MRI.

PSD Plots: The spectral content was similar to white noise slope through the range of interest. The spectral content on the left side was consistent in visits 01 through 09 in the range of wavelengths from 1 to 100 ft. In visits 10 through 13, the content for wavelengths of 5 ft and shorter increased. On the right side, the spectral content was consistent in visits 01 through 07, except that visits 04 and 05 were rougher in the wavelength range below 2 ft. In visits 08 and 09, the content was slightly higher for the wavelength range below 10 ft. In visits 10 through 13, the roughness increased significantly for wavelengths shorter than 10 ft.

Filtered Profiles: On the left side, the filtered plots for long and medium wavelength content were consistent over the first 12 visits. The short wavelength plots were consistent over the first nine visits, but profiles from the rest of the visits included an increasing number of extraneous narrow dips.

On the right side, the features of interest were best viewed by filtering the profiles to include the short wavelength range. During the first seven visits, only a few features stood out: (1) a bump about 1 ft long and up to 0.1 in high that appeared 28 ft from the start of the section and was only present in some of the repeat measurements, (2) a bump about 1 ft long and less than 0.1 in high that appeared 151 ft from the start of the section, (3) a dip about 2.5 ft long and 0.1 in deep that appeared 416 ft from the start of the section.

In visits 08 and 09, additional roughness was found 40 to 65 ft, 210 to 245 ft, and 340 to 350 ft from the start of the section. These areas included several shallow bumps that were about 0.05 in high. The shape and placement of the bumps was often poorly correlated among repeat measurements. In visit 10, the rough areas had expanded to cover more than half of the section. However, the visits afterward only included this type of roughness 100 to 150 ft, 330 to 360 ft and 400 to 460 ft from the start of the section.

Roughness Profiles: On the left side, the roughness profiles were fairly consistent over the monitoring period. The roughness was also distributed evenly throughout the section.

On the right side, the roughness was evenly distributed along the section in visits 01 through 07, with the exception of concentrated roughness at the dip 416 ft from the section start. In visits 08 and 09, localized roughness also appeared 64, 126, 225 (visit 08 only) and 350 ft from the start of the section.

Visit 10 was much rougher than previous visits, and the roughness profiles were very erratic and poorly repeated. In visits 11 through 13, extreme localized roughness was found wherever the profiles included the patches of bumps and dips described above.

Distress Surveys and Maintenance History: Distress measurements did not record anything in the locations of the rough short wavelength features noted for the right side in visits 01 through 07. In visits 08 through 10, the rough areas with shallow bumps within the profile all occurred where longitudinal cracks were recorded. Further, photographs of the surface in March 2002 and April 2003 show that (roughly) the areas of elevated roughness appear where longitudinal cracks were sealed. Note that crack sealing was performed in May 2001 (before visit 08) and April 2002 (between visits 09 and 10). The additional locations that were sealed in April 2002 explain the expansion of the rough areas between visits 09 and 10. Distress surveys from April 2003 and later record longitudinal cracking and raveling over the majority of the section on the right side.

Section 0118

Roughness: The IRI of the left side held steady in the range from 34 to 38 in/mi in visits 01 through 09, then increased from 52 to 57 in/mi in visits 10 through 13. The IRI of the right side changed erratically between 64 to 78 in/mi, with the exception of values over 100 in/mi in visits 08 and 09. The HRI was 19 to 25 percent lower than the MRI in the first nine visits, then 12 to 15 percent lower in visits 10 through 13.

PSD Plots: The spectral content of the left side was very consistent in visits 01 through 09. In visits 10 through 13, the content was higher over much of the range relevant to the IRI. On the right side, the spectral content in visits 01, 02, 03, 06, and 10 through 13 was similar to white noise slope over the valid range of the profilers. In visits 04, 05, and 07 the content was higher for wavelengths below 2 ft. In visits 08 and 09, content was significantly higher than in all other visits for wavelengths below 10 ft.

Filtered Profiles: Inspection of profile plots in the long, medium, and short wavelength ranges helped locate features of interest, but they were characterized best using a simple anti-smoothing filter with a base length of 50 ft.

Left Side: The profiles were very consistent throughout visits 01 through 09. Over the first 300 ft of the visit 10 profile measurements, features often appeared in the same locations and with similar severity as in previous visits, but different in shape. The last third of the section included two new features that were very rough in visits 10 through 13. First, the profile was elevated an average of 0.15 in above the surrounding pavement from 333 to 341 ft into the section, including a rise of 0.3 in over 3 ft at the leading edge. Second, the profile was elevated 0.15 in above the surrounding pavement from 402 to 420 ft into the section.

Right Side: Filtered profiles in the medium and long wavelength ranges were consistent in visits 01 through 09, and somewhat consistent through visit 10. In visit 06, narrow dips appeared in two of the repeat measurements from 407 to 410 ft from the start of the section. Profiles of visit 07 included a large number of narrow dips that were typically 0.1 to 0.2 in deep, and up to 0.4 in deep, from 212 to 213 ft, 223 to 226 ft, 240 to 249 ft, 265 ft, 277 to 279 ft, 399.5 ft, 403 to 407 ft, 422 ft, 429 ft, and 442 ft from the start of the section. These dips often appeared in more than one, but not all, repeats. In visit 08, dense areas of narrow dips 0.2 to 0.4 in deep appeared that were not very well correlated between repeats from 170 to 175 ft, 208 to 262 ft, 273 to 278 ft, 405 to 406 ft, and 414 to 442 ft from the start of the section. The same type of dips appeared in visit 09. The most severe dips appeared 97 to 106 ft, 170 to 175 ft, 206 to 264 ft, and 399 to 410 ft from the start of the section. Very few dips appeared in the profiles from visits 10 through 13. Visits 10 through 13 included some narrow bumps up to 0.2 in high between 400 and 415 ft from the start of the section.

Roughness Profiles: The left side profiles were roughest near the two elevated areas described above. The localized roughness caused by these two features accounts for all of the increase in roughness between visits 09 and 10.

The right side roughness profiles were not very consistent between visits, or among repeat measurements within a given visit. Over visits 01 through 07, minor localized roughness could be found at the locations of the dips listed above, but no area stood out as much rougher than the rest of the section. Visit 08 included a high level of localized roughness, particularly 210 to 270 ft from the start of the section. This was also the case in visit 09, with the addition of extreme localized roughness 174 ft from the start of the section in three of the five repeat measurements. The roughness profiles in visits 10 through 13 were not at all similar to those of previous visits, including a major reduction in overall roughness. The roughness profiles from visits 10 through 13 were also much more consistent among the repeat measurements.

Distress Surveys and Maintenance History: The distress survey from November 2005 notes that the slurry seal placed in May 2005 was stopped and restarted between 330 and 340 ft from the start of the section. This bump was there in visits 10 through 13.

The elevated roughness on the right side of the section in visits 08 and 09 was caused by wide longitudinal cracks that were not measured very consistently between repeat measurements. Note that May 2001 (between visits 07 and 08) is the earliest distress survey where a significant amount of longitudinal cracking was recorded. The maintenance record also shows that the cracks were sealed in May 2001.

The change in short and medium wavelength profile plots between visits 09 and 10 is attributed to the placement of a slurry seal coat over the entire section.

Section 0119

Roughness: The IRI of the left side increased from 39 to 56 in/mi over the monitoring period. The IRI of the right side ranged erratically 65 to 131 in/mi, although the highest values occurred in the last two visits. The HRI was 18 to 21 percent lower than the MRI.

PSD Plots: On the left side, the spectral content is consistent with time, with the exception of growth in content for wavelengths below 5 ft in the last four visits. On the right side, PSD plots were not consistent among repeat visits 04 through 07, 09, and 11. Spectral content development for wavelengths shorter than 20 ft did not follow a consistent pattern with time.

Filtered Profiles: On the left side, the profiles were very consistent in the long and medium wavelength range throughout the monitoring history. No significant short wavelength features were found in visits 01 through 09. In visits 10 through 13, a high level of chatter occurred in the form of hit or miss bumps and dips (i.e., bumps and dips that are found only in some repeats, but have the same shape when they are found).

On the right side, the profiles were not consistent with time in the medium and short wavelength range, nor were they consistent among repeats within the same visit in many areas. Profiles from visit 04 included short wavelength chatter throughout the section that was not present in visit 03. In addition, a dense area of narrow dips appeared from 430 to 480 ft from the start of the section. These dips were also detected in visit 05 in some of the repeat measurements, and included dips up to 0.3 in deep. In visits 06, 07, and 09, dense areas of narrow dips appeared from 325 to 375 ft and 480 ft to beyond 500 ft from the start of the section in most of the repeat measurements. In visits 09 and 10, short wavelength roughness was also found that was not well correlated among repeat measurements, but much of the content had transitioned from patches of narrow dips to isolated narrow bumps up to 0.15 in high. In visits 11 through 13, profiles from most of the last two thirds of the section were dominated by narrow bumps and dips that were poorly correlated between repeat measurements.

Roughness Profiles: The roughness profiles on the left side were consistent over the first 10 visits, with the exception of two areas of localized roughness that only appeared in visit 10. These areas were located at approximately 409 ft from the start of the section and between 490 and 500 feet from the start of the section. Although they were not consistent in severity among the five repeat measurements, the roughness at these locations accounts for most of the 5 in/mi increase in roughness from visit 09 to visit 10. The increase in roughness between visits 12 and 13 was caused by localized roughness about 284 and 344 ft from the start of the section, even though it was only detected in some of the repeat measurements.

The roughness profile on the right side was not very consistent with time over the last 200 ft of the section, and was often not consistent among repeat measurements from the same visit. An area of localized roughness occurred in visit 04 from 460 ft to 480 ft from the start of the section that was much more severe than others for that visit in three of the repeat measurements. In those three repeats, that area accounted for up to 20 in/mi of additional roughness over the others. This was also detected in only one of the measurements for visit 05. (Note that the "hit or miss" nature of the roughness in this location explains the high standard deviation for the IRI listed in Appendix A.) The roughness profile in visit 04 was similar to that of visit 03 over the first 350 ft of the section. Visit 07 contained localized roughness from 355 to 370 ft from the start of the section, and in the last 10 ft of the section, but the roughness was not well correlated among the repeat measurements. Visits 08 and 09 were very rough over the last 200 ft of the section, but not much rougher than visit 03 over the first 300 ft. Visit 10, on the other hand, was very similar to visit 03. In visits 10 through 13, the roughness profiles included significant localized content and were rarely well repeated, except over the first 100 ft of the section.

Distress Surveys and Maintenance History: The dense patches of narrow dips found in the right side profiles in visits 04 through 08 correspond to locations where longitudinal cracking was noted. However, several areas of longitudinal cracking were noted in distress surveys that did not cause additional roughness within the profile. (Note that by visit 08, longitudinal cracking had extended over most of the section on the right side.) The lack of consistency in the measurement of profile on the right side of this section is a result of the "hit or miss" nature of profiling a section with longitudinal cracking in the profiler's path. Photos from the distress survey in May 2001 show that the longitudinal cracking wanders from a location that is farther from the center of the lane than the likely path of the profiler over the first half of the section to a location closer to the edge of the lane, where the profiler sensors are likely to pass, in the second half of the section. The upward nature of the chatter in the profiles from visits 09 through 13 was a result of crack sealing that was performed just before visit 09.

Section 0120

Roughness: The IRI of the left side increased steadily from 53 to 69 in/mi over the monitoring period. The IRI of the right side followed an increasing trend from 64 to 79 in/mi over visits 01 through 09. In visits 10 through 13, the IRI had decreased to 64-66 in/mi. The HRI was 14 to 17 percent lower than the MRI in visits 01 through 09, and was 7 to 10 percent lower in visits 10 through 13.

PSD Plots: On the left side, the spectral content was consistent over the monitoring period for the range of wavelengths above about 5 ft, but increased modestly with time for wavelengths below 5 ft. On the right side, the spectral content in visits 01 and 02 was consistent, but the content for wavelengths below 10 ft had increased by visit 03. The spectral content of visits 03 through 09 was consistent, except for elevated content for wavelengths below 2 ft in visits 04 and 05. Compared to visit 09, the content in visits 10 through 13 was slightly reduced over the entire range from 2 ft to 50 ft.

Filtered Profiles: Very few rough features stood out. An exception was a narrow (< 1 ft long) bump 136 ft from the start of the section that appeared on the left side in several of the visits, but rarely in all five repeats within a visit. The filtered profiles were consistent over more of the section for the first nine visits. In visit 10, the short wavelength profile plots had changed significantly from those of visit 09. The medium wavelength plots showed bumps and dips in most of the same locations, but the shape or severity was often modified somewhat. Medium and short wavelength content was very consistent during visits 10 through 13.

Roughness Profiles: The roughness profiles included an area of concentrated roughness on both sides of the lane at the start of the section, where a dip nearly 0.5 in deep extended from 10 ft ahead of the start of the section to 40 ft after the start of the section.

A slope break appeared on the left side 380 ft from the start of the section. In this location, the profile transitioned from an aggressive downward trend to a flat area. Note that the severity of this area increased with time, as a bump at the start of the downward slope increased in height. The change in roughness at this area accounted for about half of the change in roughness of the entire section over visits 01 through 09. This was not nearly as severe on the right side.

On the right side, an area of localized roughness was detected on the trailing end of a long bump. After the roughness at the start of the section, this was the most severe localized roughness on the right side.

Distress Surveys and Maintenance History: Very little roughness was found on this section that could be linked to distress. The slope break 380 ft from the start of the section was not caused by distress, but a transverse crack was recorded there (after that area had become rough) in April 2002 and later. A slurry seal was applied to this section in May 2002. This affected the profile of the section much less than other sections.

Section 0121

Roughness: The IRI of the left side ranged from 35 to 39 in/mi in visits 01 through 09, then held steady between 49 and 51 in/mi in visits 10 through 13. The IRI of the right side increased somewhat erratically from 60 to 68 in/mi. The HRI was 21 to 24 percent lower than the MRI in visits 01 through 09, and was 13 to 17 percent lower in visits 10 through 13. Whatever caused the aggressive change in roughness between visit 09 and visit 10 on the left side also improved the relationship between the left and right profile.

PSD Plots: On the left side, the spectral content was consistent from visits 01 through 09, and included some roughness concentrated at a wavelength of about 32 ft. Visits 10 through 13 were consistent with each other, rougher than the earlier visits for wavelengths less than 20 ft, and included some roughness concentrated a wavelength of about 7 ft. The spectral content of the right side was very consistent over visits 01 through 08, with the exception that visits 04 and 05 were a little rougher for wavelengths below 3 ft. In visit 09 the roughness in the range below 10 ft had increased significantly compared to previous visits, but this value reduced somewhat in visit 10. The additional roughness in visits 11 through 13 compared to visit 10 appeared in the range of wavelength shorter than 5 ft.

Long Wavelengths: The long wavelength profile plots were very consistent with time.

Medium Wavelengths: On both sides, the medium wavelength profile plots were very consistent over the first nine visits. In visits 10 through 13, the medium wavelength profile plots were somewhat different than in previous visits, in that the shape and severity of bumps and dips had changed.

Short Wavelengths: On the left side, the profiles were very consistent over visits 01 through 09. In visits 10 through 13, the profiles contained several bumps up to 2 ft long and between 0.04 and 0.15 in high. These bumps were found 22.6, 40.5, 65.1, 75.6, 88.4, 116.5, 153.4, 230.7, 236.2, 244.1, 268.0, 287.3, 295.4, 414.9, and 478.9 ft from the start of the section.

On the right side, the profiles were very consistent over visits 01 through 08. In visit 09, the profiles contained several narrow (0.5-1.0 ft long) dips ranging from 0.1 to 0.5 in deep. These dips were found 45.5, 72.5, 100 (0.5 in deep), 199, 273, 351, and 479.5 ft from the start of the section. In visits 11 through 13, several narrow bumps appeared throughout the section. The most severe of them appeared 179.1, 351.8, 433.1, 434.2, 447.3 and 456.7 ft from the start of the section.

On both sides, the short wavelength profile plots in visits 10 through 13 were not very similar to those of previous visits, even in locations where the bumps and dips listed above did not appear.

<u>Roughness Profiles</u>: The left side profiles were roughest in the first 120 ft of the section, and the distribution of roughness was similar over the first nine visits. The roughness profiles from visits 10 through 13 showed localized roughness in the locations of most of the bumps listed above.

A roughness profile of the right side revealed a high level of roughness about 350 ft from the start of the section. Unfiltered plots showed that this was caused by a bump in the right side profile about 0.25 in high ranging from 330 to 350 ft from the start of the section. The dips in visit 09 only added modestly to the roughness of the section, with one exception. The dip 100 ft from the start of the section added up to 3 in/mi to the overall roughness of the section, depending on which repeat measurement was inspected. (In one of the measurements, the dip was not even detected.)

<u>Distress Surveys and Maintenance History</u>: Distress measurements show transverse cracks in the location of 13 of the 15 bumps listed for the left side profiles of visit 10, and all but one of the bumps listed for the right in visits 11 through 13. Note that most of the transverse cracks were present in visit 09, but the corresponding bumps did not appear in the profiles. Distress measurements showed transverse cracks in only three of the seven dips listed for the right side profiles of visit 09. However, no distress was noted 100 ft from the start of the section, where the dip that caused the most roughness was found.

The change in short and medium wavelength profile plots between visits 09 and 10 is attributed to the placement of a slurry seal coat over the entire section in May 2002.

Section 0122

Roughness: The IRI of the left side increased from 41 to 48 in/mi over the first nine visits, with an outlying value of 58 in/mi in visit 06. In visits 10 through 13, the IRI held between 64 and 66 in/mi. The IRI of the right side ranged from 78 to 87 in/mi over visits 01 through 09 with an increasing trend, then decreased to 69 in/mi in visit 10 and changed erratically afterward. The HRI was 16 to 20 percent lower than the MRI in the first nine visits, then 11 to 13 percent lower afterward.

PSD Plots: On the left side, the profiles included some isolated content at a wavelength of about 40 ft in all visits. Visit 06 included extra roughness at all wavelengths below 20 ft compared to the previous and subsequent visits. Visits 10 through 13 included higher content in the wavelength range above 4 ft when compared to the earlier visits.

On the right side, the spectral content in visits 06 and 10 is much higher than in other visits for wavelengths shorter than 20 ft. The rest of the visits have consistent content for wavelengths shorter than 10 ft, and follow a distinct trend of getting rougher with time for wavelengths shorter than 10 ft. In particular, visit 08 is rougher than visit 07 for wavelengths shorter than 5 ft, and visit 08 is rougher than visit 09 for wavelengths shorter than 10 ft.

Filtered Profiles: The long and medium wavelength profile plots were very consistent in visits 01 through 09 and in visits 11 through 13. However, the short and medium wavelength profile plots changed considerably between visits 09 and 10.

Left Side: In visit 06, a dip 1 ft long and 1.3 in deep appeared 391 ft from the start of the section. It did not appear in visit 07, but it did in visit 08 (0.25 in deep) and 09 (0.45 in deep). After visit 09, it did not appear again. Short wavelength profiles from visits 10 through 13 included a bump more than 0.25 in high that ranged from 174 to 176 ft from the start of the section.

Right Side: Three short wavelength features stood out over the background roughness in visits 10 through 13. First, an area 174 to 176 ft from the start of the section was elevated about 0.2 in from the surrounding pavement. This included an abrupt upward step at the start and an abrupt downward step at the end. Second, a dip appeared 31 ft from the start of the section that was about 2 ft long and up to 01.5 in deep. Third, a bump appeared 391 ft from the start of the section.

Roughness Profiles: On the left side, the roughness profiles of visits 01 through 09 were consistent over most of the section. The exception was at the dip 309 ft from the start of the section. This was roughest in visit 06, and added 11.5 to 14 in/mi to the overall roughness of the section. (This is most of the difference between the roughness of visit 06 and visits 05 and 07.) In visit 09, the dip was also somewhat rough, and added about 3 in/mi to the roughness of the entire section. Another minor area of localized roughness also appeared 418 ft from the start of the section. (This was caused by a dip 20 ft long and about 0.2 in deep. This is not the type of feature that is likely to appear in a distress survey or a photograph.) The roughest feature on the left side in visits 10 through 13 was the bump 175 ft from the start of the section. This caused a peak in the roughness profile of about 180 in/mi, and added about 7 in/mi to the overall roughness of the section.

On the right side, the roughness profile was fairly consistent over the first nine visits. The roughness was evenly distributed across the section, and changes in roughness with time were not isolated to a given location. The roughness profiles of visits 10 through 13 were not similar to those of the earlier visits in most locations.

<u>Distress Surveys and Maintenance History</u>: The dip on the left side 309 ft from the start of the section is in a location where raveling and a small pothole was listed in the February 1999 distress survey. The distressed area appeared to get larger in later surveys, but the pothole was patched in February 2001. The rough features that appeared 174 to 176 ft from the start of the section in visits 10 through 13 were at a location where the placement of a slurry seal stopped then restarted. This seam only caused significant roughness on the left side. The slurry seal also significantly altered the short and medium wavelength content in the profile.

Section 0123

<u>Roughness</u>: The IRI of the left side ranged from 38 to 42 in/mi over the first 12 visits, then increased to 47 in/mi in visit 13. The IRI of the right side fluctuated erratically with time, and covered a range from 49 to 68 in/mi over the first 10 visits, then increased to 134 in/mi by visit 13. The HRI was 14 to 18 percent lower than the MRI.

<u>PSD Plots</u>: On the left side, the spectral content was consistent in the range from 2 to 50 ft over visits 01 through 09. However, while the PSD plot of visit 10 profiles exhibited a similar roughness level in each broad wavelength range, the details of the plots were not as similar to the other nine visits as they were to each other. In visits 11 through 13, the content below 10 ft increased steadily. Slightly elevated content appeared near a wavelength of 13 to 14 ft in all PSD plots from the left side.

On the right side, the spectral content was consistent over the first 10 visits in the wavelength range from 2 to 50 ft, so long as the PSD plot with the least roughness was selected for each visit. The PSD plots for visits 07 and 08 were not very consistent among the repeat measurements. In visits 10 through 13, the content below 20 ft grew aggressively.

Filtered Profiles: On the left side, the short wavelength content of the profiles in visits 10 through 13 was somewhat different in shape than the other visits, but not different in roughness level. Otherwise, the left side profiles were quite consistent over the monitoring period in the long, medium, and short wavelength range. One exception was the appearance of a bump about 2 ft long and up to 0.15 in high that was 327 ft from the start of the section in visits 11 through 13.

Inspection of filtered plots of the right side profiles revealed several unusual features:

> A dip about 8 ft long appears 320 ft from the section start. It exists in all visits, but its depth varies up to 0.2 in.
>
> Visit 03 is rougher than visits 01, 02, and 04 over the range from 270 ft to 350 ft into the section.
>
> A dip exists in visit 03 that is 280 ft from the start of the section and did not appear in any of the other visits.
>
> Visit 07 includes an area from 200 to 280 ft from the start of the section that is not very consistent in its medium and short wavelength content. The profiles are very consistent over the rest of the section.
>
> Repeat 9 from visit 08 is much rougher than the others in the area from 200 to 280 ft from the start of the section. Repeats 5, 6, and 7 of visit 08 are consistent with each other and with the profiles in visit 07.
>
> Visit 10 profiles included narrow bumps about 0.1 in high and 62 and 182 ft from the start of the section.
>
> Visits 11 through 13 profiles all included several large areas of spurious bumps and dips. These appeared throughout the entire section, but rarely appeared in all five repeats within a visit, or with the same shape in any two repeats.

Roughness Profiles: The roughness of the left side profiles was evenly distributed across the section, and very consistent among the first 10 visits. In visits 11 through 13, the roughness 300 to 350 ft from the start was slightly higher than that of the rest of the section.

The roughest area of the section on the right side was from 210 to 320 ft from the start, but often by only a small margin. The exception was that in visits 03 and 06 though 09, a severe area of localized roughness appeared near 320 ft from the start. The roughness at this location was not measured very consistently, and short interval roughness profiles show that it contributed up to 6 in/mi to the overall roughness. Much of the erratic trend in roughness over time on the right side of this section can be attributed to presence or absence of the dip at this location between visits. Less severe localized roughness also appeared 64 and 185 ft from the start of the section in some of the repeat measurements of visit 10 . The short interval roughness report also showed that the distribution of roughness in visit 10 was not very similar to that of the previous visits.

Roughness profiles in visits 11 through 13 became progressively dominated by localized roughness that was not well correlated among repeat measurements.

Distress Surveys and Maintenance History: Distress surveys showed longitudinal cracking on the right side, which was first recorded before visit 05, and covered much of the length of the section by visit 07. The distress record does not include anything to explain the dip that appears 320 ft from the start of the section, but this may be caused by roughness that is not associated with surface distress. Distress measurements taken after visit 10 show a severe area of cracking to explain the localized roughness that appeared 64 ft from the start of the section, but nothing unusual 185 ft from the start of the section.

Crack sealing was done between visits 07 and 08, and between visits 09 and 10. This may explain the lack of a relationship between the roughness profiles in visits 09 and 10.

Section 0124

Roughness: The IRI of the left side ranged from 31 to 34 in/mi in visits 01 through 09 and 11, and ranged from 42 to 46 in/mi in visits 10, 12, and 13. The IRI of the right side increased slowly at first, then at an increasing rate from 38 in/mi in visit 01 to 148 in/mi in visit 13. The HRI was 17 to 25 percent lower than the MRI.

PSD Plots: On both sides, the roughness was distributed relatively evenly across the measured wavelength range. On the left side, the spectral content was very consistent from visits 01 through 09. In visits 10 through 13, the content for wavelengths shorter than 10 ft increased. On the right side, the content was consistent throughout the first nine visits for wavelengths above 10 ft. Content for wavelengths shorter than 10 ft grew gradually over visits 07 through 10, and aggressively afterward.

Long Wavelengths: The long wavelength content was very consistent with time.

Medium Wavelengths: On the left side, the profile was very consistent in visits 01 through 09, but became slightly rougher afterward. On the right side, the medium wavelength content increased steadily after visit 07. The profiles in visit 10 were somewhat different in shape to visit 09 on both sides. In visits 11 through 13 the profiles included much more roughness in the medium wavelength range and repeat measurements did not agree well.

Short Wavelengths: On the left side, the short wavelength profiles were consistent in their roughness level for visits 01 through 09. In visits 10 through 13, the overall content level was higher, and the last 50 ft of the section included some narrow bumps about 1 ft long and more than 0.125 in high. Profiles of the right side did not include any excessive short wavelength content or localized roughness in visits 01 through 06. In visit 07, an area with a high density of dips appeared from 272 to 286 ft from the start of the section. In visits 08 through 10 several areas, covering about half of the section, included closely spaced bumps up to 0.125 in high and 1-3 ft long. In visits 11 through 13, the same type of content covered most of the section. These bumps often appeared in the same location in multiple repeats within the same visit, but did not necessarily appear in the same place in more than one visit.

Roughness Profiles: On the left side, the roughness profile was very consistent through visit 09. In visit 10, an area of localized roughness appeared 70 ft from the start of the section that accounted for up to 3 in/mi of roughness beyond that of visit 09. The last 50 ft of the section were also significantly rougher in visits 10 through 13 than in previous visits. On the right side, significant localized roughness appeared about 410 ft from the start of the section in visits 06 and 07, but not in later visits. In visits 08 and 09, short interval (10 ft) roughness profiles showed that localized roughness existed throughout the section, but the location and severity were not consistent among repeat measurements. Roughness profiles in visits 11 through 13 became progressively dominated by localized roughness that was not well correlated among repeat measurements.

Distress Surveys and Maintenance History: The rough area (~410 ft) found in visits 06 and 07 corresponds to an area of significant cracking recorded in a distress survey from January 2000. This did not register in later visits because of crack sealing witch was performed in May 2001. The inconsistent measurement of localized roughness in visits 08 and 09 is attributed to sealed longitudinal cracks, which may not have been detected in the same location in each measurement because of the lateral placement of the profiler. The localized roughness found 245 ft from the start of the section in visit 10 did not correspond to anything noted in the distress survey that followed. It is not clear why the short interval roughness profile was so much more consistent in visit 10 than in visits 08 and 09. It is suspected that this was merely a product of more consistent lateral tracking of the profiler. The rough area in the last 50 ft of the section on the left side for the later visits was caused by longitudinal cracking and raveling. The rough, uncorrelated content on the right side in visits 11 through 13 was caused by sealed longitudinal cracking.

Section 0160

Roughness: The IRI of the left side ranged from 88 to 116 in/mi and the IRI of the right side ranged from 95 to 122 in/mi. The roughness did not follow a systematic trend with time. The HRI was 9 to 16 percent lower than the MRI. This is a lesser difference than most of the other sections, but a higher difference than on many Portland cement concrete pavements.

PSD Plots: The spectral content of profile slope was relatively uniform across the measured range. The PSD plots for all visits were similar, with the exception of some content that was concentrated at wavelengths near 15 ft. The periodic content was highest in profiles from visit 06, and elevated in visit 07. On the left side, some periodic content also existed at a wavelength of 8.5 ft.

Long Wavelengths: The long wavelength profile plots were less consistent with time than on other sections.

Medium Wavelengths: The changes in roughness with time were the most obvious in the medium wavelength profile plots. The plots show that significant roughness was caused by upward curl of 15-ft long slabs, and that the curl was most severe in visits 06 and 07.

Short Wavelengths: On the left side, the short wavelength content within the profiles was much smoother in the last 100 ft of the section than in the first 400 ft. On the right side, the profiles in repeats 3, 4, and 5 of visit 01 included several very large narrow spikes. The correct IRI for visit 01 is closer to the average of the other two repeats, which is roughly 98 in/mi.

Roughness Profiles: The last 100 ft of the section were half as rough as the first 400 ft. The roughness distribution of the left side was consistent over visits 01 through 05 and over visits 06 through 13. In visits 01 through 05, a short interval (10 ft) roughness profile showed several areas of localized roughness on the left side. The most severe appeared 43, 121-125, 221, and 306 ft from the start of the section. In visits 06 through 13, severe localized roughness appeared 46, 125, 221, and 389 ft from the start of the section. The roughness distribution of the right side was fairly consistent over visits 01 through 13. On the right side, the most severe localized roughness appeared 391 ft from the start of the section.

Distress Surveys and Maintenance History: The localized roughness cited above corresponds to profile features other than cracking or high roughness at joints. As such, they do not correspond directly to items recorded in the distress surveys. The photos provided with the distress surveys show that roughly the last 100 ft of the section were diamond ground.

Section 0161

Roughness: The IRI of the left side ranged from 69 to 77 in/mi over the 13 visits except for a value of 62 in/mi in visit 10. The IRI of the right side fluctuated between 71 and 87 in/mi over the 13 visits except for a value of 100 in/mi in visit 09. The MRI was 16 to 18 percent higher than the HRI in visit 01 through 09, but only 7 to 9 percent higher in visits 10 through 13. The transition corresponds to the application of a slurry seal coat in May 2002.

PSD Plots: On the left side, the PSD plots were very consistent in over all visits except 10 in the wavelength range from 2 to 100 ft. In visit 10, the spectral content was reduced somewhat from 2.5 to 25 ft. On the right side, the PSD plots were fairly consistent from visit 01 to visit 08, with the exception of elevated content in visit 04 and 05 for wavelengths below 2 ft. The PSD plot of the right side was significantly higher in visit 09 than in visit 08 at wavelengths below 100 ft. Over the range from 1 to 100 ft, the PSD plots of visits 10 through 13 were higher than in visit 08, but lower than visit 09.

Left Side: With the exception of the device effect, profiles filtered to show long wavelength content were consistent with time. Profiles filtered to show medium and short wavelength content were also consistent in visits 01 through 09. In visit 10, the medium wavelength profile plots showed features in the same location in visits 09 and 10, but the features were often not as rough in visit 10. The area from 90 to 150 ft from the start of the section included a higher level of short wavelength roughness than the rest of the section in visits 01 through 09. In visit 10, this area had become smoother. However, narrow dips began to appear in other locations that grew in number and severity with time. By visit 13, narrow dips from 0.1 to 0.4 in deep appeared 23.5, 119, 158.5, 204, 232.5, and 353.2 ft from the start of the section.

Right Side: Filtered profiles in the long, medium, and short wavelength range were somewhat consistent in visits 01 through 08. In visit 09, an abrupt downward step appears 485 ft from the start of the section; this is about 1 in deep. In visits 10 through 13, a less severe (0.75 in) downward step appears in the same location. This corresponds to the location where a full-depth patch was placed. The date of the patch was listed as August 2001, although no evidence of it is found until after visit 08. Over the rest of the section, profiles filtered to show short wavelength content are not as rough starting in visit 10.

Both Sides: The decrease in short wavelength roughness between visit 09 and 10 is attributed to the placement of a slurry seal coat in May 2002.

Roughness Profiles: The left side roughness profiles showed that the area from 90 to 150 ft from the start of the section was rougher than the rest in visits 01 through 09. This area was no rougher than the rest of the section in visit 10, but grew in roughness afterward. The narrow dips listed above for the left side profiles did not stand out as severe, localized roughness in visits 11 through 13, but they did increase the roughness of the overall section somewhat.

The right side roughness profiles were consistent from visits 01 through 08, and the roughness was evenly distributed along the section. In visit 09, an extreme area of localized roughness appeared in the location of the downward step that contributed 21 to 23 in/mi to the overall roughness of the section. Over the rest of the section, the roughness distribution of visit 09 was similar to that of visit 08. In visits 10 through 13, the first 480 ft of the section were smoother than in previous visits. However, the downward step 485 ft from the start contributed 15 to 18 in/mi to the overall roughness of the section.

Distress Surveys and Maintenance History: Very little cracking was noted in the distress surveys for the left side of this section until April 2002. In April 2002 transverse cracking was recorded in all four locations where narrow spikes were evident in the profiles. These appeared 158.5, 204, 232.5, and 353.2 ft from the start of the section. Transverse cracks were also recorded 23.5 and 119 ft from the start of the section in later distress surveys.

No distress was listed in May 2001 in the last 15 ft of the section. However, the distress survey in April 2002 shows a patched area that extends over the last 13 ft of the section. This patch must have been present before visit 09. The reduction in medium and short wavelength roughness between visit 09 and visit 10 may have been caused by the application of a slurry seal coat in May 2002.

Section 0162

Roughness: The IRI of the left side ranged from 66 to 75 in/mi, and was lowest in visit 10. The IRI of the right side ranged from 78 to 92 in/mi, and was lowest in visit 12. The MRI was 16 to 18 percent higher than the HRI in visit 01 through 09, but only 9 to 11 percent higher in visits 10 through 13. The transition corresponds to the application of a slurry seal coat in May 2002.

PSD Plots: On the left side, the PSD plots were very consistent in visits 01 through 09, and in visits 11 through 13. In visit 10, the content was lower in the wavelength range from 2 to 10 ft than in other visits. Significant content was concentrated around wavelengths from 26 to 29 ft. in all visits. On the right side, the spectral distribution was consistent for wavelengths from 2 to 50 ft in visits 03 through 13. Visits 04 and 05 included elevated content compared to other visits for wavelengths shorter than 2 ft.

Filtered Profiles: With the exception of the device effect, profiles filtered to show long wavelength content were consistent with time. Profiles filtered to show medium and short wavelength content were also consistent in visits 01 through 09 and in visits 10 through 13. Between visit 09 and 10, the medium and short wavelength profile plots showed roughness in the same location and with similar severity as in previous visits, but with slightly different shape. On the right side, some areas showed a visible reduction in short wavelength roughness from visit 09 to visit 10.

A bump appears in both the left and right profiles in visits 11 through 13 over the last 10 ft of the section. It was up to 0.4 in high, and it was followed by a slight drop-off beyond the end of the section.

Roughness Profiles: The left side roughness profiles showed no concentrated roughness and were very consistent over the first nine visits. The right side roughness profiles were also very consistent with time in the first nine visits, but the roughness was not as consistent across the section. A short interval (10 ft) roughness profile demonstrated that the section was rougher over much of the section in visit 09 than in visit 10. In visits 10 through 13, a peak in the roughness profile appeared on the left side (170-240 in/mi) and the right side (235-305 in/mi) at the end of the section.

Distress Surveys and Maintenance History: Very little cracking was noted in the distress surveys for this section. A slurry seal coat was applied to this section in May 2002. This may explain the reduction in short wavelength roughness between visit 09 and visit 10. Photos from April 2005 and March 2006 show a seam where the seal coat terminates just beyond the end of the section. This is probably the cause of the roughness at the end of the section noted above for visits 10 through 13.

Section 0163

Roughness: The IRI of the left side ranged from 61 to 83 in/mi over the monitoring period, but did not show a consistent trend with time. The IRI of the right side increased aggressively from 65 to 126 in/mi over visits 01 through 08, held steady over the next two visits, then fluctuated significantly afterward. The MRI was 11 to 15 percent higher than the MRI in visits 01 through 08. Afterward, the gap between MRI and HRI grew steadily to 21 percent.

PSD Plots: On the left side, the spectral distribution was consistent in visits 01 through 09. In visit 10, the content for wavelengths from about 5 to 50 ft decreased. However, the content for wavelengths below 5 ft increased progressively after visit 09. Much of the content for wavelengths below 50 ft approximated white noise slope.

On the right side, the spectral distribution was consistent in visits 01 through 03. Visits 04 and 05 exhibited elevated content for wavelengths below 2 ft. Visits 06 though 09 exhibited elevated content for wavelengths from 2 to 5 ft, but reduced content for wavelengths below 2 ft. Visits 10 and 12 included the highest content for wavelengths under 5 ft. Visits 11 and 13 included slightly lower content than visits 10 and 12 for all wavelengths lower than 20 ft.

Filtered Profiles: Inspection of profile plots in the long, medium, and short wavelength ranges helped locate features of interest, but they were characterized best using a simple anti-smoothing filter with a baselength of 50 ft.

Left Side: With the exception of the device effect, profiles filtered to show long wavelength content were consistent with time. Profiles filtered to show medium wavelength content were consistent in visits 03 through 09. In all visits, an area with five narrow dips appeared from 450 to 475 ft from the start of the section. These dips grew in severity with time. The most severe dip was at 475 ft and grew in depth gradually to a maximum depth of 0.65 in. This appears at the lowest point within a very long (> 100 ft), deep dip at the end of the section. A dip 451 ft from the start of the section also grew in severity with time to 0.3 in deep. Both dips were about 2 ft long. After visit 10, a dip up to 0.4 in deep appeared about 10 ft from the start of the section, but it was not visible in the majority of the repeat measurements.

Right Side: With the exception of the device effect, plots filtered to show long wavelength content were consistent with time. However, the growth in roughness over the first 10 visits was obvious in profiles filtered to show medium wavelength content.

Narrow dips (2-3 ft long) appeared throughout the section starting in visit 03, and usually grew in severity over time. The most severe dips (> 0.25 in deep) appeared 15, 225, 252, 273, 308, 472, and 475 ft from the start of the section. Less severe dips (0.10-0.25 in deep) appeared 40, 67, 111, 126, 171, 180, 191, 210, 218, 237, 265, 286, 297, 340, 388, 431, and 448 ft from the start of the section. Several narrow (> 0.5 ft long) bumps up to 0.15 in high also appeared throughout the profiles. The bumps and dips were usually very consistent in location, shape, and severity among the repeat measurements within each visit. Over visits 03 through 10, they generally progressed in severity with time. However, the most severe dips were significantly less severe in visits 11 and 13 than in visits 10 and 12.

Roughness Profiles: Severe localized roughness appeared on the left side over the last 70 ft of the section, with peak roughness levels of up to 350 in/mi by the later visits. Very short interval (10 ft) roughness profiles showed that the roughness near 475 ft from the start of the section increased significantly throughout the first 10 visits, and that the change in roughness at this location caused an increase in roughness of the entire section of about 7 in/mi.

On the right side, the last 50 ft was much rougher than the rest of the section, particularly in the first nine visits. Short interval (10 ft) roughness profiles show localized roughness in the locations of the most severe dips listed above. At these locations, the localized roughness usually first appears in visits 03 through 06, and grows in severity with time. Most of the decrease in roughness in visits 11 and 13 compared to 10 and 12 occurs between 210 and 360 ft from the start of the section, and is attributed to the reduced severity of the narrow dips.

Distress Surveys and Maintenance History: Transverse cracking near the five dips in the left side profiles noted above was first recorded between visits 06 and 07 (January 2000). A distress survey prior to visit 08 (May 2002) showed transverse cracks in the locations of all five dips. That distress survey also cited potholes in the left side of the lane near 450 and 475 ft from the start of the section. However, these potholes were patched in February 2001.

The May 2002 distress survey also listed transverse cracks in the location of all of the dips listed above for the right side profiles, with one exception. The longitudinal locations of the dips within the profiles matched the cracks in the survey best using a location that was about 3 ft from the lane edge. Note that several transverse cracks appeared in the distress survey with no corresponding dip in the profile.

Most of the narrow bumps found in the right side profiles in visits 10 through 13 correspond to locations where transverse cracking was recorded in April 2005. However, a bump does not appear at the location of every crack.

The long dip in the last 100 ft of the section appears clearly in Figure 45 below. This is certainly considered a rough feature by passing vehicles.

Figure 45. Section 0163 showing long dip in last 100 ft.

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