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PROFILE ANALYSIS OF THE LTPP SPS-9A SITE IN ARIZONA

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16. Abstract

This report characterizes the longitudinal profiles of eight pavement sections within the Arizona Specific Pavement Studies 1 project throughout their service life. This project was built and monitored as part of the Long-Term Pavement Performance Study. Road profile measurements were collected on this site about once per year since 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, as well as linking profile properties to each section's maintenance history and observations of surface distress.

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INTRODUCTION

This report provides the results of profile and roughness analyses for a Long-Term Pavement Performance (LTPP) Specific Pavement Studies 9A (SPS-9A) site in Arizona. SPS-9A sites were designed to compare Superpave mix performance with that of standard mix designs. (*1*) This report covers site 04B900.

The construction report provides details about the project, and key items are excerpted here. (*1*) The test pavement surfaces were constructed on westbound Interstate 10 near Phoenix, Arizona in March 1995. The site extends from Milepost 112.72 to 122.29. Three sections were constructed as part of the standard LTPP experiment. This SPS-9A site also included five supplemental test sections designed by the Arizona Department of Transportation. Table 1 summarizes the mix designs of the test sections. Note that section B962 is also General Pavement Studies Section 041007.

Table 1. Arizona SPS-9A Descriptions.

Section	Description
B901	Agency Standard PG76-10
B902	Superpave Level I PG76-10
B903	Superpave Level I AC-40
B959	SMA Polymer with ACFC
B960	SMA Polymer
B961	SMA Cellulose
B962	Superpave Level III
B964	ARAC

ARAC — Asphalt Rubber Asphalt Concrete
ACFC — Asphalt Concrete Friction Course
SMA — Stone Matrix Asphalt

This report seeks to characterize the surface roughness of these sections throughout their service life, and link the observations to records of pavement distress and its development. Road profile measurements were collected on this site about once per year since 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-9A site on eight dates, listed in Table 2. Raw profile data were available for all eight visits. In each visit, a minimum of five repeat profile measurements were made.

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 01 through 06 at a

0.98 in sample interval and in visits 07 and 08 at a sample interval of about 0.77 in. These data appeared in the database after the application of an 11.8-in moving average and decimation to a sample interval of 5.91 in. 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. (*2*)

Table 2. Profile Measurement Visits of the SPS-9A Site.

Visit	Date	Repeats by Section							
		B901	B902	B903	B959	B960	B961	B962	B964
01	29-Jan-1997	7	7	7	7	7	7	7	7
02	02-Feb-1997	—	—	—	—	—	—	9	9
03	05-Dec-1997	7	7	7	7	7	7	7	7
04	07-Dec-1998	5	7	5	5	5	5	7	7
05	10-Nov-1999	7	7	7	7	7	7	7	7
06	12-Nov-2001	7	9	7	9	7	9	7	9
07	09-Feb-2004	9	9	9	9	9	9	9	9
08	17-Dec-2004	9	9	9	9	9	9	9	9

In visit 01, all eight sections were covered together in each profile. Visit 02 only covered sections B962 and B964. Visit 03 covered B962 and B964 together in one set of passes, and all of the other sections together in another. Each section was measured individually in visits 04 through 08.

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 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. (*3*) 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 IRI filter was applied to the profiles, rather than using the un-filtered 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.

    The first repeat measurement was used for this purpose. All of the sections were 500 ft long.

2. Automatically synchronize the other eight repeats from visit 08 to the basis set.
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 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 were selected which 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. The details of this method are described elsewhere. (*3*) 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 un-filtered 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. (*3*)

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

Each comparison between profiles produced a single value that summarized their level of agreement. When nine repeat profile measurements were available, they produced a total of thirty-six correlation values. Any subgroup of five measurements could be summarized by averaging the relevant ten 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 3 through 10 list the selected repeats for each visit of each section, and the composite correlation level produced by them.

Table 3. Selected Repeats, Section B901.

Visit	Repeat Numbers					Composite Correlation
01	1	2	3	5	6	0.901
03	1	3	4	5	7	0.898
04	1	2	3	4	5	0.916
05	2	4	5	6	7	0.912
06	2	3	4	6	7	0.870
07	1	3	5	7	9	0.659
08	2	3	5	7	8	0.722

Table 4. Selected Repeats, Section B902.

Visit	Repeat Numbers					Composite Correlation
01	2	3	4	5	7	0.935
03	1	3	4	5	7	0.896
04	1	2	4	5	6	0.931
05	2	3	4	5	6	0.871
06	5	6	7	8	9	0.827
07	3	6	7	8	9	0.639
08	1	5	7	8	9	0.768

Table 5. Selected Repeats, Section B903.

Visit	Repeat Numbers					Composite Correlation
01	2	3	5	6	7	0.929
03	1	2	4	6	7	0.914
04	1	2	3	4	5	0.918
05	3	4	5	6	7	0.943
06	1	3	4	6	7	0.894
07	1	3	5	6	7	0.853
08	1	2	3	8	9	0.588

Table 6. Selected Repeats, Section B959.

Visit	Repeat Numbers					Composite Correlation
01	1	3	4	6	7	0.932
03	1	2	4	5	7	0.923
04	1	2	3	4	5	0.921
05	2	3	4	5	6	0.922
06	2	5	7	8	9	0.944
07	1	3	5	6	7	0.905
08	3	5	6	8	9	0.870

Table 7. Selected Repeats, Section B960.

Visit	Repeat Numbers					Composite Correlation
01	1	2	3	5	7	0.925
03	1	2	4	6	7	0.915
04	1	2	3	4	5	0.903
05	1	2	3	4	6	0.924
06	1	2	3	4	7	0.949
07	1	2	3	4	5	0.853
08	5	6	7	8	9	0.864

Table 8. Selected Repeats, Section B961.

Visit	Repeat Numbers					Composite Correlation
01	1	2	3	4	7	0.943
03	2	4	5	6	7	0.948
04	1	2	3	4	5	0.915
05	1	2	4	5	7	0.942
06	1	2	3	4	6	0.953
07	2	3	5	6	9	0.901
08	1	6	7	8	9	0.826

Table 9. Selected Repeats, Section B962.

Visit	Repeat Numbers					Composite Correlation
01	2	3	4	6	7	0.873
02	2	4	5	7	9	0.910
03	1	2	4	5	7	0.876
04	1	2	5	6	7	0.914
05	1	2	3	4	6	0.901
06	1	2	3	4	6	0.793
07	3	5	6	8	9	0.735
08	1	3	4	6	7	0.651

Table 10. Selected Repeats, Section B964.

Visit	Repeat Numbers					Composite Correlation
01	1	2	4	5	6	0.914
02	2	5	7	8	9	0.934
03	1	2	5	6	7	0.878
04	1	2	4	5	6	0.888
05	1	2	5	6	7	0.883
06	2	3	6	7	9	0.937
07	1	5	7	8	9	0.833
08	1	2	4	6	9	0.728

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 3 through 10 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 profiler, and may be very difficult to achieve on highly distressed surfaces. Note that the IRI values provided in this report will be the average of five observations, which will tighten the tolerance even further.

Overall, the many of the groups of measurements listed in Tables 3 through 10 exhibited good or better correlation, and most of them exhibited acceptable correlation. Any group of repeat measurements that produced a composite correlation level below 0.82 was investigated using filtered plots, and they are discussed here.

Section B901, Visit 07 and 08: Narrow downward spikes throughout the profiles significantly diminished the correlation.

Section B902, Visit 07: Narrow downward spikes throughout the left side profiles significantly diminished the correlation. These appeared in the same location in some, but rarely all, repeat measurements.

Section B902, Visit 08: Narrow downward spikes in isolated locations within the profiles significantly diminished the correlation.

Section B903, Visit 08: Narrow downward spikes in the left side profiles significantly diminished the correlation. These appeared in the same location in some, but rarely all, repeat measurements.

Section B961, Visit 08: Correlation was diminished by short wavelength "noise" throughout the section on both the left and right side and several extraneous spikes in the left side profiles.

Section B962, Visits 06 through 08: Narrow downward spikes that rarely appeared in the same location in more than two repeat measurements significantly diminished the correlation.

Section B964, Visits 07 and 08: Correlation was diminished by short wavelength "noise" throughout the section on both the left and right side.

SUMMARY ROUGHNESS VALUES

Figures 1 through 8 show the left and right IRI values for each pavement section over their monitoring period. For most of the sections, this includes fourteen summary IRI values; two per visit over seven visits. The figures show the IRI values versus time in years. In this case, "years" refers to the number of years between the measurement date and April 1, 1995. (All of the test sections were constructed in the second half of March 1995.) 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 Level E 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 1 through 8 provide a snapshot of the roughness history of each pavement section. The remainder of this report is devoted to characterizing the profile content that made up the roughness, and explaining the profile features that contributed to roughness progression.

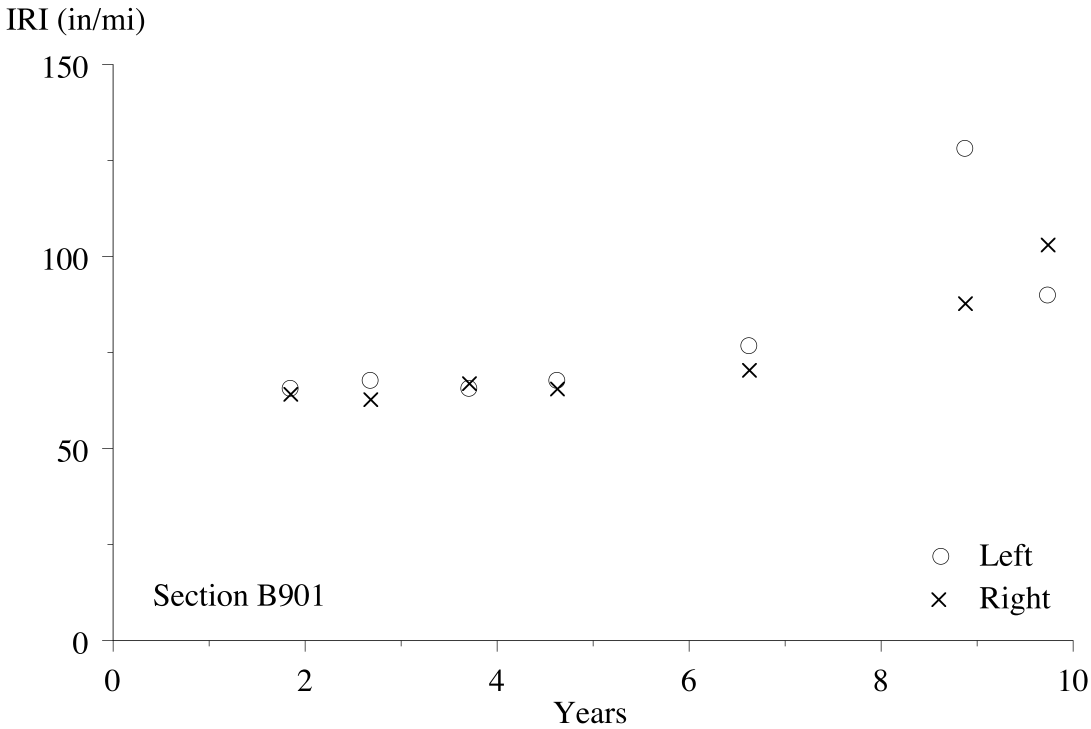

Figure 1. IRI progression, section B901.

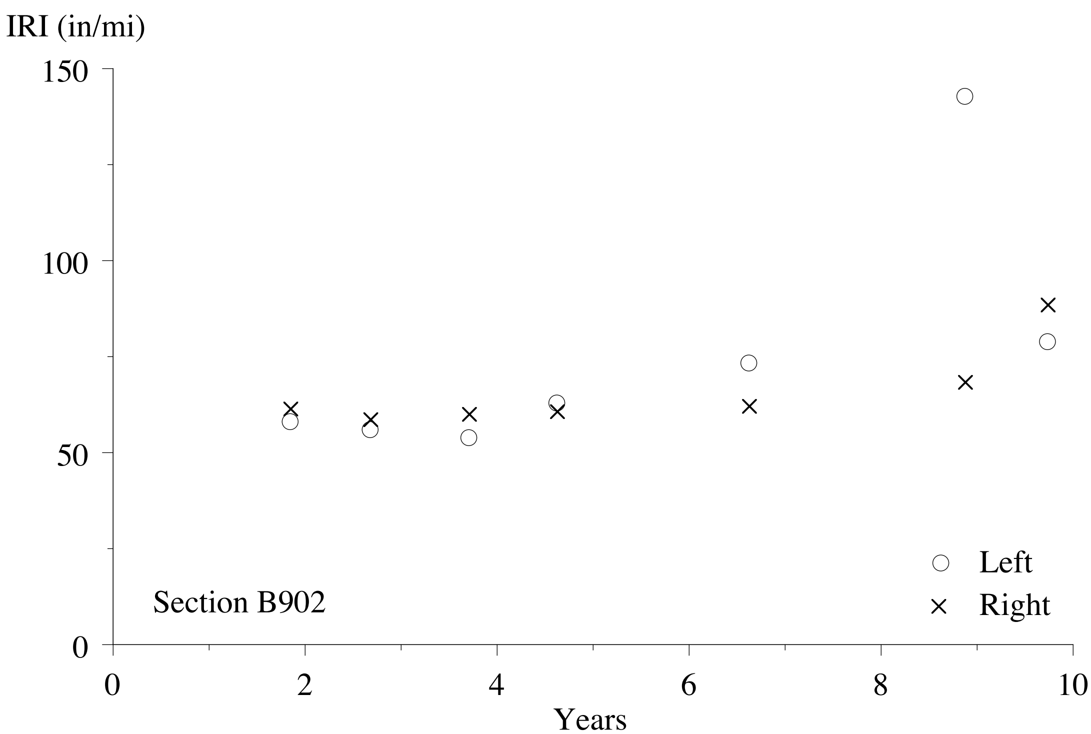

Figure 2. IRI progression, section B902.

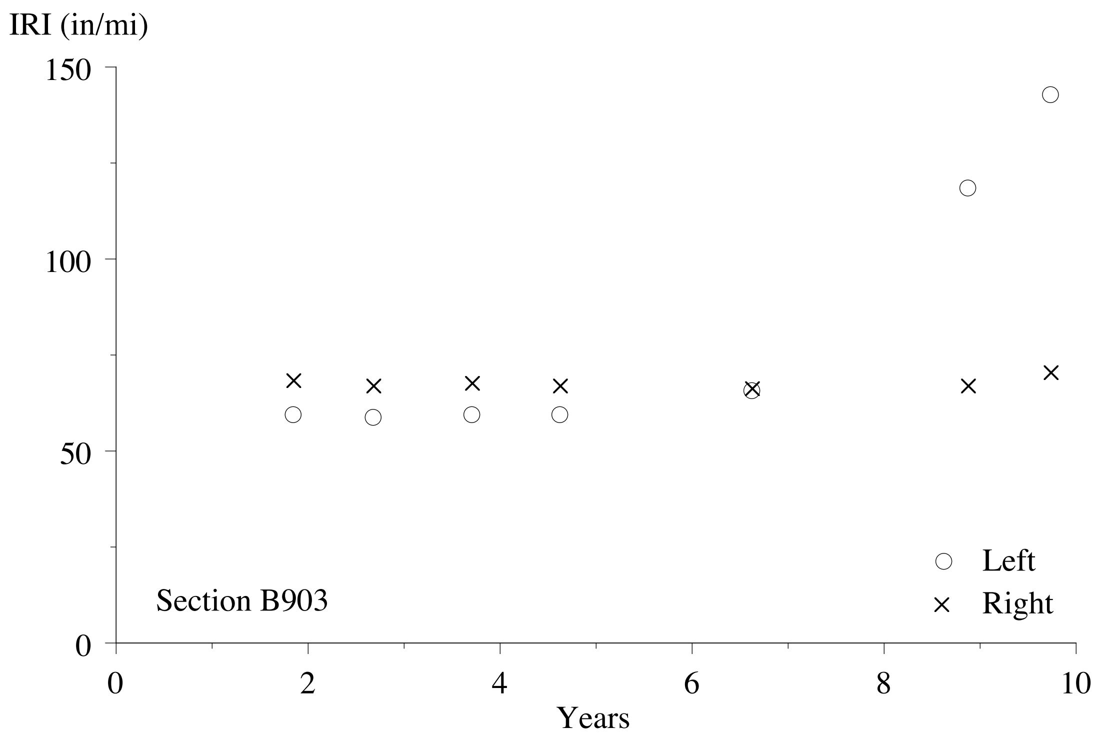

Figure 3. IRI progression, section B903.

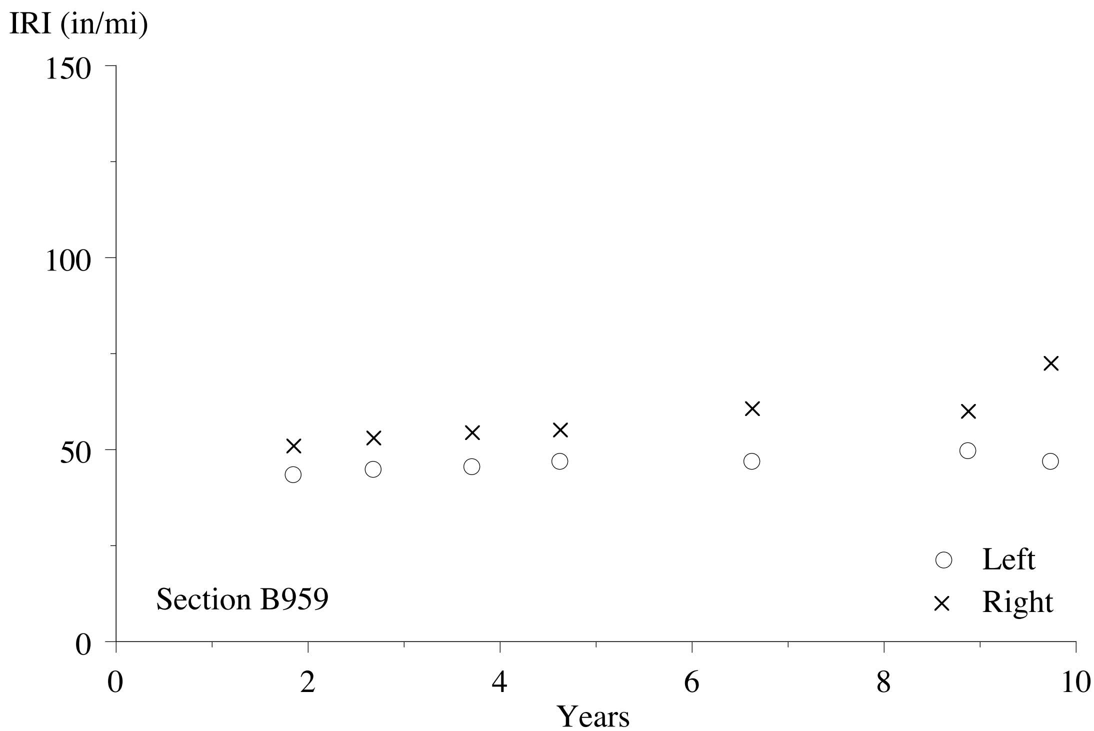

Figure 4. IRI progression, section B959.

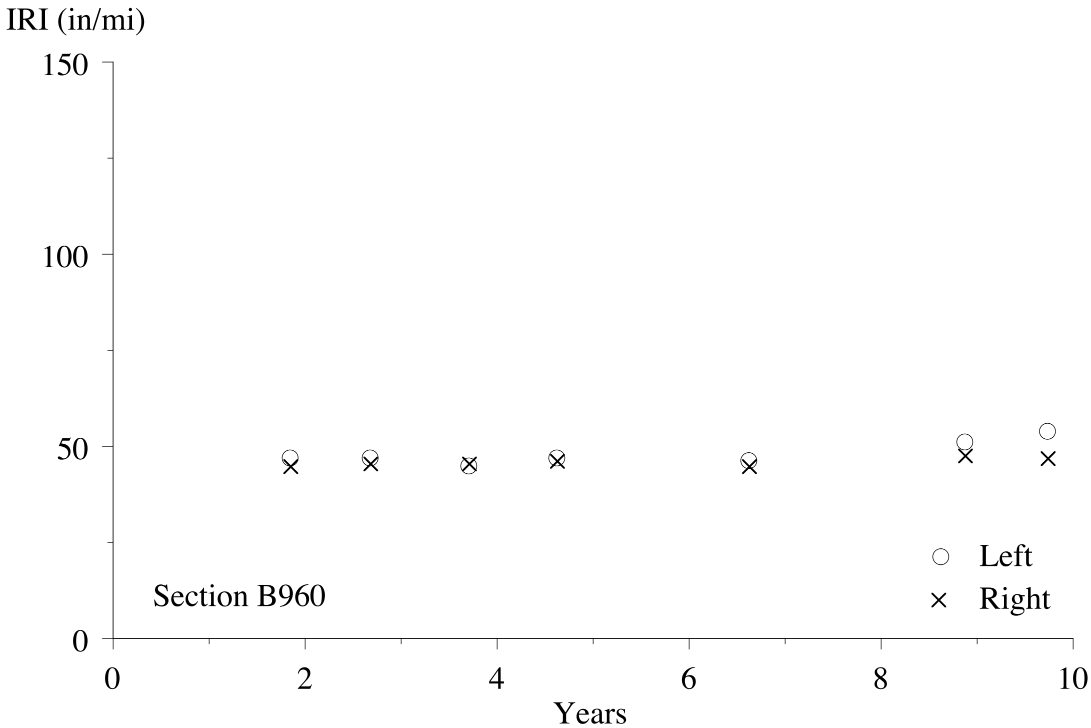

Figure 5. IRI progression, section B960.

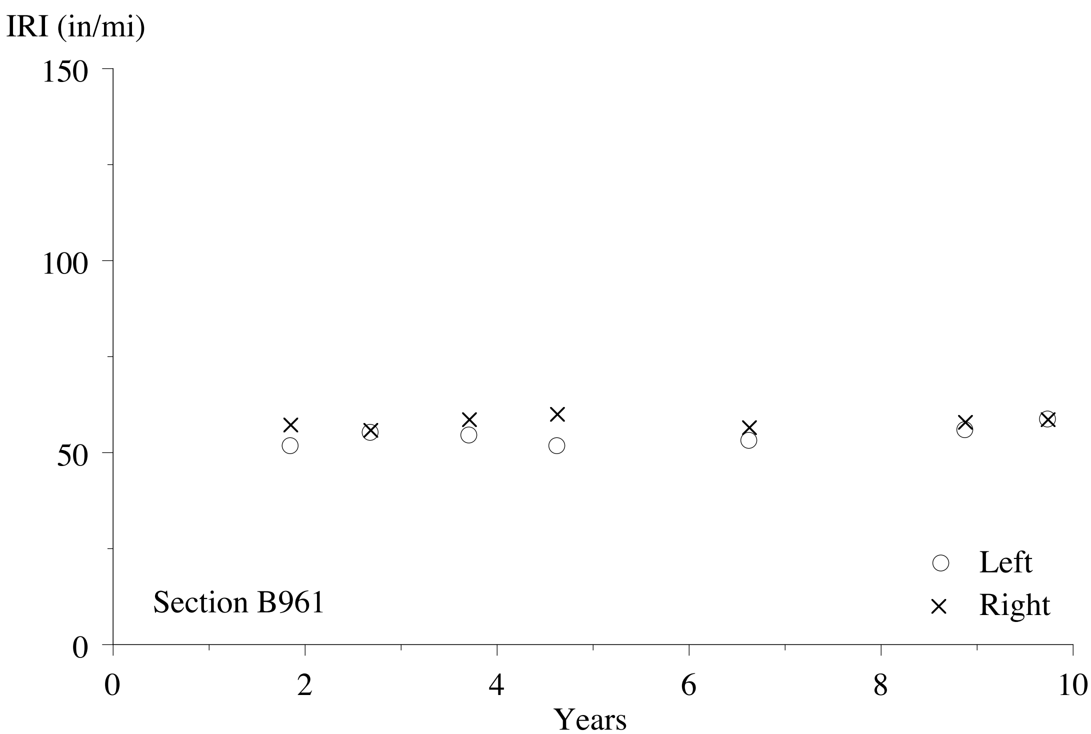

Figure 6. IRI progression, section B961.

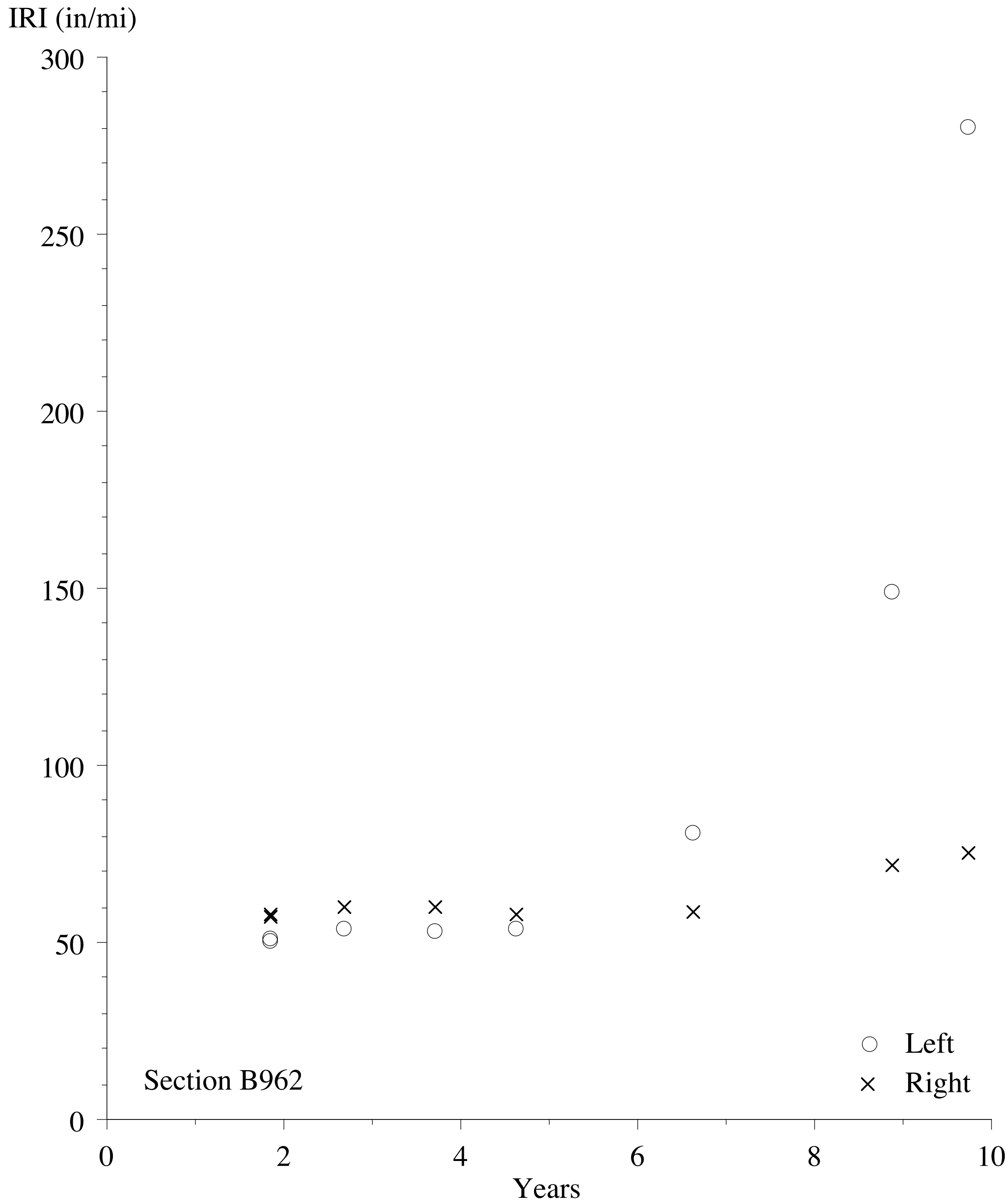

Figure 7. IRI progression, section B962.

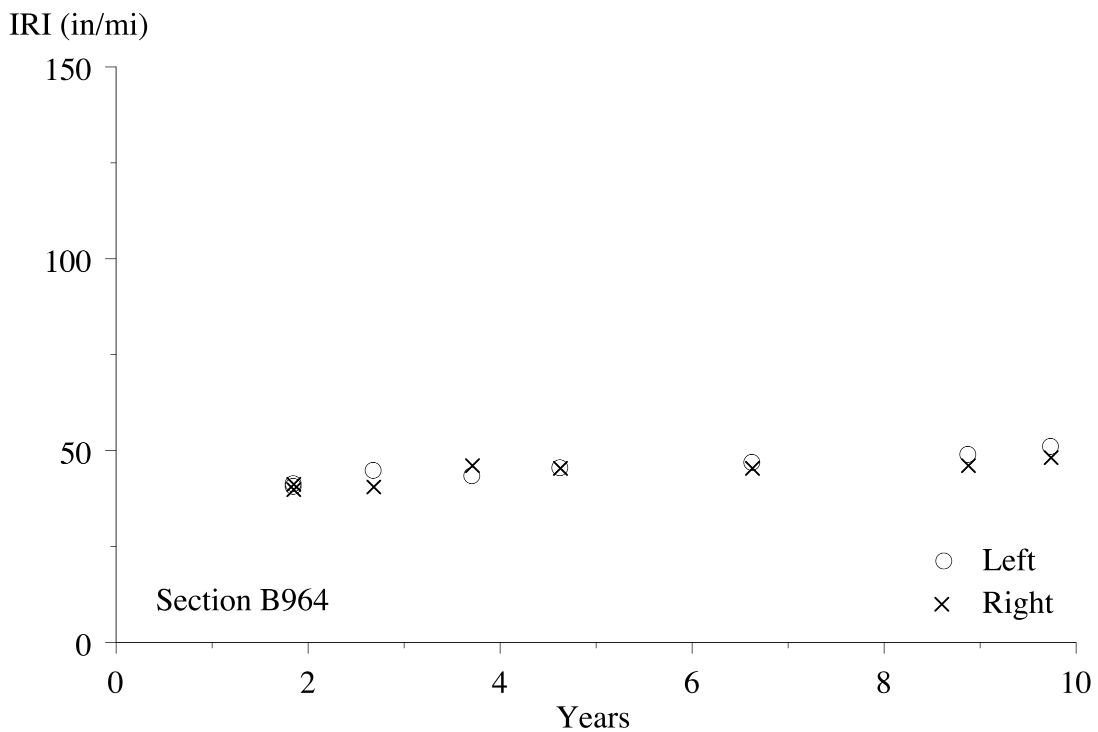

Figure 8. IRI progression, section B964.

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, all of the methods listed here are described in detail elsewhere. *(4)*

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.

Elevation 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. 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 06 and 07. 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 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.

In addition to filtered plots, every profile was viewed in its raw form. This helped reveal noteworthy features that did not necessarily affect the IRI, but helped establish a link between surface distress and profile properties. Two examples of this were: (1) narrow downward spikes in the profiles caused by cracking, and (2) deep, short-duration dips at potholes.

Roughness Profile

A roughness profile provides a continuous report of road roughness using a given segment length. (*5*) 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 baselength along the pavement, using a sliding window.

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

In this work, roughness profiles were generated and viewed using a baselength 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. Any location where a peak occurs in the roughness profile that is greater than or equal to 2.5 times the average IRI for the entire section is considered an area of *localized roughness*. All areas of localized roughness are discussed in the detailed observations by identifying them, listing their severity, and describing the underlying profile features that caused them.

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. PSD plots were 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 typically covers fewer orders of magnitude than an elevation PSD.

A PSD plot is generated by performing a Fourier transform on a profile (or in this case, a slope 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.

The slope 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 type of roughness that increases with time, and (4) the type of roughness that is stable with time.

For this SPS-9A project, the PSDs rarely provided much value beyond what was learned using filtered elevation plots and roughness profiles. Whenever a valuable observation could be made from a PSD plots, it was discussed in the following section.

Distress Surveys

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 on at least six dates over the monitoring history, starting in February 1995. 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.

DETAILED OBSERVATIONS

This section reports key observations from the roughness index progression, PSD plots, filtered elevation profile plots, roughness profiles and distress surveys. In many cases, similar behavior was noted for multiple sections. These 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 here. These observations are summarized at the end of the report.

Section B901

<u>Roughness</u>: The IRI of the left side increased steadily from 66 to 90 in/mi over the monitoring period, with the exception of a value of 128 in/mi in visit 07. The IRI of the right side increased from 65 to 103 in/mi over the monitoring period, but most of

the increase occurred in the last two visits. The HRI was 11 to 14 percent below the MRI in visits 01 through 06, and was 19 to 21 percent below the MRI in visits 07 and 08.

Elevation profile plots: The left side profiles were very consistent with each other over the first five visits. Visit 06 profiles were also consistent with previous visits in the medium and long wavelength range. However, the agreement in the short wavelength range was not as good because of narrow downward spikes in some locations within the visit 06 profiles. By visit 07, a very high concentration of narrow downward spikes up to 0.5 in deep appeared in the left side profiles over the entire length of the section. These sometimes appeared at the same location in more than one repeat measurement, but rarely appeared in all five. In visit 08, very few narrow downward spikes appeared in the profiles, with the exception of a patch of spikes about 0.5 in deep 5 to 10 ft and 37 to 39 ft from the start of the section.

The right side profiles were consistent with each other over the first six visits. (A minor exception was repeat 5 from visit 01, which was different from the rest in the long wavelength range.) Visit 07 profiles were very similar to those of previous visits, except they included several narrow downward spikes that were rarely in the same location in more than one repeat measurement. The spikes appeared with the highest density in the last 140 ft of the section. Profiles from visit 08 included a much higher number of downward spikes over the entire section, and they were most prevalent in the first 100 ft of the section.

Two bumps stood out in the right side profiles from all seven visits. The first was about 115 ft from the start of the section and was 4 ft long and up to 0.15 in high. The second was about 200 ft from the start of the section and was about 10 ft long and 0.2 in high.

Roughness profiles: The left side roughness profiles were very consistent in visits 01 through 05. No localized roughness appeared in these visits, although the roughness was not particularly evenly distributed. The roughness was highest about 125 ft from the start of the section. This is near a series of four bumps up to 5 ft long and more than 0.1 in high. The final bump in the series was about 131 ft from the start of the section. It was 5 ft long and over 0.2 in high. By visit 08, the peak value of the roughness profiles in this location was 195 to 215 in/mi.

In visits 06 and 07, the roughness profiles were not consistent with each other, because of the hit-or-miss nature of the downward spikes within the elevation profiles.

The right side roughness profiles were fairly consistent with each other in visits 01 through 06. In visits 07 and 08, additional roughness appeared in every repeat measurement, but rarely in the same locations in any two repeats. Localized roughness appeared in all visits within the last 25 ft of the section. This area had peak roughness values of over 160 in/mi in all visits. This roughness was caused by a series of disturbances about 5 ft long. (It is not clear if these are bumps or dips.) In visit 07 and one repeat measurement from visit 08, the peak roughness was much higher in this location. This is because a narrow dip up to 1 in deep appeared 480.5 ft from the start of the section in these profiles.

Distress surveys: Wheelpath cracking was first recorded in January 1999. This covered more than half of the left wheelpath. By April 2002 cracking had covered all of the left wheelpath, and longitudinal cracking covered about half of the right wheelpath. In January 2005, areas of cracking covered both wheelpaths over the entire length of the section. Transverse cracking was also recorded on both sides in multiple locations. (Ten feet of longitudinal distance without at least one transverse crack was rare.) Nothing in the distress surveys explain the localized roughness on the left side described above, or the reduction in roughness on the left side between visit 07 and 08. The narrow dip 480.5 ft from the start of the section on the right side is in about the same location as a transverse crack recorded in April 2002 and January 2005.

Section B902

Roughness: The IRI of the left side did not follow a clear trend, but increased overall from 58 in/mi in visit 01 to 79 in/mi in visit 08. In visit 07, the left side IRI averaged 143 in/mi, with a standard deviation of 28.1 in/mi. These values were much higher than in any other visit. The IRI of the right side held steady between 59 and 63 in/mi in visit 01 through 06, then increased to 89 in/mi by visit 08. The HRI was 14 to 22 percent below the MRI.

Elevation profile plots: The right side profiles were consistent in visits 01 through 06, and similar in visit 07. (A minor exception was repeat 5 from visit 01, which was different from the rest in the long wavelength range.) A bump appears in the profiles from all visits from 195 to 203 ft that is about 0.2 in high. The profiles from visit 08 include narrow downward spikes throughout the section. These often appear in only one repeat measurement in a given specific location, but some areas include a higher density of the spikes than others.

The left side profiles were consistent in visits 01 through 05. (A minor exception was repeat 5 from visit 01, which was different from the rest in the long wavelength range.) A patch of densely spaced narrow dips, up to 0.3 in deep, appeared 120 to 145 ft from the start of the section in visit 05. Three new areas of densely spaced narrow dips appeared in the visit 06 profiles, from 215 to 235 ft, 305 to 330 ft and 405 to 435 ft from the start of the section.

All visit 07 profiles included narrow downward spikes throughout the entire length of the section. These spikes were typically 0.4 in or more deep, and were poorly correlated among the five repeat measurements. Visit 07 profiles also included four bumps about a foot long: (1) about 120 ft from the start of the section, 0.5 in high, (2) about 134 ft from the start of the section, 0.35 in high, (3) about 304 ft from the start of the section, 0.2 in high, detected in two repeats, and (4) about 307 ft from the start of the section, 0.3 in high, detected in four repeats.

Visit 08 profiles included narrow dips in the same areas as visit 06, along with a few narrow downward spikes in other areas. None of the four bumps listed for visit 07 appeared in the visit 08 profiles. The patches of narrow dips in visit 08 were much more repeatable, isolated, and in some cases more severe than in previous visits.

Roughness profiles: An area of localized roughness appears in the right side profiles about 197 ft from the start of the section in all visits. This was caused by the 8-ft long bump described above. A peak also appears in visits 01 through 07 of up to 140 in/mi that is 120 ft from the start of the section. It is caused by a bump about 0.1 in high from 113 to 117 ft from the start of the section. The right side roughness profiles from visit 08 are not very consistent, because of the lack of repeatability in the appearance of the narrow downward spikes.

The roughness profiles from the left side included localized roughness in four of the five repeat measurements about 135 ft from the start of the section in visit 05. In visit 06, and particularly in repeat 6, the roughness profiles show a significant increase over those of visit 05 in the areas where the narrow dips appeared. Visit 07 is much rougher than visit 06 in several areas, again because of the narrow dips. The roughness was highest in the first 150 ft of the section and in the last 100 ft (in repeat 7 only).

Visit 08 roughness profiles were much more repeatable on the left side than in visit 06 and 07. Areas of high roughness appeared that were centered about 125, 220, 315 and 420 ft from the start of the section.

Distress surveys: The patch of narrow dips in the left side profiles in visit 05 corresponds to an area of cracking recorded in the left wheelpath in January 1999. This was the only cracking recorded in that survey. In April 2002, the distress survey recorded areas of cracking over most of the left wheelpath, and longitudinal cracking over much of the length of the section in the right wheelpath.

Three of the four bumps listed for the left side profiles in visit 07 appear in locations where potholes were recorded in January 2005. The only pothole that was not in the vicinity of a corresponding bump was about 235 ft from the start of the section. In January 2005, potholes were detected in the left wheelpath 121, 235, 305, 307 and 312 ft from the start of the section. These are locations where narrow dips were the most prevalent in visit 08 profiles, and all of these areas correspond to peaks in the roughness profiles from visit 08.

Section B903

Roughness: The IRI of the left side increased from 59 to 66 in/mi in visits 01 through 06, then increased to 143 in/mi by visit 08. The IRI of the right side held steady between 67 and 71 in/mi over the monitoring period. The HRI was 15 to 20 percent below the MRI.

Elevation profile plots: In visit 06, narrow dips began to emerge in the left side profiles. They were up to 0.15 in deep, and appeared in the same location in more than one profile in some cases. Visit 07 profiles included more narrow dips on the left side. The dips were up to 0.5 in deep, and the majority of them did not appear in the same location in multiple repeat measurements. Visit 08 included a much higher density of narrow dips. Many of the dips under 0.3 in deep were not well repeated, but several deeper dips appeared at the same location in more than one repeat measurement.

Similar dips appeared in the right side profiles from visits 06 through 08, but not nearly as many, and they were much less severe.

A dip 1 ft long and at least 2.4 in deep appeared in the left side profiles from visit 07 about 122 ft from the start of the section. A dip 1 ft long and 2 in deep appeared in three of the five left side profiles from visit 08 about 333 ft from the start of the section.

Roughness profiles: The roughness was very uniform along the section on the left side in visit 03 and 04. In visit 06, the roughness was somewhat uniform along the section, but not very consistent among the repeat measurements. Severe localized roughness with a peak value of 540 in/mi appeared in the location of the deep dip in visit 07. This feature alone added more than 25 in/mi to the overall IRI of the left side. Severe localized roughness with a peak value of 630-695 in/mi appeared about 333 ft from the start of the section in three of the five repeat measurements from visit 08. This accounted for about 30 in/mi of additional roughness in those repeat measurements. It also explains the high (15.4 in/mi) standard deviation among the left side IRI values.

No localized roughness was found in the right side profiles. The right side roughness profiles were very consistent with time in visits 01 through 07.

Distress surveys: No distress was recorded until April 2002. In April 2002, longitudinal cracking and large areas of wheelpath cracking were recorded. In January 2005, both wheelpaths were covered with cracking over the entire length of the section. Nothing in the distress survey explains the deep dips in visits 07 and 08.

Section B959

Roughness: The IRI of the left side increased from 41 in/mi in visit 01 to 47 in/mi in visit 08 with a peak value of 50 in/mi in visit 07. The IRI of the right side increased steadily from 51 to 73 in/mi. The HRI was 13 to 16 percent below the MRI.

Elevation profile plots: Profiles were very consistent over the monitoring period on the left side. The only feature that stood out was a dip at the start of the section 0.1-0.2 in deep and about 10 ft long. The deepest part of the dip was only a few feet from the start of the section. Its shape was only fully developed in profiles that included lead-in, such as visits 07 and 08.

The right side profiles included narrow dips 188.5 ft from the start of the section in some of the repeat measurements from visits 04 and 05. Otherwise, the profiles were fairly consistent in visits 01 through 07. In visit 08, several narrow dips up to 0.1 in deep appeared, particularly in the first third of the section.

Roughness profiles: The roughness of the left side was uniform along the section, with the exception of localized roughness at the very start of the section. This was caused by (1) the long dip described above, and (2) roughness that appeared just ahead of the section start. The localized roughness only appeared in visits 07 and 08, because they included profile upstream of the section start.

In the early visits, the roughness of the right side was uniform along the section. In later visits, and particularly in visit 08, most of the increase in roughness occurred in the first third of the section.

Distress surveys: Nothing in the distress surveys explains the narrow dip in visits 04 and 05. Very little distress was recorded before January 2005. By January 2005, significant cracking had appeared. Much of the cracking was found in the first third of the section along the right wheelpath. This included transverse cracks and large areas of cracking within the wheelpath. Narrow dips appeared in the visit 08 profiles in the position of most of the transverse cracks.

Section B960

Roughness: The IRI of the left side held steady between 45 and 47 in/mi in visits 01 through 06, then increased to 54 in/mi by visit 08. The IRI of the right side only ranged from 45 to 48 in/mi. The HRI was 13 to 18 percent below the MRI.

Elevation profile plots: The right side profiles were very consistent with time. Two small disturbances stood out in the medium wavelength (and raw) profiles that were about 190 and 380 ft from the start of the section. The same features appeared on the left side, but they did not stand out among the roughness from the rest of the section. The left side profiles were very consistent with time in visits 01 through 06. In visit 07, a sunken area appeared 441 to 447 ft from the start of the section that included two dips within it, each at least 0.1 in deep. In visit 08, this entire area was about 0.1 in below the surrounding pavement, and it included three dips within it, each at least another 0.2 in deep.

Roughness profiles: The right side roughness profiles were very consistent with time. In all visits, the roughness was about double the average near 190 and 380 ft from the start of the section. The left side roughness profiles were fairly consistent with time in visit 01 through 06. In visit 07, a peak of about 100 in/mi appeared in the roughness profile about 445 to 450 ft from the start of the section. By visit 08, the same area showed peak roughness of up to 160 in/mi. This localized roughness was caused by the sunken area with dips described above, and was responsible for the majority of the increase in roughness of the entire section after visit 06.

Distress surveys: The distress surveys recorded very little distress before April 2002. Some transverse and longitudinal cracking was recorded in April 2002. This included longitudinal cracking from 435 to 450 ft from the start of the section on the left side of the lane, and transverse cracking across the left wheelpath about 443 and 447 ft from the start of the section. This corresponds to the sunken area and the dips within it described above. The distress survey from January 2005 observed cracking over the entire section in both wheelpaths, but several transverse cracks in the area from 440 to 450 ft were also specifically recorded.

Section B961

Roughness: The IRI increased from 52 to 59 in/mi on the left side, but the progression was not steady. The IRI only ranged from 56 to 60 in/mi on the right side. The HRI was 10 to 12 percent below the MRI. This was the lowest difference observed for the SPS-9A project, and it is an unusually low difference for a full-depth asphalt pavement.

Elevation profile plots: Profiles were very consistent over the monitoring period on both sides of the lane. They were unusually consistent with time in the short wavelength range. Very few features stood out. A minor exception was a series of short (~ 0.05 in), narrow bumps 60 to 100 ft from the start of the section on both sides.

Roughness profiles: No localized roughness was detected on the left side, although the area from 60 to 100 ft from the start of the section was rougher than the rest. On the right side, a peak value of up to 140 in/mi appeared about 95 ft from the start of the section. This localized roughness was caused by the bumps described above.

Distress surveys: Nothing in the distress surveys directly explains the series of narrow bumps observed in the profiles. Very little distress was observed before the final survey in January 2005. That survey recorded a significant amount of raveling, particularly on the left side of the lane.

Section B962

Roughness: The IRI of the left side held steady between 51 and 54 in/mi in visits 01 through 05, then increased rapidly to 281 in/mi in visit 08. The IRI of the left side held steady between 58 and 61 in/mi in visits 01 through 06, then increased to 76 in/mi by visit 08. The HRI was 13 to 17 percent below the MRI.

Elevation profile plots: Profiles from the left side were consistent over visits 01 through 05, and profiles from the right side were very consistent over visits 01 through 06. Those profiles included areas with small bumps 2 to 5 ft long from 180 to 210 ft and 360 to 420 ft from the start of the section on both sides.

The right side profiles included several narrow downward spikes throughout the section in visits 07 and 08. Heavy concentrations of these spikes appeared 162 to 172 ft, 230 to 245 ft, 295 to 305 ft, 355 to 365 ft, and 475 ft from the start of the section. (These account for the additional roughness compared to visits 01 through 06.)

In visit 06, the left side profiles included narrow downward spikes in the ranges from 60 to 80 ft, 150 to 180 ft and 410 to 440 ft from the start of the section. The dips often appeared in the same location in more than one repeat measurement, but rarely in all five. The deepest, and most well repeated, dip was less than 1 ft long, up to 1.4 in deep, and appeared 430 ft from the start of the section.

In visit 07, the left side profiles included narrow downward spikes up to 1 in deep over the entire section. They usually appeared in the same location in more than one repeat measurement, but not in all repeats. The highest concentration of downward spikes appeared between 360 and 450 ft from the start of the section. In one repeat measurement, a dip 0.5 ft long and 0.8 in deep appeared 170 ft from the start of the section. In two other repeat measurements, a dip appeared 80 ft from the start of the section that was 0.5 ft long and at least 0.7 in deep.

The visit 07 profiles from the left side also included five longer disturbances that were detected in all five repeat measurements: (1) a 2 ft long, 0.5 in deep dip centered 418 ft from the start of the section, (2) a 4 ft long, 0.5 in deep dip centered 431 ft from the start of the section, (3) a 1.5 ft long, 0.4 in high bump 471 ft from the start of the section, (4) a 2 ft long, 0.4 in high bump 484 ft from the start of the section, and (5) a 1.5 ft long, up to 0.3 in high bump 492 ft from the start of the section. All of these features appeared among a high concentration of narrow downward spikes.

The visit 08 profiles from the left side included many areas with a high concentration of narrow downward spikes up to 2.5 in deep, but the spikes rarely appeared in more than the same location in more than two repeat measurements. The highest concentration of spikes appeared in repeats 4 and 7. The profiles also included some bumps up to 2 ft long and 0.5 in high in the last 40 ft of the section and a 4 ft long, 0.5 in deep dip in the last 5 ft of the section.

Roughness profiles: Roughness profiles for the right side were very consistent in visits 01 through 06. Although no localized roughness appeared in these profiles, the distribution of roughness long the section was not particularly uniform. The growth in roughness after visit 06 took place over the entire length of the section.

No localized roughness was detected on the left side in visits 01 through 06, although the areas with small bumps described above were rougher than the surrounding pavement.

In visits 06 and 07, localized roughness (or at least increased roughness) in the left side profiles appeared about 80 ft from the start of the section in one repeat measurement per visit and about 175 ft from the start of the section in one or two repeat measurements per visit. These are locations where deep, narrow dips were found in some, but not all, repeat measurements. Localized roughness also appeared in visit 06 about 430 ft from the start of the section and in the last 20 ft of the section. Both of these areas appeared as severe localized roughness in visit 07, with peak values of up to 550 in/mi in the roughness profiles.

In visit 08, the left side profiles were very rough over much of the section. (The exception was the area from 230 to 350 ft from the start of the section.) The most severe localized roughness appeared (1) at the very end of the section, (2) in one repeat measurement about 20 ft from the start of the section, and (3) in all but one repeat measurement about 80 ft from the start of the section.

Distress surveys: The distress survey of January 1999 shows five areas of longitudinal cracking or wheelpath cracking. Many of these areas correspond to the locations where narrow downward spikes appeared in the left side profiles from visit 06. In visits 07 and 08, cracking covered the entire left wheelpath (and most of the right wheelpath). This probably explains the downward spikes that appeared throughout the profiles, and the "hit or miss" nature of their distribution.

The distress survey in April 2002 recorded potholes about 427 ft and 434 ft from the start of the section. The distress survey in January 2005 recorded a large number of potholes and patches in the left wheelpath over the last 100 ft of the section. Their locations correspond to the locations of longer bumps and dips in the visit 07 and 08 profiles.

The deep narrow dip in the left side profiles from visit 06 through 08 does not correspond to anything in the distress surveys beyond the wheelpath cracking found over the entire section.

Section B964

Roughness: The IRI increased fairly steadily from 41 to 52 in/mi on the left side and from 42 to 49 in/mi on the right side. The HRI was 11 percent below the MRI in visit 01. The gap between HRI and MRI grew steadily to 17 percent by visit 08.

Elevation profile plots: The profiles changed very little over the monitoring period with the exception of three rough features.

1. After visit 02, a dip appeared about 136 ft from the start of the section on the left side. It was about 1 ft long and grew in depth from 0.15 in to 0.4 in over visits 03 through 08. However, the dip was not present in every repeat measurement.
2. A dip up to 0.15 in deep appeared 155 ft from the start of the section in all visits on the left side.
3. Starting in visit 04, a narrow dip appeared in the right side profiles about 160 ft from the start of the section. The dip rarely appeared in all five repeat measurements within a visit, and ranged in depth up to 0.25 in.

Roughness profiles: Together, the first two dips described above caused an area of localized roughness that grew in severity to a peak value of 130 in/mi by visit 08. The increased roughness at this area contributed significantly to the growth in roughness with time on the left side between visits 01 and 07.

In the most extreme case (visit 04, repeat 01) the third dip described above caused a peak value in the roughness profile of 106 in/mi on the right side. Other than the influence of the dip 160 ft from the start of the section, roughness was very evenly distributed along the section on the right side.

PSD Plots: Although the content was biased toward long wavelengths, some content was isolated around wavelengths of about 15-16 ft on the left side.

Distress surveys: Nothing in the distress surveys directly explains the three narrow dips described above. Very little distress was observed before April 2002. In April 2002 and January 2005 the distress surveys recorded raveling along the entire section in both wheelpaths.

SUMMARY

This section of the report provides a summary of important observations from each pavement section within the Arizona SPS-9A site on westbound Interstate 10. Some 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 1 through 8), provides the essential information about each pavement section. The interested reader is encouraged to read the entire report if data handling, data quality control, and great detail about the profile properties are of interest.

Profiles from sections B901, B902, B903 and B962 included narrow downward spikes dispersed throughout their length. The spikes usually appeared in only one or two repeat measurements at each location. These were caused by cracking, which covered both wheelpaths of sections B901, B902, B903 and B962 in the later visits. The spikes typically first appeared in profile measurements from November 2001 (visit 06), but were much more prevalent in February and December 2004 (visits 07 and 08). The spikes were usually more severe and numerous in the left side profiles. On sections B901 and B902, the spikes were most severe in the left side profiles from visit 07. Although it is not clear why fewer spikes were detected in visit 08 on those two sections, it may be a consequence of a subtle difference in profiler positioning. The spikes account for most of the increase in the IRI values, particularly on the left side, on sections B901, B902, B903 and B962 after November 2001.

Section B902 and B962 included several potholes in the left wheelpath that were observed in the distress survey from January 2005. The profiles in the location of these potholes were rarely consistent among the five repeat measurements from the last two profiling visits. On section B902 the narrow downward spikes found throughout the profiles were somewhat more likely to appear near the potholes than in other locations, but no direct relationship was observed. Bumps appeared near two of the potholes in two of the five repeat profile measurements in February 2004. This may have been caused by narrow patching that was only covered by the lateral placement of the profiler in two of the passes, but no patching was noted. On section B962 two of the seven potholes caused dips about 0.5 ft long and up to 1 in deep in the last profiling visit that were fairly well repeated.

The final distress survey (January 2005) for sections B901, B902, B903, B960, B962 and B964 all show areas of cracking that cover both wheelpaths over the entire section length. In these instances fatigue cracking is so prevalent that it is difficult to match individual cracks to roughness within the measured profile. However, in a few cases features in the profiles that affected the roughness were found that correspond directly to the location of transverse cracks noted in the distress survey. Several narrow dips appeared on section B959 in the final profiling visit that correspond to the locations of transverse cracks noted in January 2005. On section B901, a narrow dip appeared in the right side profiles about 480 ft from the start of the section in the last two profiling visits. This is a location where transverse cracking was noted in April 2002. An area of localized roughness about 10 ft long appeared in the last two visits of section B960 that included multiple transverse cracks.

Profiler Model

The change in profiler 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. The change in high-pass filtering methods had no probable effect on the measurement of localized roughness or the study of narrow bumps and dips caused by distresses.

Another minor device effect within the profiles was peaks in the PSD plots with no pavement-related explanation. In visits 01 through 06 (measured by a 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 0.52 ft and another at a wavelength of double the first.

Individual Sections

The rest of this report provides a summary of the most important observations made about each test section. The summaries are extracted from the Detailed Observations section of this report. To help provide context for the summary statements below, Figure 9 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 1 through 8.)

<u>Section B901</u>: This section started out moderately smooth, with an MRI value of 65 in/mi. The roughness grew significantly to a final MRI value of 97 in/mi. The roughness of the right side grew steadily. However, the roughness of the left side reached a peak IRI value of 128 in/mi in February 2004, then reduced to a final value of 90 in/mi. In the last three profiling visits the profiles included narrow downward spikes that often did not appear in the same location in more than one repeat measurement. The highest concentration of dips appeared in the left side profiles in February 2004. This accounts for much of the additional roughness over the previous and subsequent visits. Localized roughness appeared in the right side profiles over the last 25 ft of the section because of 5-ft long bumps and dips. In 2004, the profiles in this area also often included a 1-in deep narrow dip at a transverse crack 480.5 ft from the start of the section.

<u>Section B902</u>: The section was somewhat smooth until 2004. Starting with the profile measurement of November 2001, the profiles included an increasing number of narrow dips, particularly on the left side, that often did not appear in the same location in more than one repeat measurement. These were most severe in the left side profiles from February 2004, which had an average roughness value of 143 in/mi, but were not at all consistent with each other. Although the spikes were less severe in November 2004, the profiles included patches of narrow dips in three areas where potholes were recorded in the distress surveys.

<u>Section B903</u>: The right side of this section remained somewhat smooth throughout the monitoring history, but the left side IRI more than doubles between visit 06 and 08. Starting in visit 06 the profiles included an increasing number of narrow dips, particularly on the left side, that often did not appear in the same location in more than one repeat measurement. In visit 07, a deep (2.4 in) narrow dip appeared 122 ft from the start of the section on the left side. A deep (2 in) narrow dip appeared 333

ft from the start of the section in three of the five repeat measurements from visit 08 on the left side. Both dips caused severe localized roughness. Roughness at the dip in visit 08 accounted for the high (15.4 in/mi) standard deviation in the left side IRI from visit 08.

Section B959: This section remained smooth throughout the monitoring period, although the MRI progressed by 13 in/mi. An area of localized roughness appeared on the left side at the start of the section because of a long dip and some rough features just ahead of the section start. The roughness of the right side was uniform along the section, until the roughness progressed significantly in the first third of the section because of the influence of cracking.

Section B960: The MRI increased from 46 to 51 in/mi over the monitoring period. An area of localized roughness appeared on the left side about 445 ft from the start of the section by the end of the monitoring period. It was caused by a sunken area of pavement, including three narrow dips about 0.2 in deep at transverse cracks. This area accounts for the majority of the roughness progression of the entire section.

Section B961: The MRI ranged from 55 to 59 in/mi over the entire monitoring period. An area of increased roughness appeared on the right side of the lane 60 to 100 ft from the start of the section because of a series of short, narrow bumps in the profiles. The bumps appeared on the left side of the lane also, but they did not increase the roughness as much there. The bumps were very consistently measured over the monitoring period.

Section B962: This section remained smooth until 2004, when the final MRI value was 178 in/mi, more than three times the initial value of 55 in/mi. The sharp increase in roughness occurred primarily within the left side profiles. By the final visit, the left side profiles were strongly affected by roughness at potholes and patching, and included a high concentration of deep narrow downward spikes caused by cracking in the wheelpath. Most of the potholes and patches appeared in the last 100 ft of the section.

Section B964: The MRI increased from 41 to 50 in/mi over the monitoring period. The majority of the roughness progression on this section was caused by three narrow dips that grew in severity with time: (1) 136 ft from the start of the section on the left side, (2) 155 ft from the start of the section on the left side, and (3) 160 ft from the start of the section on the right side.

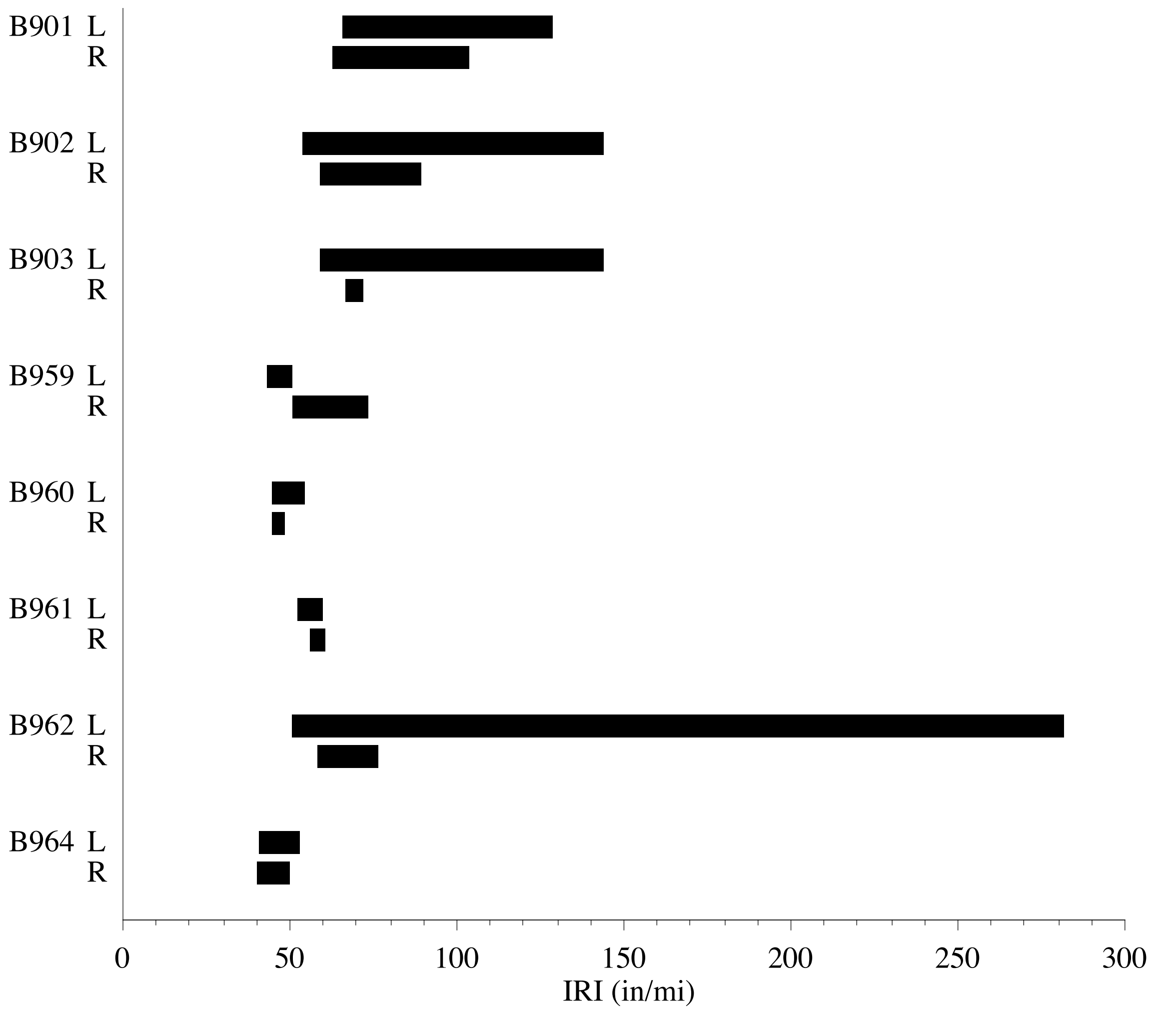

Figure 9. Summary of IRI ranges.

REFERENCES

1. Nichols Consulting Engineers, Chtd, "Construction Report on Site 04B900." (1998) 17 p.

2. Evans, L. D. and A. Eltahan, "LTPP Profile Variability" *Federal Highway Administration Report FHWA-RD-00-113* (2000) 178 p.

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

4. Sayers, M. W. and Karamihas, S. M., "Interpretation of Road Roughness Profile Data." Federal Highway Administration, *FHWA/RD-96/101* (1996) 177 p.

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

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. (*1*) 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. (*2*) 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 290 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 0.845. This is typical for asphalt pavement.

RN has shown a closer relationship to road user opinion than the other indexes. (*3*) 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, and potential sensitivity to narrow dips and measurement errors caused by coarse surface texture.

Table A-1 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. Negative values indicate measurements that were made before rehabilitation.

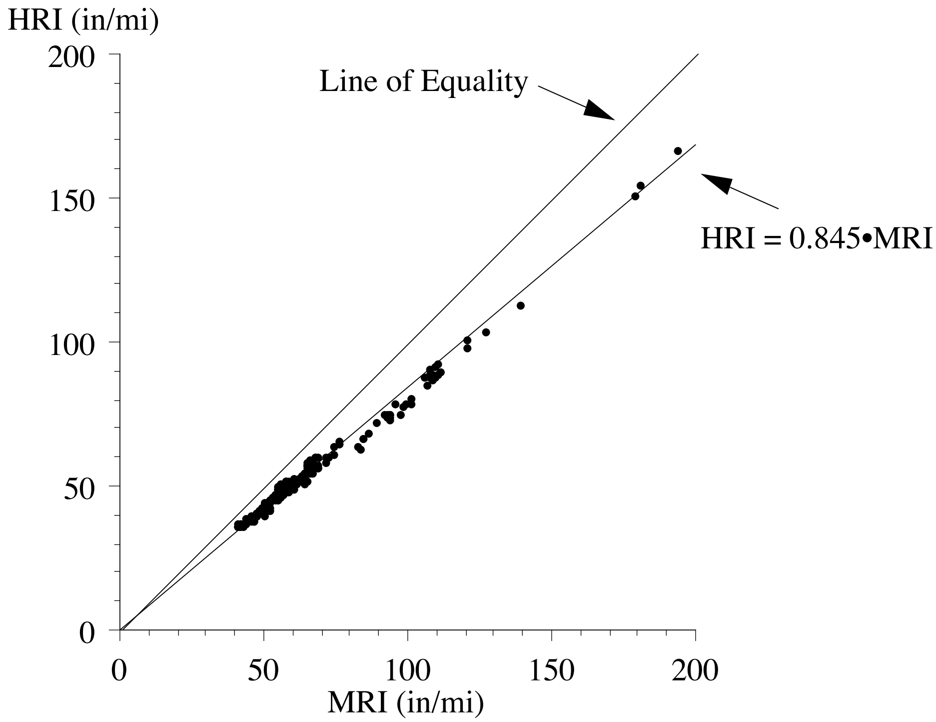

Figure A–1. Comparison of HRI to MRI.

Table A-1. Roughness Values.

Section	Date	Years	Left IRI (in/mi) Ave	Left IRI (in/mi) St Dev	Right IRI (in/mi) Ave	Right IRI (in/mi) St Dev	MRI (in/mi)	HRI (in/mi)	RN
B901	29-Jan-97	1.84	66	1.0	65	1.2	65	58	3.79
B901	5-Dec-97	2.68	68	1.5	63	1.5	65	57	3.67
B901	7-Dec-98	3.69	66	1.1	68	1.2	67	59	3.68
B901	10-Nov-99	4.61	68	1.0	66	1.9	67	58	3.72
B901	12-Nov-01	6.62	77	2.1	70	2.1	74	63	3.51
B901	9-Feb-04	8.86	128	4.9	88	4.2	108	88	2.41
B901	17-Dec-04	9.71	90	4.2	103	4.1	97	77	2.82
B902	29-Jan-97	1.84	58	1.3	61	1.4	60	50	3.87
B902	5-Dec-97	2.68	56	1.6	59	1.1	58	49	3.82
B902	7-Dec-98	3.69	54	0.8	61	0.5	58	49	3.82
B902	10-Nov-99	4.61	63	3.1	61	0.7	62	53	3.68
B902	12-Nov-01	6.62	73	10.3	63	0.6	68	57	3.46
B902	9-Feb-04	8.86	143	28.1	69	2.9	106	86	2.56
B902	17-Dec-04	9.71	79	2.3	89	0.6	84	66	2.94
B903	29-Jan-97	1.84	59	0.6	69	1.1	64	54	3.77
B903	5-Dec-97	2.68	59	1.8	67	0.5	63	53	3.71
B903	7-Dec-98	3.69	60	0.5	68	1.0	64	54	3.73
B903	10-Nov-99	4.61	60	0.9	68	1.0	64	53	3.80
B903	12-Nov-01	6.62	66	3.2	67	1.3	66	54	3.69
B903	9-Feb-04	8.86	119	1.8	68	1.9	93	75	2.37
B903	17-Dec-04	9.71	143	15.4	71	2.9	107	87	2.42
B959	29-Jan-97	1.84	43	0.6	51	0.7	47	41	4.22
B959	5-Dec-97	2.68	45	0.6	53	0.7	49	43	4.08
B959	7-Dec-98	3.69	46	0.5	55	0.8	50	44	4.09
B959	10-Nov-99	4.61	47	0.5	55	1.1	51	44	4.13

Table A-1. 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			
B959	12-Nov-01	6.62	47	0.6	61	1.1	54	46	4.10
B959	9-Feb-04	8.86	50	0.9	60	1.4	55	46	3.95
B959	17-Dec-04	9.71	47	1.1	73	4.2	60	51	3.81
B960	29-Jan-97	1.84	47	1.1	45	0.9	46	39	4.07
B960	5-Dec-97	2.68	47	0.6	46	0.7	46	39	3.95
B960	7-Dec-98	3.69	45	1.0	46	0.8	46	39	3.99
B960	10-Nov-99	4.61	47	0.7	46	0.6	47	40	4.05
B960	12-Nov-01	6.62	46	0.6	45	0.4	46	40	4.06
B960	9-Feb-04	8.86	52	0.7	48	0.7	50	41	3.75
B960	17-Dec-04	9.71	54	1.3	47	1.1	51	42	3.66
B961	29-Jan-97	1.84	52	0.3	58	0.6	55	49	4.00
B961	5-Dec-97	2.68	56	0.8	56	0.6	56	50	3.86
B961	7-Dec-98	3.69	55	1.5	59	1.7	57	51	3.88
B961	10-Nov-99	4.61	52	1.0	60	0.9	56	50	3.99
B961	12-Nov-01	6.62	54	1.1	57	0.4	55	50	3.97
B961	9-Feb-04	8.86	56	1.1	58	0.4	57	51	3.82
B961	17-Dec-04	9.71	59	2.8	59	1.3	59	52	3.77
B962	29-Jan-97	1.83	52	1.9	59	2.0	55	48	3.84
B962	2-Feb-97	1.84	51	1.0	58	0.7	54	47	3.86
B962	5-Dec-97	2.68	54	2.0	60	0.9	57	50	3.71
B962	7-Dec-98	3.69	53	1.4	61	1.6	57	49	3.73
B962	10-Nov-99	4.61	54	1.7	58	0.9	56	49	3.79
B962	12-Nov-01	6.62	81	5.5	59	1.1	70	58	3.06
B962	9-Feb-04	8.86	149	12.3	72	1.8	111	92	2.26
B962	17-Dec-04	9.71	281	49.8	76	3.0	178	152	1.77
B964	29-Jan-97	1.83	41	0.3	42	0.9	41	37	4.24
B964	2-Feb-97	1.84	41	0.8	40	0.5	41	36	4.23
B964	5-Dec-97	2.68	45	1.2	41	0.5	43	37	4.02
B964	7-Dec-98	3.69	44	0.4	47	1.5	45	38	4.03
B964	10-Nov-99	4.61	46	0.8	46	1.4	46	39	4.02
B964	12-Nov-01	6.62	47	0.8	46	0.6	47	40	4.01
B964	9-Feb-04	8.86	49	1.4	47	1.1	48	41	3.79
B964	17-Dec-04	9.71	52	1.8	49	2.4	50	41	3.76

REFERENCES

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

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

3. Sayers, M. W. and S. M. Karamihas, “Estimation of Rideability by Analyzing Road Profile.” *Transportation Research Record 1536* (1996) pp 110-116.