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PROFILE ANALYSIS OF THE LTPP SPS-5 SITE IN ARIZONA

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16. Abstract

This report characterizes the longitudinal profiles of eleven pavement sections within the Arizona Specific Pavement Studies 5 (SPS-5) project throughout their service life. The pavement associated with this project was rehabilitated and monitored as part of the Long-Term Pavement Performance Study. Road profile measurements were collected on the in-service pavement before rehabilitation was performed and twelve times over the sixteen years afterward. 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 the Long-Term Pavement Performance (LTPP) Specific Pavement Studies 5 (SPS-5) site in Arizona. SPS-5 sites were established for the study of asphalt pavement rehabilitation strategies, including the level of surface preparation, the overlay material and overlay thickness. *(1)*

These test pavements were constructed in the travel lane of eastbound Interstate 8 in the summer of 1990. The site extends from Milepost 159 to 161. Eight sections were constructed as part of the standard experiment. These sections have the same design characteristics as the standard eight sections on the SPS-5 sites throughout the LTPP study, as well as the same guidelines for pre-construction maintenance and subsequent rehabilitation activities. This SPS-5 site also included a control section and two supplemental test sections designed by the Arizona Department of Transportation.

Table 1 summarizes the rehabilitation designs for the test sections. Section 0502 through 0509 make up a standard set of test sections for an SPS-5 site. Minimum surface preparation refers to, among other activities, about 0.5 in of milling depth. Intensive surface preparation refers to about 2.5 in of milling depth. Section 0501 was a control section, and it only received routine maintenance. Section 0560 used asphalt rubber asphalt concrete as an overlay material, and section 0559 "inverted" the design of section 0509 by placing the recycled layer over the virgin asphalt concrete layer. The milling depth for section 0559 was about 4 in. The construction report provides more detail on the layout and structural properties of the site. (*1*)

Table 1. Arizona SPS-5 Site Rehabilitation Alternatives. (*1*)

Section	Surface Preparation	Overlay Material	Overlay Thickness (in)
0501	Routine Maintenance		—
0502	Minimum	Recycled	2
0503	Minimum	Recycled	5
0504	Minimum	Virgin	5
0505	Minimum	Virgin	2
0506	Intensive	Virgin	2
0507	Intensive	Virgin	5
0508	Intensive	Recycled	5
0509	Intensive	Recycled	2
0559	Intensive	Recycled	2
0560	Minimum	ARAC	2.5

ARAC — Asphalt Rubber Asphalt Concrete

This report seeks to characterize the surface roughness of these sections over time, 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 initial roughness of the road and provided a basis for quantifying and explaining the changes in roughness with time.

Profile Data Synchronization

Profile data were collected at the Arizona SPS-5 site on fourteen dates, listed in Table 2. Raw profile data were available for visit 00 and visits 03 through 13. In each visit for which raw data were available, a minimum of seven repeat profile measurements were made. Raw data were not available for visits 01 and 02. Whenever it was possible, profiles for these visits were extracted from the public database. Visit 00 took place before the original rehabilitation and visit 01 took place just after the original rehabilitation. Section 0501 was removed from the study after visit 03 because it was in extremely poor condition.

Table 2. Profile Measurement Visits of the SPS-5 Site.

Visit	Date	Time	Repeats	Sections
00	05-Feb-1990	17:18	7	0501-0509, 0559-0560
01	21-Sep-1990	21:56	—	0501-0509
02	15-Jan-1992	17:50-18:49	—	0504, 0507
03	22-Feb-1993	13:54	9	0501-0509, 0559-0560
04	03-Feb-1997	09:34-10:44	9	0502-0509, 0559-0560
05	09-Dec-1997	14:04-14:55	7	0502-0509, 0559-0560
06	11-Dec-1998	12:54-13:35	7	0502-0509, 0559-0560
07	11-Nov-1999	11:30-12:06	7	0502-0509, 0559-0560
08	01-Dec-2000	10:53-11:46	9	0502-0509, 0559-0560
09	15-Nov-2001	10:49-11:38	9	0502-0509, 0559-0560
10	04-Nov-2002	12:02-13:10	9	0502-0509, 0559-0560
11	06-Feb-2004	15:24-16:35	9	0502-0509, 0559-0560
12	14-Dec-2004	12:49-14:00	9	0502-0509, 0559-0560
13	24-Mar-2006	11:54-12:48	9	0502-0509, 0559-0560

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 04 through 09 at a 0.98 in sample interval and in visits 10 through 13 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)*

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 a year or more 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 International Roughness Index (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 of Visits 03 through 13

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 09.

   This was done using the event markers from a raw measurement. The first repeat measurement was used for this purpose. Event markers appeared at the start of every section, and appeared at the end of every section except 0505. The locations of the event markers were compared to the layout provided in the construction report. *(1)* They exhibited a linear relationship with a bias of less than 0.05 percent. Once the bias was removed, no individual section starting point in the construction report differed from the event markers by more than 5 ft.

   Most of the sections were assumed to begin at the appropriate event marker, and continue for 500 ft. The exception was section 0560, which continued from the event marker for 600 ft.

2. Automatically synchronize the other eight repeats from visit 09 to the basis set.

3. Automatically synchronize the measurements from the previous visit to the current basis set.
4. Replace the basis set with a new set of synchronized measurements from the first repeat of the current visit.
5. Repeat steps 3 and 4 until visit 03 is complete.

Visits 10 through 13 were synchronized using steps 3 through 5, but going forward in time. Since section 0501 was out of the study after visit 03, its original basis measurement was extracted from the first repeat measurement of visit 00.

Synchronization of Visit 00

Visit 00 could not be synchronized by comparison to later visits, because it took place before major rehabilitation was performed on most of the test sections. A basis set of measurements from visit 00 was created using the first repeat measurement. The rest of the repeats were then automatically synchronized to it. Comparison of the profiles from section 0501, which did not receive any rehabilitation, with later visits verified that visit 00 was lined up with the others.

Synchronization of Visit 01 and 02

Raw data were not available for visits 01 and 02. Thus, data were extracted from the public database and automatically synchronized to profiles from visit 03. For visit 01 this was fairly successful, and most of the measurements lined up with visit 03 within 6.6 ft. Unfortunately this was not the case for visit 02. In visit 02, the profiles within the public database were extracted as if the sample interval was 6 in. However, detailed comparisons with the profiles from other visits showed that the sample interval was actually 5.91 in. As a consequence, the further along the site a section appeared, the more serious the cumulative error in the location of the section starting point became. Thus, only the data from the first two segments along the site, 0504 and 0507, could be used. The sample interval of these profiles was corrected to 5.91 in, and their starting points were shifted slightly to maintain consistency with other visits.

Longitudinal Distance Measurement

The basis set of profile measurements for visit 09, established in step 1, above, was set using the event markers in one raw profile measurement (the first repeat). The other eight repeats from visit 09 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 0.9994 to 1.0000. Thus, the longitudinal distance measurement for the nine profile measurements of visit 09 was consistent within 0.06 percent. This is a very high level 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.

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. *(4)* If tire inflation pressure were the dominant cause, the disagreement would grow more positive with each successive repeat measurement as the tire heated up. 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 04 through 09, but the effect was rarely greater than 0.10 percent of the overall distance. Note that the field procedures require the operator to warm up the tire prior to the measurements. Visits with very consistent longitudinal distance measurement are attributed to proper tire warm-up.

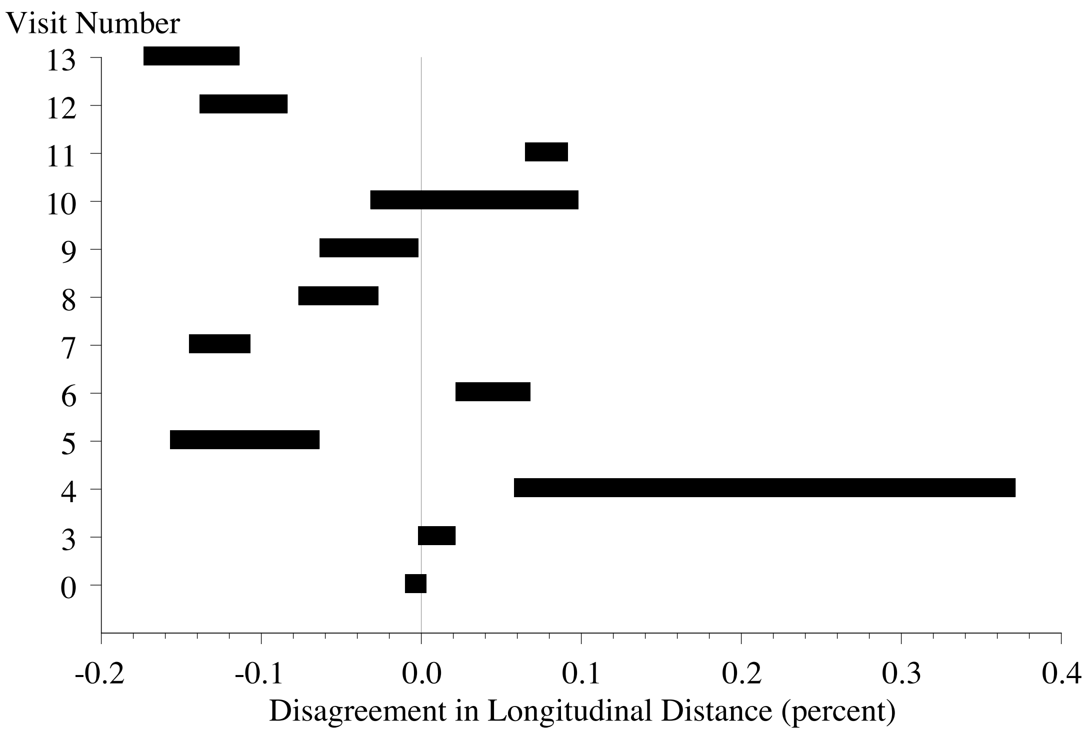

Figure 1. Consistency in longitudinal distance measurement.

The variation between visits in Figure 1 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 pressure must also be close to the level that existed during calibration for consistent results.

Modest inconsistency in longitudinal distance measurement between visits in 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. *(4)* Figure 1 shows that longitudinal distance was measured with a very high level of agreement throughout visits 03 through 13. Note that in visit 04, all of the values for disagreement in longitudinal distance were between 0.06 and 0.13 percent except for one. With this value removed, Figure 1 would show an excellent level of consistency.

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 13 list the selected repeats for each visit of each section, and the composite correlation level produced by them.

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

13 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.

Table 3. Selected Repeats, Section 0501.

Visit	Repeat Numbers					Composite Correlation
00	1	3	4	5	6	0.649
01	1	4	6	7	8	0.608
03	2	3	4	5	6	0.751

Table 4. Selected Repeats, Section 0502.

Visit	Repeat Numbers					Composite Correlation
00	1	3	4	5	6	0.837
01	1	2	3	4	5	0.955
03	2	4	5	6	9	0.977
04	2	3	4	6	7	0.971
05	1	2	3	4	7	0.939
06	1	4	5	6	7	0.950
07	1	2	4	5	6	0.921
08	3	4	6	8	9	0.972
09	1	4	5	7	8	0.967
10	1	4	6	7	8	0.822
11	1	2	3	6	7	0.936
12	2	3	4	5	7	0.912
13	3	4	5	7	9	0.948

Table 5. Selected Repeats, Section 0503.

Visit	Repeat Numbers					Composite Correlation
00	1	3	4	5	7	0.717
01	1	2	3	4	5	0.945
03	2	4	5	6	7	0.963
04	2	5	6	7	8	0.963
05	2	4	5	6	7	0.937
06	1	2	3	4	5	0.952
07	1	4	5	6	7	0.966
08	2	3	5	8	9	0.982
09	1	2	3	7	9	0.966
10	1	3	5	7	9	0.901
11	2	3	5	6	7	0.918
12	1	3	4	6	9	0.937
13	1	2	3	4	5	0.938

Table 6. Selected Repeats, Section 0504.

Visit	Repeat Numbers					Composite Correlation
00	1	4	5	6	7	0.803
01	1	2	3	4	5	0.928
02	3	4	5	6	7	0.934
03	2	4	7	8	9	0.958
04	2	3	5	7	9	0.968
05	1	2	3	4	5	0.963
06	2	3	4	6	7	0.972
07	1	2	3	4	5	0.983
08	1	4	7	8	9	0.987
09	1	3	4	6	8	0.985
10	1	2	3	4	6	0.963
11	1	2	3	4	5	0.957
12	1	3	4	5	6	0.968
13	1	4	5	6	8	0.976

Table 7. Selected Repeats, Section 0505.

Visit	Repeat Numbers					Composite Correlation
00	1	2	3	4	5	0.928
01	1	2	3	4	5	0.945
03	1	2	3	7	8	0.963
04	1	2	5	6	8	0.958
05	1	3	5	6	7	0.912
06	3	4	5	6	7	0.939
07	1	3	4	6	7	0.923
08	1	2	3	4	5	0.922
09	1	2	4	5	6	0.947
10	2	3	4	5	9	0.835
11	2	3	4	6	7	0.887
12	2	3	4	5	8	0.827
13	1	3	5	8	9	0.877

Table 8. Selected Repeats, Section 0506.

Visit	Repeat Numbers					Composite Correlation
00	1	3	4	5	6	0.833
01	1	2	3	4	5	0.913
03	2	3	4	5	6	0.965
04	2	3	5	7	8	0.969
05	1	2	3	4	5	0.935
06	1	3	4	5	6	0.967
07	1	2	3	5	7	0.969
08	1	4	5	6	9	0.980
09	1	5	7	8	9	0.970
10	1	2	3	6	8	0.955
11	3	6	7	8	9	0.966
12	2	3	6	7	8	0.962
13	1	2	3	5	8	0.977

Table 9. Selected Repeats, Section 0507.

Visit	Repeat Numbers					Composite Correlation
00	1	2	5	6	7	0.810
01	1	2	3	4	5	0.890
02	3	4	5	6	7	0.908
03	2	3	4	5	8	0.941
04	1	2	4	7	8	0.965
05	1	3	4	6	7	0.936
06	1	3	4	5	7	0.961
07	1	2	3	4	6	0.958
08	1	4	6	8	9	0.982
09	1	2	4	6	9	0.976
10	2	4	6	7	8	0.956
11	1	4	5	7	9	0.945
12	2	3	4	5	7	0.960
13	1	3	4	5	9	0.959

Table 10. Selected Repeats, Section 0508.

Visit	Repeat Numbers					Composite Correlation
00	1	3	5	6	7	0.803
01	1	2	3	4	5	0.958
03	2	5	7	8	9	0.963
04	2	3	6	7	9	0.962
05	2	3	4	6	7	0.931
06	1	3	4	5	6	0.967
07	1	2	3	4	5	0.972
08	1	2	4	5	8	0.980
09	3	6	7	8	9	0.978
10	1	3	5	6	9	0.941
11	1	2	3	4	8	0.948
12	4	6	7	8	9	0.941
13	3	5	6	8	9	0.964

Table 11. Selected Repeats, Section 0509.

Visit	Repeat Numbers					Composite Correlation
00	1	3	4	5	6	0.848
01	1	2	3	4	5	0.943
03	2	3	4	5	6	0.967
04	2	4	5	6	9	0.976
05	2	3	5	6	7	0.924
06	3	4	5	6	7	0.967
07	1	3	5	6	7	0.971
08	2	4	5	7	8	0.962
09	1	2	3	5	7	0.958
10	1	2	6	7	8	0.838
11	1	2	3	6	7	0.886
12	1	3	4	7	9	0.822
13	3	4	5	7	9	0.929

Table 12. Selected Repeats, Section 0559.

Visit	Repeat Numbers					Composite Correlation
00	1	2	4	5	6	0.866
03	1	2	4	7	8	0.966
04	2	4	5	7	8	0.964
05	2	3	4	5	6	0.963
06	1	3	4	5	6	0.970
07	1	2	3	4	5	0.978
08	1	3	4	7	8	0.984
09	1	3	6	7	8	0.976
10	1	2	4	5	8	0.967
11	3	4	7	8	9	0.973
12	2	3	4	5	7	0.961
13	2	3	5	6	9	0.973

Table 13. Selected Repeats, Section 0560.

Visit	Repeat Numbers					Composite Correlation
00	1	2	5	6	7	0.789
03	1	2	5	6	9	0.946
04	1	2	4	5	9	0.914
05	1	2	4	5	6	0.873
06	1	2	4	5	6	0.882
07	1	2	3	4	5	0.883
08	2	4	6	8	9	0.880
09	2	4	7	8	9	0.919
10	1	2	5	7	9	0.731
11	2	3	4	7	9	0.832
12	1	3	4	5	6	0.815
13	2	5	6	7	8	0.874

Overall, the majority of the groups of measurements listed in Tables 3 through 13 exhibited good to excellent correlation, particularly in visits 03 through 09 and 11. Agreement was lowest overall for visit 00, and all visits of section 0501. Any group of repeat measurements that produced a composite correlation level below 0.85 was investigated using filtered plots, and they are discussed here.

In visit 00, the profile measurements showed a lack of agreement in the shape and severity of localized distresses on many of the sections. Overall, the content within the profiles from wavelengths shorter than about 10 ft was not repeatable. This was often most serious for the right side profile. A lack of repeatability for short wavelength content is not uncommon on pavements with significant distress. The same overall behavior was evident for visits 00, 01, and 03 of section 0501. The correlation exhibited for these three cases was so poor that very little credence should be placed on the analysis results for section 0501.

In visit 10, the left and right side profiles of section 0502 included dips, often more than 0.2 in deep, throughout the entire section. In many cases, the dips did not appear consistently in all five repeat measurements. In particular, the profiles of the last third of the section were dominated by dips that appeared in more than one repeat, but not in all five.

This suggests that the profiles were affected by some type of surface distress that was not consistent across the width of the lane. The inconsistency in the profiles may have been the result of small changes in lateral tracking position of the profiler.

In visit 10, profiles of section 0505 and section 0509 included extraneous narrow dips and spikes that degraded their agreement. Additionally, the shape and severity of genuine narrow dips along section 0509 were not totally consistent between repeat measurements. In visit 12 of section 0505, narrow dips appeared with inconsistent depth and location. Profiles from visit 12 of section 0509 included patch of uncorelated short wavelength content 370 to 440 ft from the start of the section on right and from 225 to 240 and 310 to 380 ft from the start on the left.

In visits 10 and 11, profiles of section 0560 included patches of uncorrelated short wavelength content. This is typically caused by pavement distress that causes aggressive transverse variations in surface profile. Visit 12 also included dense patches of narrow dips that were not well correlated between repeats runs on the right side.

Summary Roughness Values

Figures 2 through 12 show the left and right IRI values for each pavement section over their monitoring period. For most of the sections, this includes twenty-six summary IRI values; two per visit over thirteen visits. (See Table 2.) 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 the date that the site was opened to traffic, which was June 13, 1990. 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 within the LTPP study. 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 2 through 12 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.

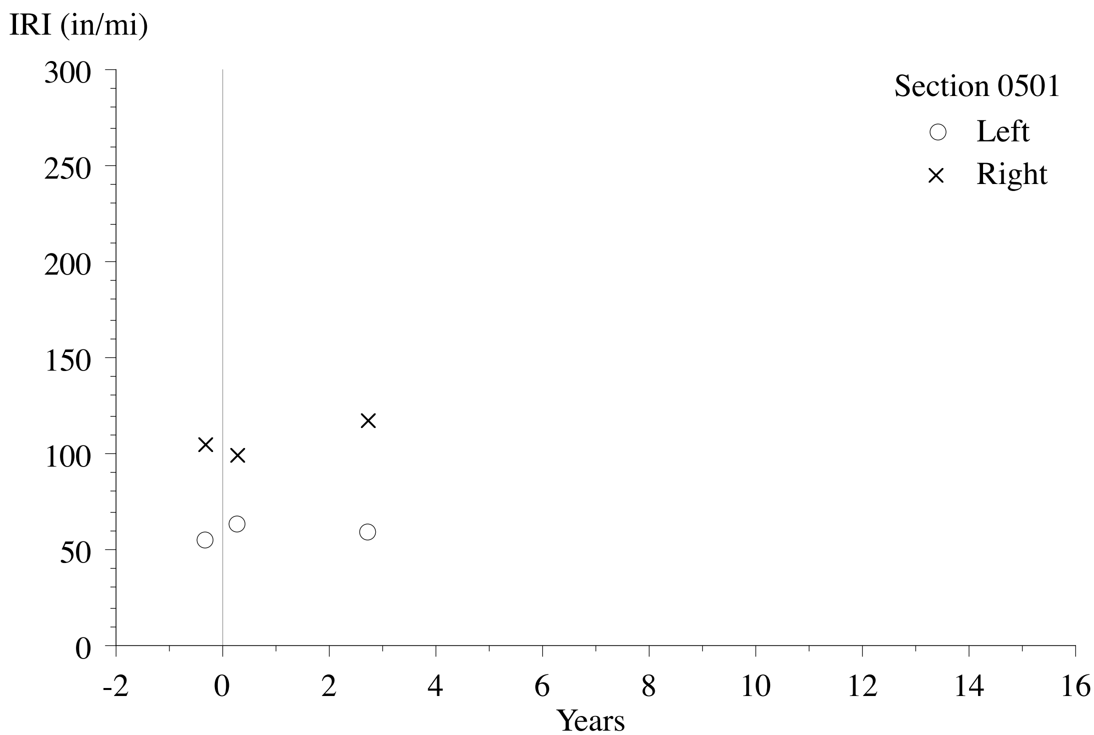

Figure 2. IRI progression, section 0501.

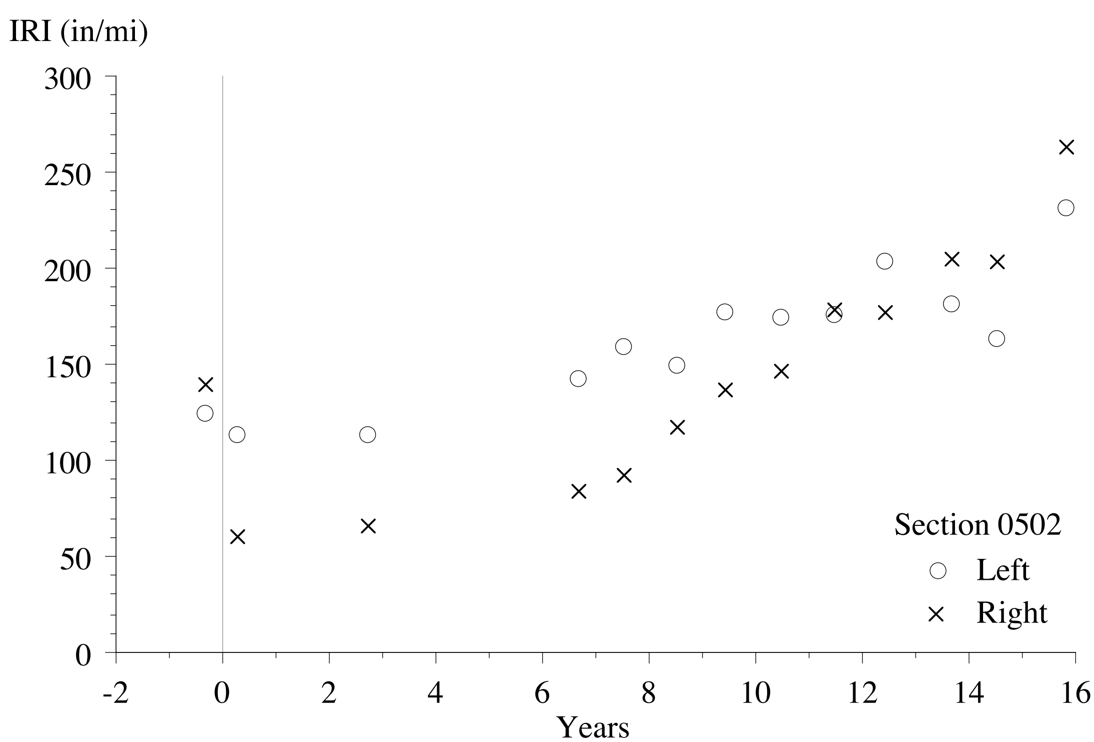

Figure 3. IRI progression, section 0502.

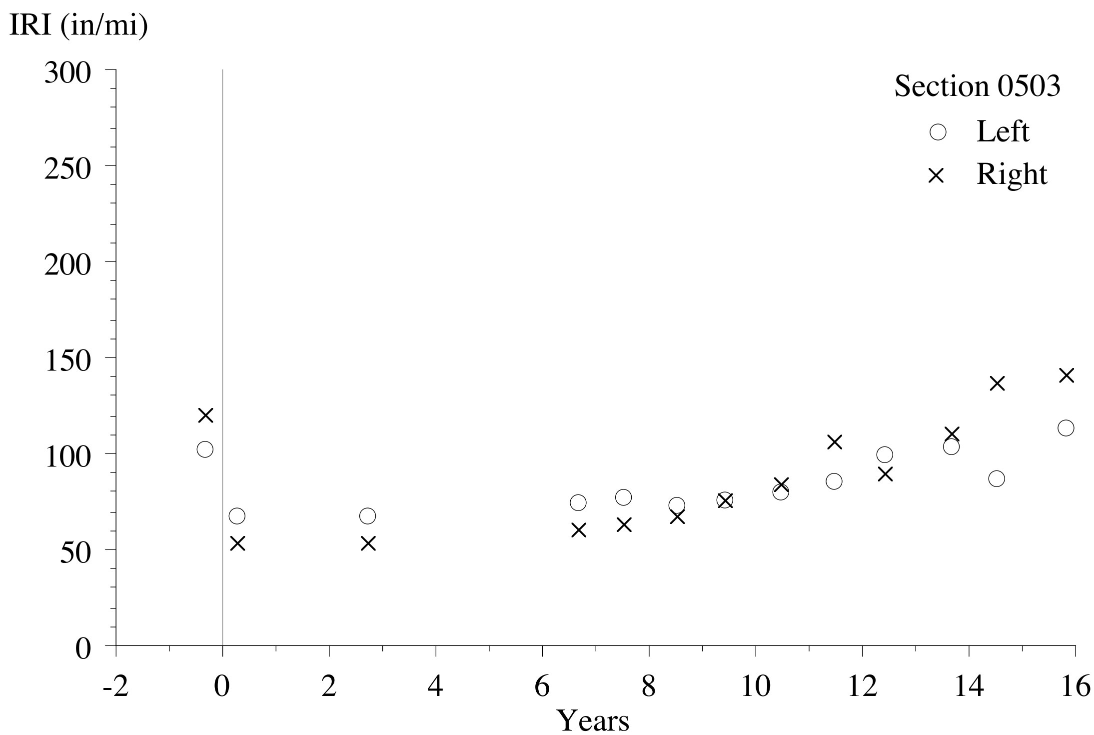

Figure 4. IRI progression, section 0503.

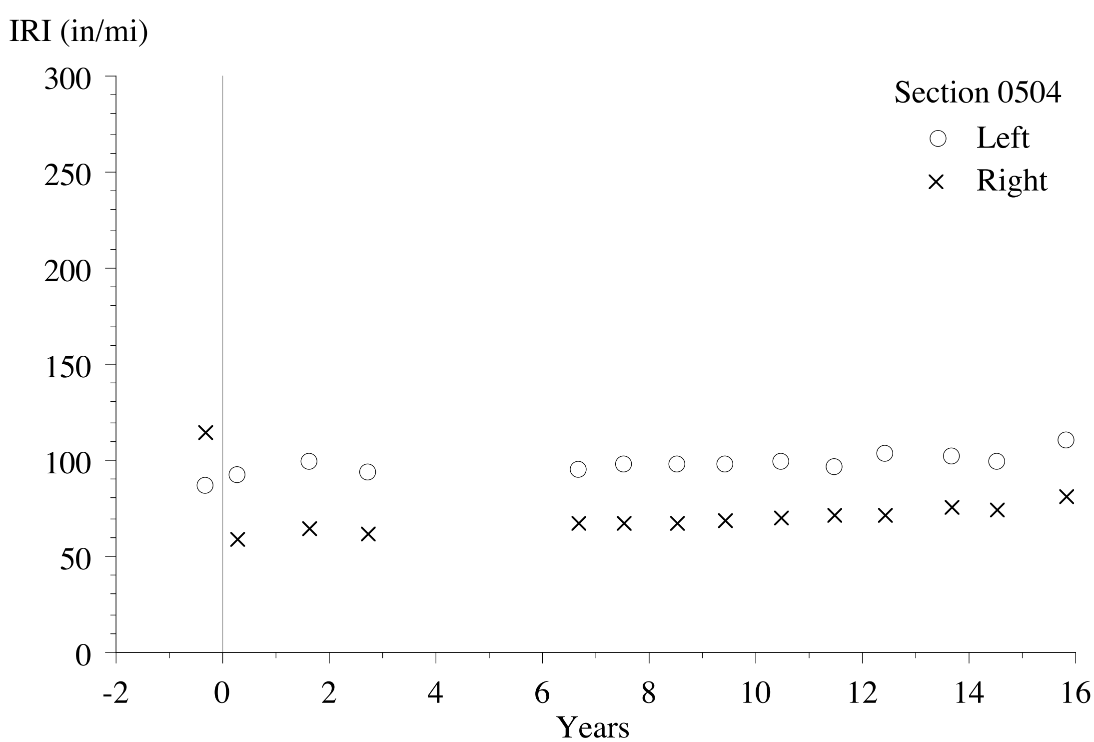

Figure 5. IRI progression, section 0504.

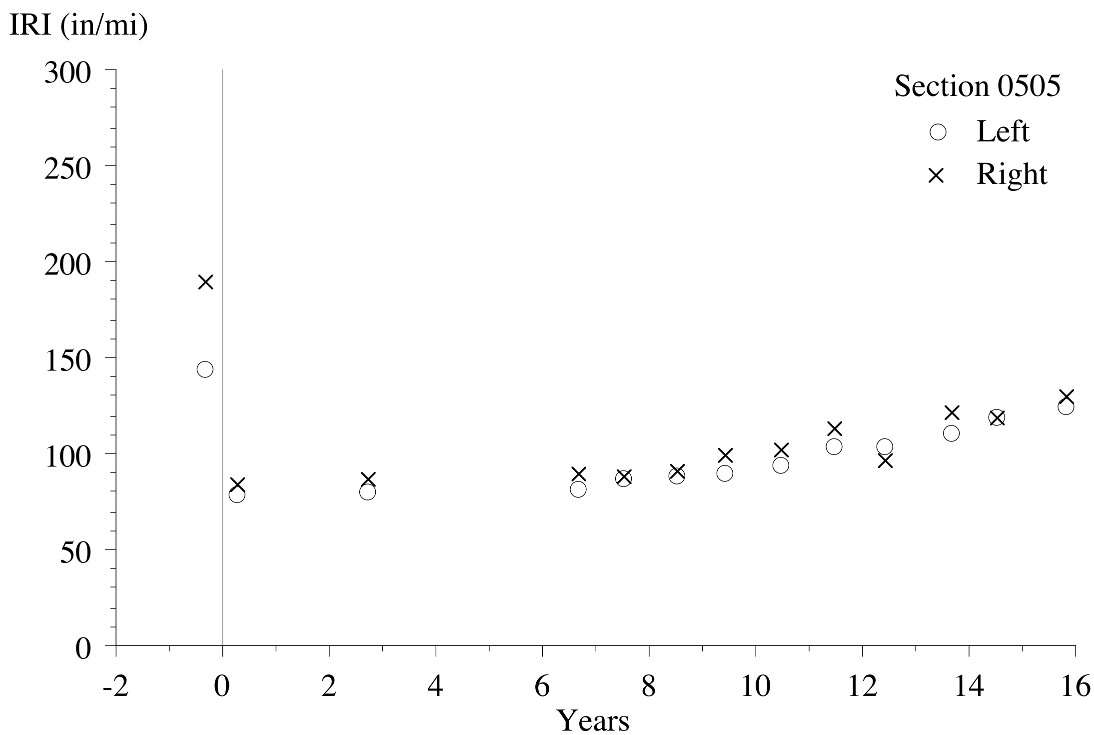

Figure 6. IRI progression, section 0505.

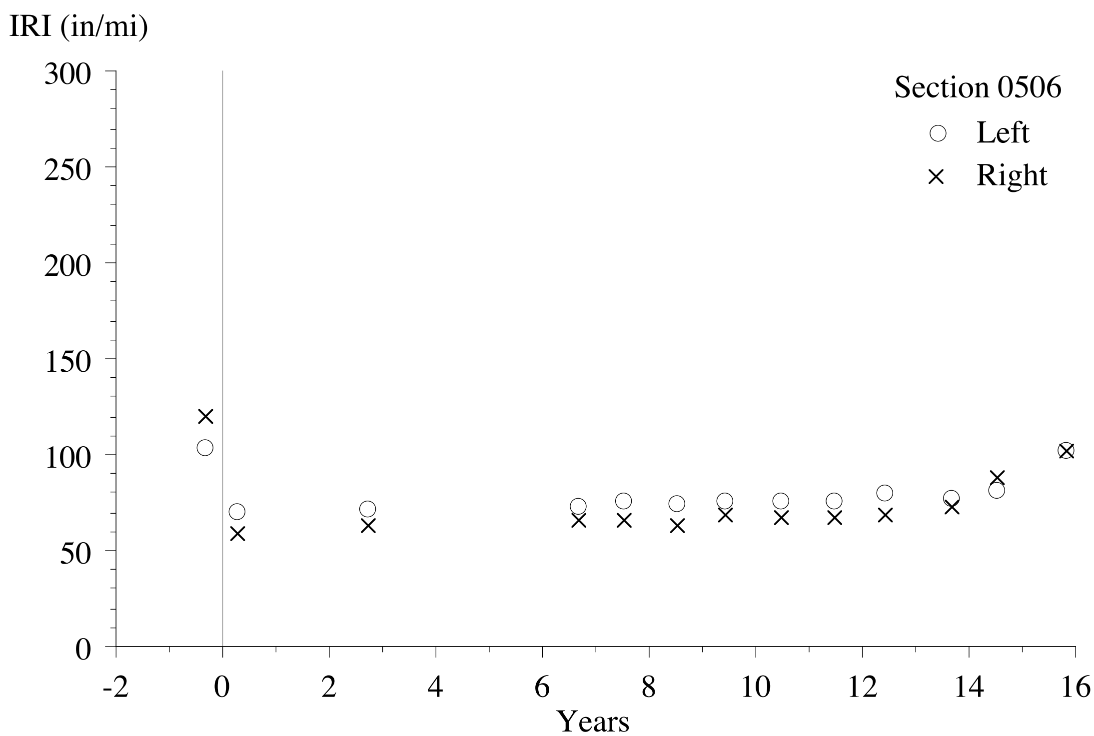

Figure 7. IRI progression, section 0506.

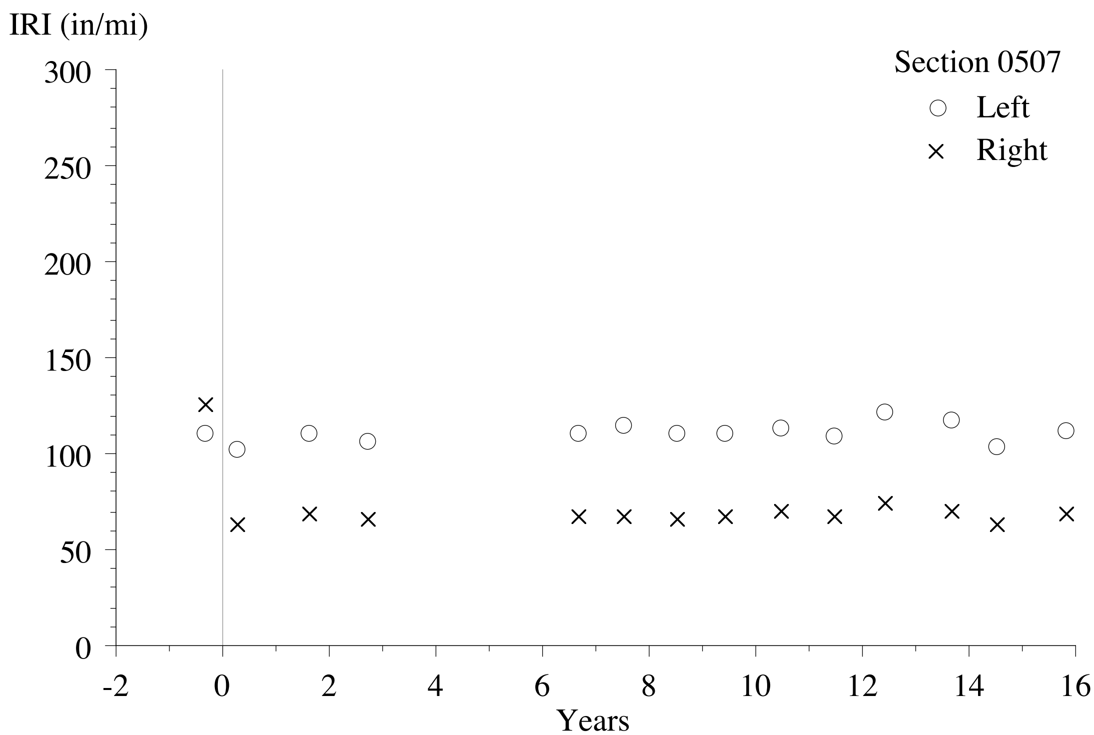

Figure 8. IRI progression, section 0507.

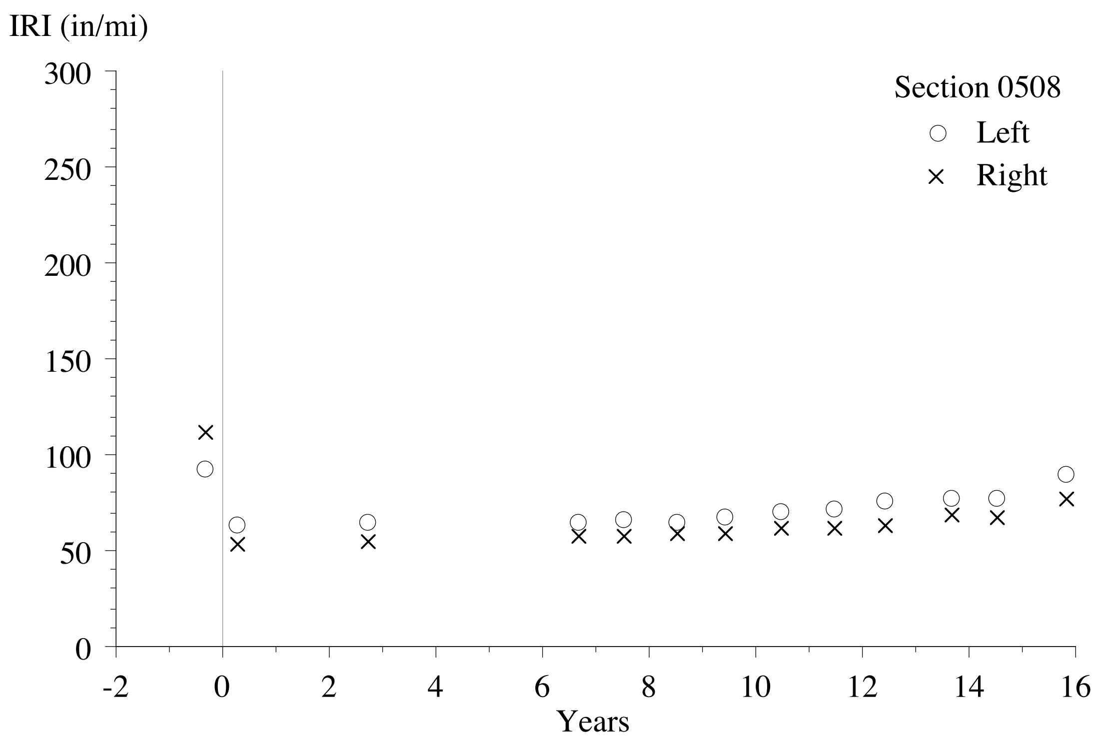

Figure 9. IRI progression, section 0508.

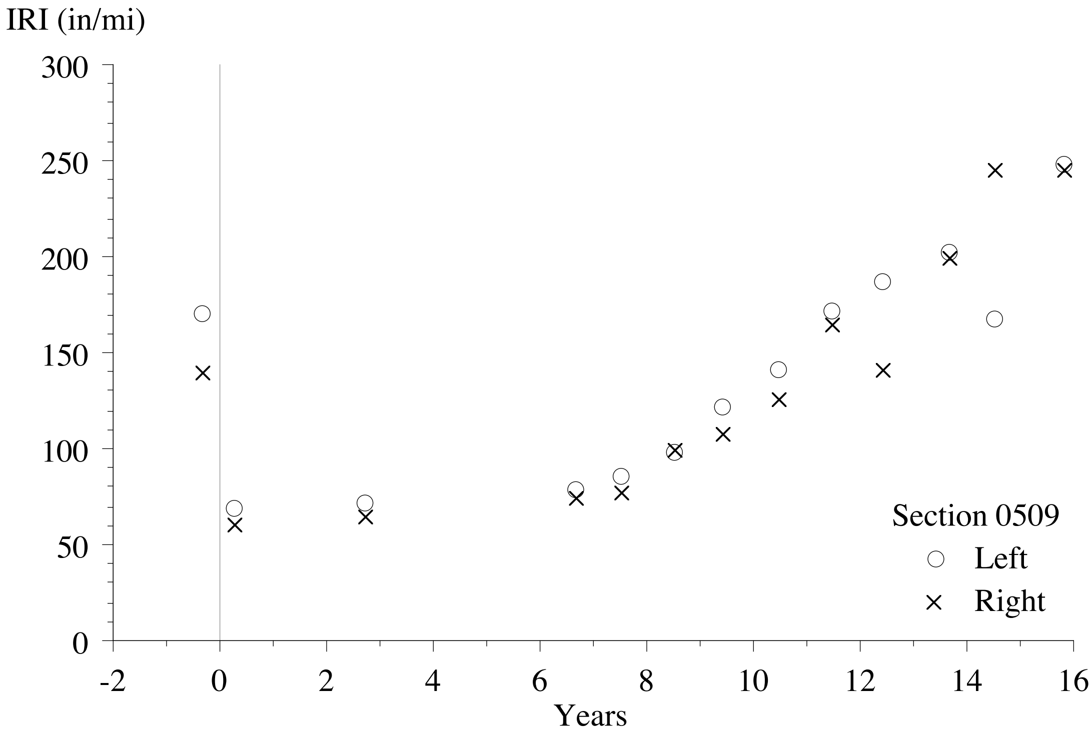

Figure 10. IRI progression, section 0509.

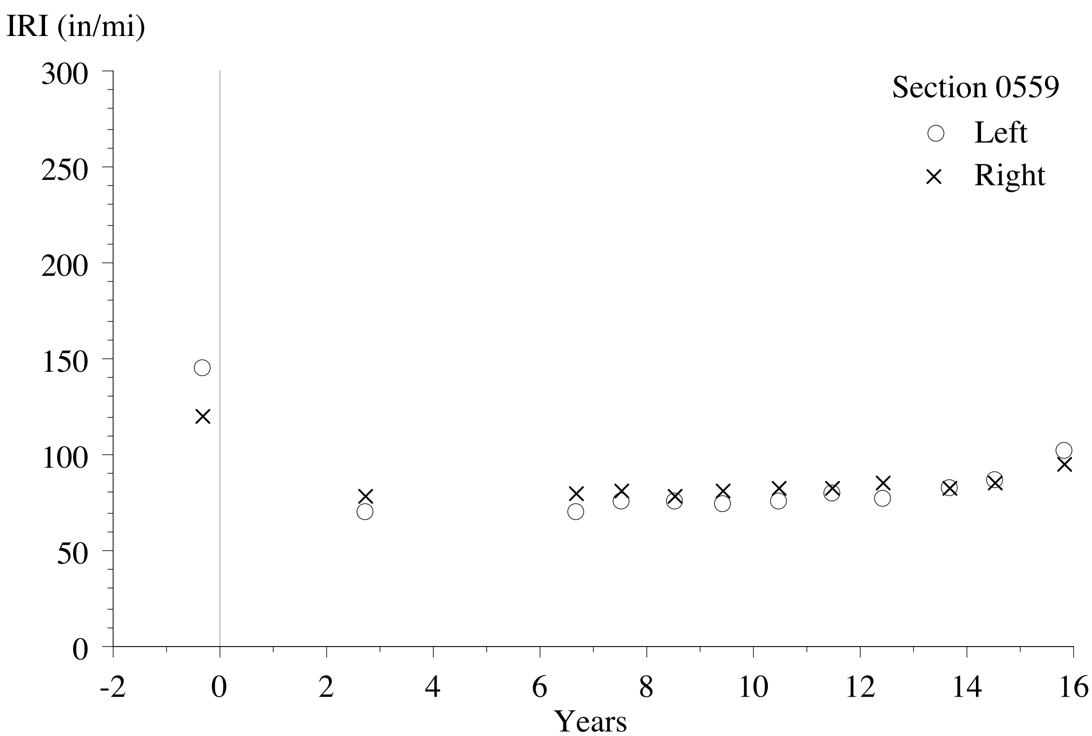

Figure 11. IRI progression, section 0559.

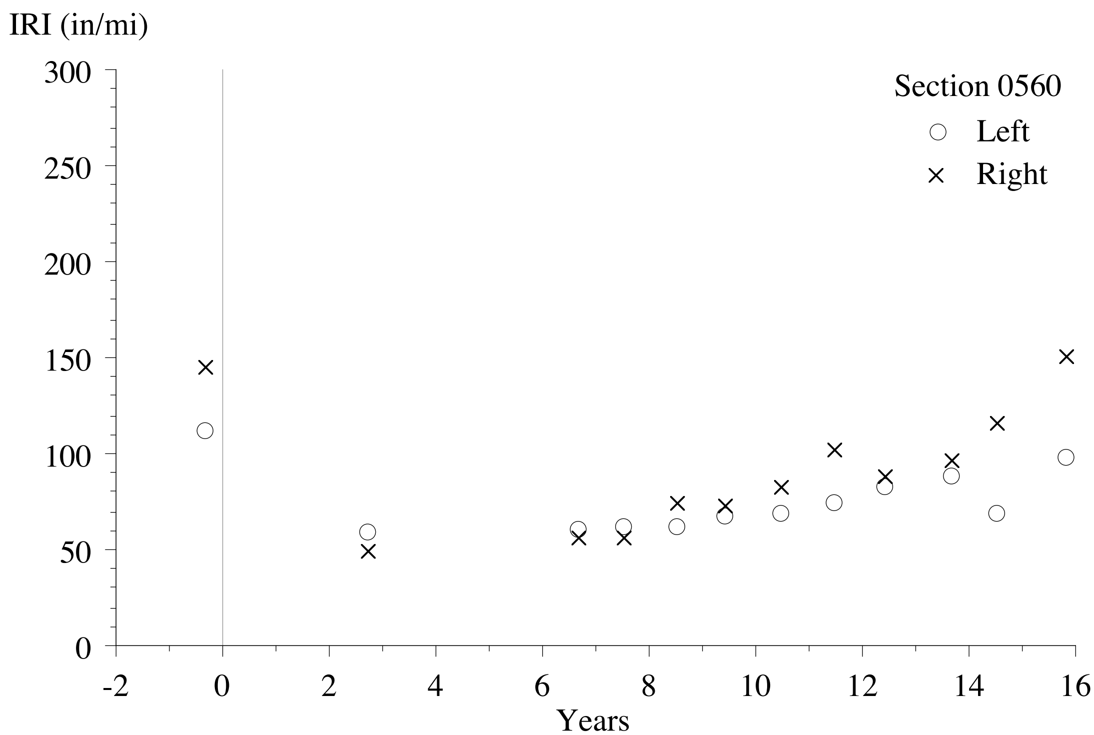

Figure 12. IRI progression, section 0560.

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 elsewhere. *(5)*

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 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, PSDs were typically displayed using twelve 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 PSDs 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 typically covers fewer orders of magnitude than an elevation PSD.

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 rehabilitation 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 13 shows the PSD of the left profile for section 0502 during visit 04 and visit 11. This PSD 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 from about 12 ft to 100 ft (wave numbers between 0.01 cycles/ft and 0.08 cycles/ft) did not change significantly with time.
- The spectral content for wavelengths shorter than 12 ft increased between visits. In fact, this progression was fairly steady from visits 04 through 11.
- In visit 11, the PSD grew with decreasing wavelength (increasing wave number) for wavelengths below 8 ft. This should be interpreted cautiously, however, because a single anomalous reading in the elevation profile or a single severe narrow dip would appear on a PSD plot this way. Alternatively, it may indicate uniform growth in short wavelength roughness over the entire length of the profile.
- The peak at about 0.092 cycles/ft indicates a tremendous amount of roughness with a wavelength of about 10.9 ft. Note that the vertical axis is on a log scale, so the peak at this wavelength is actually more significant than it looks. In fact, the roughness concentrated at wavelengths near 10.9 ft is responsible for more than half of the IRI of the visit 04 profile. This content was present in the first visit after rehabilitation, which indicates that the roughness was built in, rather than a result of deterioration. Inspection of right profile PSD plots show that this periodic content is much more dominant on the left side than the right.

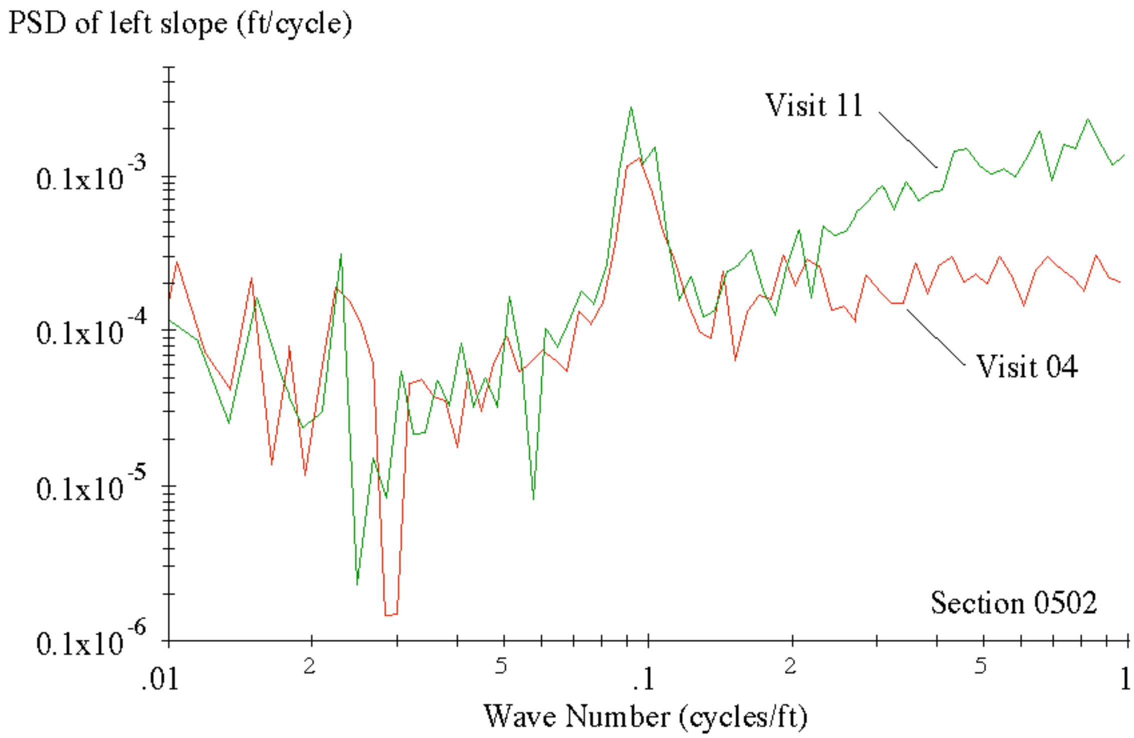

Figure 13. PSD of section 0502 profile, left side.

Each of the final four observations listed above provide important information about the nature of the roughness on section 0502 and its progression. However, the PSD provides no information about where the roughness exists within the 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 provides insight into the filtering practices of the profiler that made the measurements. Figure 14 shows the PSD of the left profile for section 0508 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 true profile of the section. Rather, it is the result of a change in profiler, and an associated change in the high-pass filtering methods. (*6*)
- 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. (*7*)
- The PSD plot for visit 09 includes a spike at a wave number of about 2.6 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 04 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. The wave number where the left-most spike occurred ranged from about 2.04 cycles/ft to 2.72 cycles/ft.

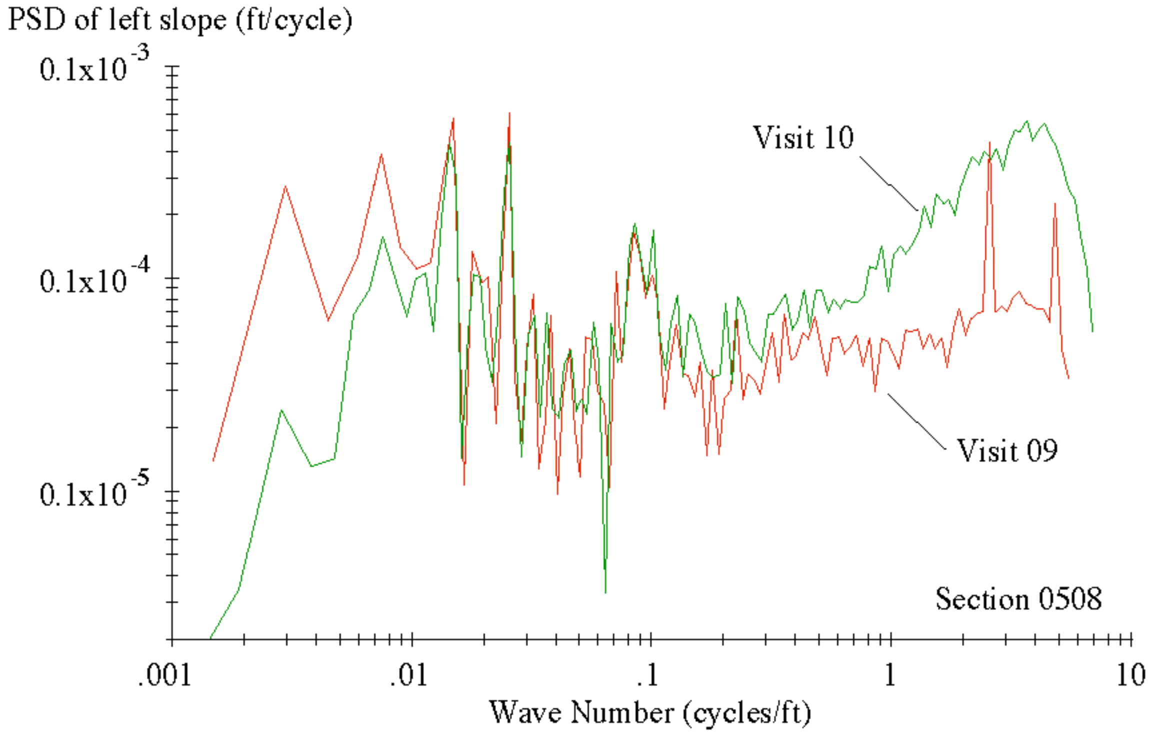

Figure 14. PSD of section 0508 profiles, left side.

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 15 shows the raw profile trace for three visits of section 0509 throughout its monitoring history. The plot shows that the long wavelength content, or the trend, in each plot is quite consistent with time. On the other hand, narrow dips appear in the plots that become more prevalent and severe as time progresses.

Although the raw profile plots in Figure 15 provide very useful information about the nature of the roughness on section 0509, a filtered plot may provide much more detail. In particular, a closer look at the narrow dips may help study their progression. Figure 16 shows a small segment of the profile after it has been high-pass filtered. An anti-smoothing moving average filter was applied with a baselength of 25 ft. (The anti-smoothing is performed by applying a smoothing filter, then subtracting it from the original profile.) Without the filter, the overall trend in the profile masks the dip, such that it is barely visible in the trace from visit 04. When the profile is filtered the dip and its growth with time is much more obvious.

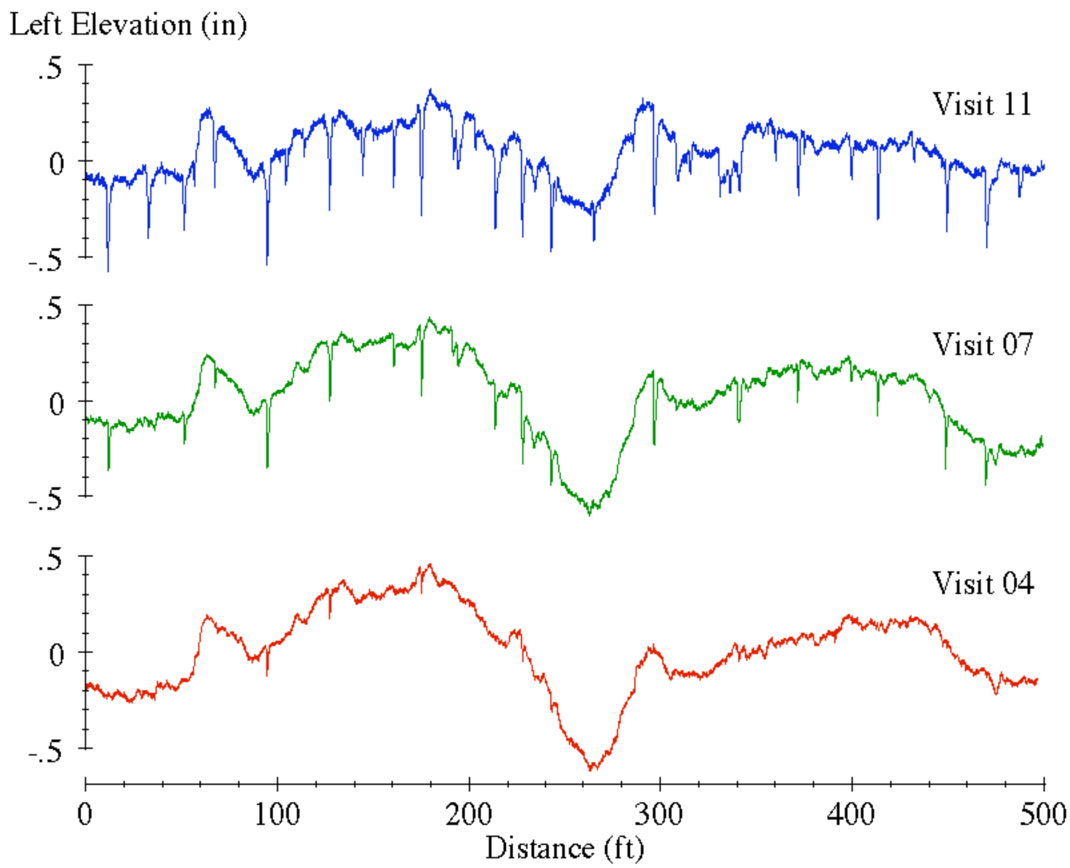

Figure 15. Raw profile of section 0509.

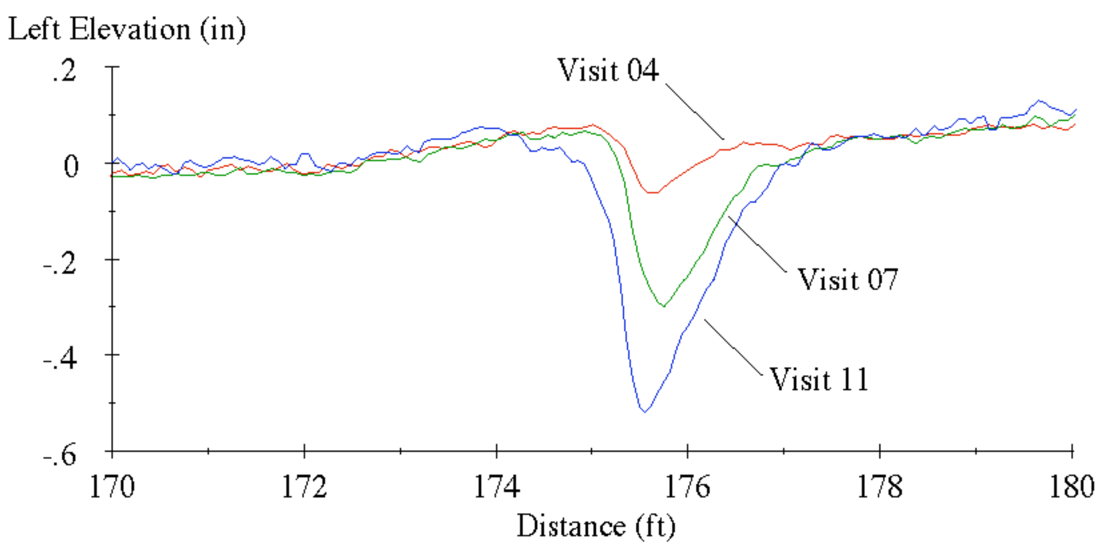

Figure 16. Filtered profile of section 0509.

In addition to a closer view of short-duration features, filtered plots help provide a clearer view of longer trends in profile. Figure 17 provides one such example. The figure shows two profile measurements of section 0560 after they have been smoothed with a baselength of 25 ft and anti-smoothed with a baselength of 125 ft. One trace was collected before rehabilitation, and the other was collected several years later. On this section, the longer wavelength features displayed in the plot were not altered very much by the rehabilitation. (This was not the case on every test section.) On the other hand, the content within the profile in the wavelength range shorter than 25 ft was altered completely.

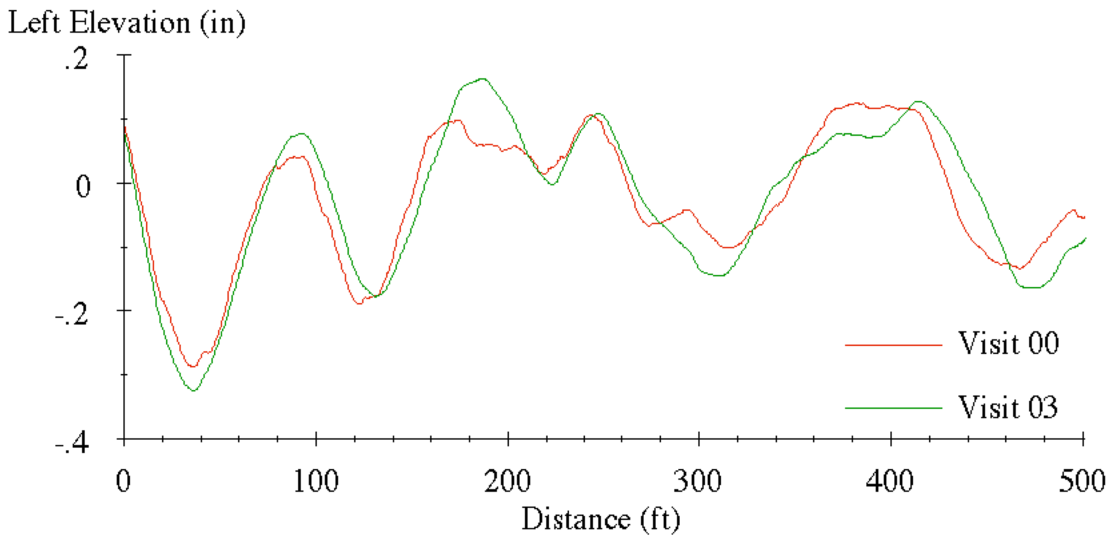

Figure 17. "Long wavelength" profile of section 0560.

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. 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.

Roughness Profile

A roughness profile provides a continuous report of road roughness using a short segment length. 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. (*8*)

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 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 18 shows an example of a roughness profile for visit 11 of section 0503. The roughness profile was generated 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. The plot shows that the first 100 ft and the last 150 ft of the section are very smooth. On the other hand, the area from 100-350 ft from the start of the section is substantially rougher.

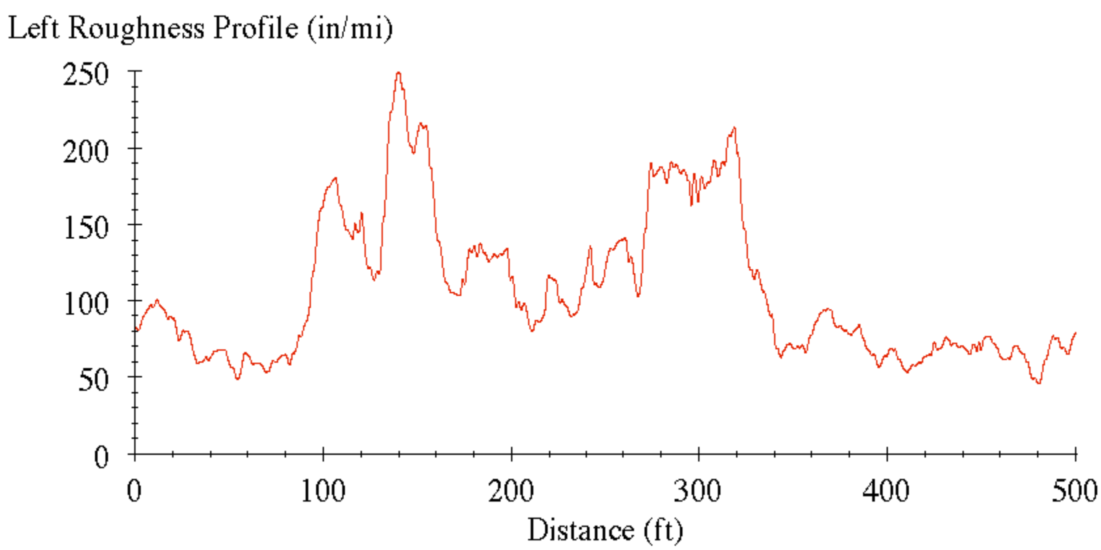

Figure 18. Roughness profile of section 0503, 25-ft baselength.

Figure 19 shows how a roughness profile can help find localized roughness and quantify its impact on the overall roughness of a section. The figure shows the roughness profile of section 0509 using a 10 ft baselength for visits 04, 07 and 11. With a 10 ft baselength, isolated roughness is easy to identify. For example, the dips highlighted in Figure 16, which appear at a location of 175.5 ft, increase in roughness significantly with time. In visit 11, the peak value of the roughness profile in the vicinity of the dip is 546 in/mi. Since that value represents the roughness over just one fiftieth of the segment, it suggests that the single dip contributes more than 10 in/mi to the overall IRI of the section.

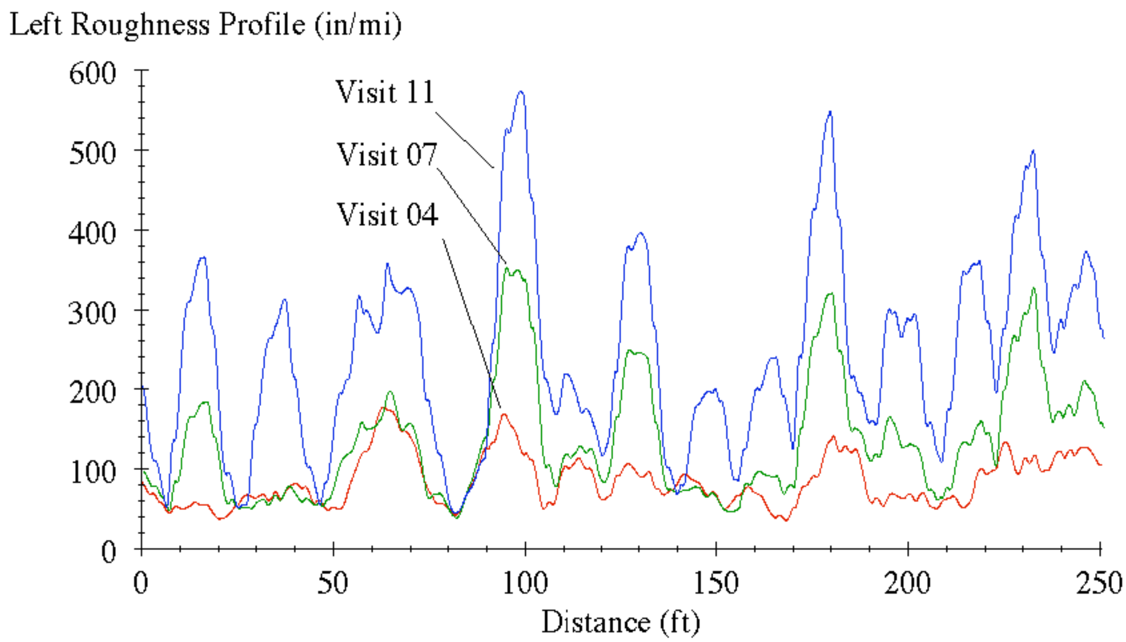

Figure 19. Roughness profile of section 0509, 10-ft baselength.

Distress Surveys and Maintenance Records

Once the analysis and plotting described above were completed, all of the observations were compared to the manual distress survey 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. This provided a means of relating profile features to known distresses. For this SPS-5 project, two observations were common. First, dips that grew progressively rough with time were often found in the vicinity of transverse cracks. This was the case for the dip shown in Figure 16, and the locations of peak roughness in Figure 19. Often, the first appearance of peaks within a very short interval roughness profile corresponded to the year when transverse cracks were first observed in the distress survey. (The presence of the dips could typically be verified using short wavelength elevation plots.) Second, areas where cracks appeared with a very high density within a wheel path sometimes caused areas of isolated roughness to appear within a profile, as well as areas in which the short wavelength content within the same area was not well correlated between repeat runs.

Observations of changes in profile properties were also compared to maintenance records. Crack sealing was performed on all of the sections except 0501 and 0507 in May 2002. The entire test site received a fog seal coat on 28-May-1998 and 16-Apr-2003. The site also received a fog seal on 23-Aug-2001 on test sections 0502, 0505, 0506, 0909, 0559 and 0560.

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 behavior was noted for multiple sections. Those observations are repeated under the heading of every section where it is appropriate. However, Appendix B does not discuss changes in profile properties with time caused by changes in profiler make.

Summary

This section provides a summary of important profile properties and the roughness progression of each section within the Arizona SPS-5 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 2 through 12), 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.

Before rehabilitation, all eleven sections included narrow dips, typically 0.5-0.40 in deep and up to 2 ft wide, dispersed throughout them. The dips were usually more severe on the left side than on the right. Rehabilitation completely removed the dips within every section with the exception of section 0501, which was not rehabilitated.

In many of the sections, some aspects of the long wavelength roughness survived rehabilitation. Sections 0505, 0559 and 0560 had profiles after rehabilitation with very long wavelength content that was very similar to the content before rehabilitation. Sections 0502, 0503 and 0509 exhibited some similarities between the long wavelength content before and after rehabilitation. After rehabilitation, the content within the profiles with wavelengths greater than 30 ft rarely changed over the entire monitoring history of the site.

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 two device. This had no probable effect on the measurement of localized roughness or the study of narrow bumps and dips caused by cracking and other distress. However, it did confound the study of changes in the long-wavelength content within the profiles between visit 09 and 10.

One other minor device effect within the profiles was peaks in the PSD plots with no pavement-related explanation. In visits 04 through 09 (measured by the K.J. Law T-6600) most PSD plots from the left side included a strong peak at a wavelength somewhere between 0.37 and 0.49 ft and another at a wavelength of double the first.

Sections 0502 and 0509 exhibited the most dramatic increase in IRI over their post-rehabilitation monitoring history. They both grew in roughness at an increasing rate and were both very rough by the end of the monitoring period. Both sections included transverse cracks that became more severe with time. Concentrated roughness appeared at many of the cracks within a few years of their detection by manual distress surveys. The roughness appeared as narrow dips that grew in severity with time. Note that the dips were much wider than a typical crack, often 1-2 ft wide. Thus, some genuine depressions in the pavement were constantly developing around the cracks. Some of the dips grew to as much as 0.75 in deep.

Sections 0503, 0505 and 0560 also exhibited a large change in roughness with time. They grew in roughness at an increasing rate, and their MRI changed by 67 in/mi, 45 in/mi, and 70 in/mi, respectively, throughout their post-rehabilitation monitoring history. Section 0505 developed roughness because dips appeared of increasing severity near transverse cracks. Section 0505 developed roughness in a manner that was very similar to sections 0502 and 0509. It included fewer rough transverse cracks, but included roughness at densely-cracked areas within the wheel paths.

Sections 0503 and 0560 also included dips at transverse cracks. However, a significant portion of their roughness development was caused by large densely cracked areas, not necessarily in the transverse direction, within the wheel paths. The hit or miss nature of their placement relative to the path of the profiler caused inconsistencies in the shape of rough features between repeat measurements and between visits. Nevertheless, the cracks caused a consistent growth in roughness over the affected areas.

Sections 0504, 0506, 0508 and 0559 increased in roughness at a steady rate after rehabilitation until 2004. The MRI of these sections increased by no more than 15 in/mi during their post-rehabilitation monitoring history through February 2004. These sections, particularly section 0508, included dips near transverse cracks in prior visits. However, the dips were usually not very severe until the final two profiling visits in late 2004 and 2006. In sections 0506, 0508 and 0559, the rounghess increased more rapidly in the last 2 years than over the previous 14 years because of narrow dips in the vicinity of recorded transverse cracks. Section 0507 showed little roughness linked to transverse cracking.

Sections 0502, 0504 and 0507 showed little, in any, improvement in IRI on the left side after rehabilitation. In addition, the roughness of the left side after rehabilitation was much higher than that of the right. This was caused by a continuous (sinusoidal) series of bumps and dips with peaks 8-13 ft apart and a peak-to-trough difference in elevation of up to 0.2 inches. These were present on the right side, and a dominant part of the roughness on the left side. This may have been caused by problems with the rolling process, but that could not be verified.

Crack sealing was performed on all of the sections except 0501 and 0507 in May 2002. Very little evidence was found that this directly affected the roughness. (Of course, crack sealing very well could have decelerated the deterioration of these sections.) The entire test site received a fog seal coat on 28-May-1998 and 16-Apr-2003. The site also received a fog seal on 23-Aug-2001 on seven of the test section (excluding the first four along the length of the site - 0507, 0504, 0503, 0508). Fog sealing did not cause an immediate change on the IRI.

Sections 0501, 0502 and 0560 had HRI values that were 20 percent or more below the MRI values. In section 0502, the HRI grew increasingly small compared to the MRI with time. This is a larger difference than was observed on most other sections. The difference is caused by the presence of profile features that are not consistent across the lane. Typically, this also signifies the presence of localized distress.

Table 14 provides a summary of the roughness behavior of each section within the SPS-5 site.

Table 14. Roughness behavior summary.

Section	0502	0503	0504	0505	0506	0507	0508	0509	0559	0560
MRI change after rehabilitation (in/mi)	-44	-51	-24	-85	-48	-26	-44	-91	-59	-75
MRI change since rehabilitation (in/mi)	160	67	21	45	38	11	25	183	24	70
MRI change over 7 years after rehab. (in/mi)	26	7	7	6	7	9	3	18	4	5
MRI growth at an increasing rate	X	X		x	x		x	X		X
MRI growth at a steady rate			X			X			X	
HRI about 20 percent below MRI	X			X						X
Left IRI much higher than right IRI			X			X				
Dominant periodic content, 8-13 ft	X		X			X				
Very long features preserved after rehab.	x	x		X				x	X	X
Severe dips near transverse cracks	X	X		X	X		X	X		
Patches or roughness near dense cracking		X		X						X

X — Yes x — Somewhat

When the information in Table 14 is considered in light of the rehabilitation that was performed on each section, the following observation can be made:

- The two test sections with a 2-inch recycled overlay (0502 and 0509) exhibited the largest post-rehabilitation increase in MRI over the monitoring history by a wide margin (160 in/mi and 183 in/mi, respectively).
- The two test sections with a 5-inch virgin overlay (0507 and 0504) exhibited the smallest post-rehabilitation increase in MRI over the monitoring history (11 in/mi and 21 in/mi, respectively).
- All of the test sections except those with a 2-inch recycled overlay (0502 and 0509) increased in MRI by less than 10 in/mi over the first seven years after rehabilitation.
- Test sections with narrow dips at transverse cracks increased in roughness the most.

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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 670 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 0.830. A typical value for asphalt pavement is about 0.85.

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 the roughness of a section is dominated by a particular type of distress. 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 noise within the profile 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.

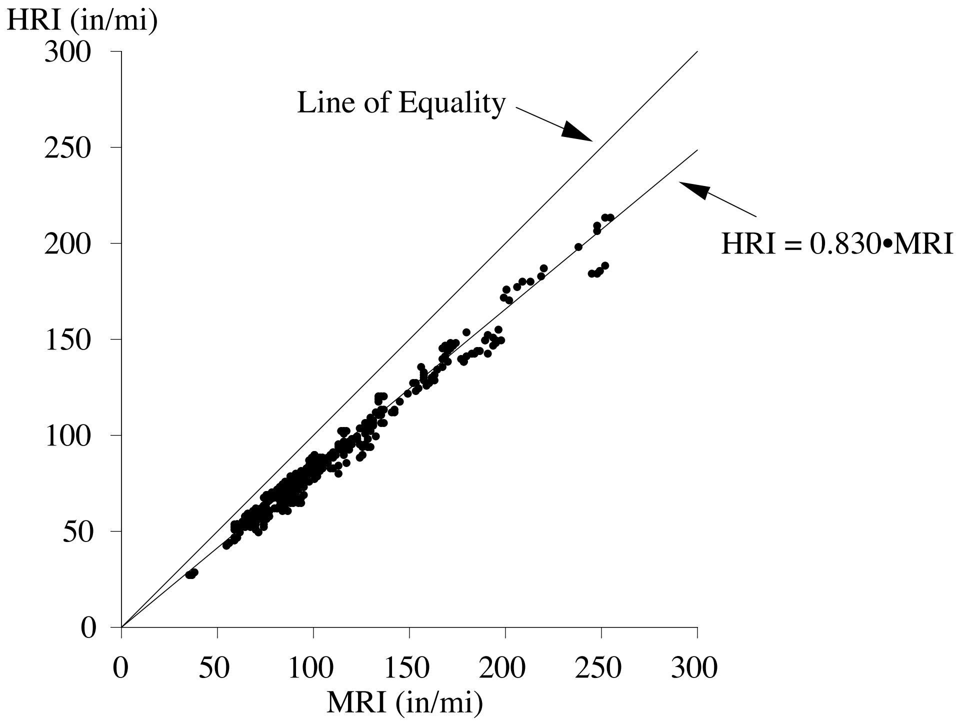

Figure A–1. Comparison of HRI to MRI.

Table A-1. Roughness Values.

Section	Date	Years	Left IRI (in/mi)		Right IRI (in/mi)		MRI (in/mi)	HRI (in/mi)	RN
			Ave	St Dev	Ave	St Dev			
0501	05-Feb-90	-0.35	55	7.1	105	10.6	80	64	3.09
0501	21-Sep-90	0.27	63	12.1	100	3.8	82	64	3.01
0501	22-Feb-93	2.70	60	4.8	118	6.6	89	71	2.77
0502	05-Feb-90	-0.35	125	6.5	140	5.8	132	106	2.41
0502	21-Sep-90	0.27	114	2.6	61	1.3	88	78	3.90
0502	22-Feb-93	2.70	114	1.5	66	0.7	90	79	3.80
0502	03-Feb-97	6.64	143	2.0	85	0.6	114	96	3.07
0502	09-Dec-97	7.49	160	4.0	93	1.4	126	105	2.81
0502	11-Dec-98	8.50	150	3.1	119	1.1	134	113	2.59
0502	11-Nov-99	9.41	178	6.7	137	1.7	157	127	2.17
0502	01-Dec-00	10.47	175	2.2	148	1.4	161	130	2.09
0502	15-Nov-01	11.43	176	2.9	179	2.2	178	139	1.85
0502	04-Nov-02	12.39	205	7.8	177	6.7	191	149	1.68
0502	06-Feb-04	13.65	182	4.3	205	1.4	194	150	1.55
0502	14-Dec-04	14.51	164	4.2	204	4.5	184	145	1.62
0502	24-Mar-06	15.78	232	7.6	264	4.5	248	186	1.02
0503	05-Feb-90	-0.35	102	4.7	121	7.4	112	84	2.70
0503	21-Sep-90	0.27	67	2.5	54	0.5	61	53	4.16
0503	22-Feb-93	2.70	68	0.6	54	0.2	61	53	4.07
0503	03-Feb-97	6.64	75	0.7	61	0.6	68	56	3.97
0503	09-Dec-97	7.49	78	0.8	63	0.5	71	59	3.82
0503	11-Dec-98	8.50	74	1.2	68	1.2	71	57	3.73
0503	11-Nov-99	9.41	76	0.4	76	1.1	76	61	3.56
0503	01-Dec-00	10.47	81	0.5	85	0.2	83	68	3.32

Table A-1 (cont). Roughness Values.

Section	Date	Years	Left IRI (in/mi)		Right IRI (in/mi)		MRI	HRI	RN
			Ave	St Dev	Ave	St Dev	(in/mi)	(in/mi)	
0503	15-Nov-01	11.43	86	1.5	107	1.2	96	80	2.94
0503	04-Nov-02	12.39	101	1.0	90	2.6	95	77	2.97
0503	06-Feb-04	13.65	104	2.1	111	2.1	108	90	2.76
0503	14-Dec-04	14.51	87	2.3	138	2.9	112	94	2.61
0503	24-Mar-06	15.78	114	4.2	141	2.2	128	107	2.35
0504	05-Feb-90	-0.35	87	6.5	115	6.8	101	84	2.90
0504	21-Sep-90	0.27	94	1.9	60	2.4	77	69	4.04
0504	15-Jan-92	1.59	100	2.7	65	1.3	83	73	3.98
0504	22-Feb-93	2.70	95	1.7	62	0.9	79	70	3.97
0504	03-Feb-97	6.64	96	0.5	68	0.8	82	70	3.90
0504	09-Dec-97	7.49	99	0.9	68	0.8	84	71	3.82
0504	11-Dec-98	8.50	98	0.7	68	0.8	83	71	3.85
0504	11-Nov-99	9.41	99	0.5	70	0.4	84	72	3.88
0504	01-Dec-00	10.47	100	0.6	71	0.3	86	74	3.87
0504	15-Nov-01	11.43	97	0.5	72	0.5	85	73	3.86
0504	04-Nov-02	12.39	105	1.1	73	0.6	89	76	3.67
0504	06-Feb-04	13.65	103	1.9	76	0.8	89	77	3.65
0504	14-Dec-04	14.51	101	0.5	75	1.1	88	79	3.55
0504	24-Mar-06	15.78	113	0.5	83	0.8	98	85	3.22
0505	05-Feb-90	-0.35	144	8.3	190	4.3	167	138	2.26
0505	21-Sep-90	0.27	79	1.1	84	0.8	82	71	3.95
0505	22-Feb-93	2.70	80	1.7	88	0.7	84	73	3.86
0505	03-Feb-97	6.64	82	1.2	90	0.9	86	71	3.71
0505	09-Dec-97	7.49	88	2.3	89	1.0	88	73	3.58
0505	11-Dec-98	8.50	89	1.5	91	0.3	90	74	3.43
0505	11-Nov-99	9.41	90	2.3	100	0.9	95	80	3.24
0505	01-Dec-00	10.47	95	2.2	103	0.9	99	82	3.13
0505	15-Nov-01	11.43	104	1.6	114	2.1	109	89	2.88
0505	04-Nov-02	12.39	104	4.0	98	3.4	101	80	2.86
0505	06-Feb-04	13.65	112	1.3	123	4.5	117	94	2.69
0505	14-Dec-04	14.51	119	4.2	120	4.4	119	98	2.47
0505	24-Mar-06	15.78	124	2.6	130	4.8	127	97	2.33
0506	05-Feb-90	-0.35	104	8.5	121	5.4	113	91	2.69
0506	21-Sep-90	0.27	71	2.0	59	1.8	65	58	4.09
0506	22-Feb-93	2.70	73	1.1	63	0.5	68	59	4.05
0506	03-Feb-97	6.64	74	0.9	67	0.6	70	58	3.99
0506	09-Dec-97	7.49	77	0.7	67	0.5	72	59	3.89
0506	11-Dec-98	8.50	74	0.5	64	1.0	69	58	3.95
0506	11-Nov-99	9.41	77	0.5	69	0.4	73	60	3.96
0506	01-Dec-00	10.47	76	0.3	69	0.6	72	60	3.97
0506	15-Nov-01	11.43	76	0.9	68	0.6	72	60	3.92
0506	04-Nov-02	12.39	80	0.8	69	0.7	74	61	3.83
0506	06-Feb-04	13.65	77	0.5	74	0.5	76	61	3.54
0506	14-Dec-04	14.51	82	0.6	89	0.6	85	71	2.81
0506	24-Mar-06	15.78	102	1.9	103	0.5	103	88	2.50
0507	05-Feb-90	-0.35	111	8.1	127	4.8	119	97	2.58
0507	21-Sep-90	0.27	103	5.6	63	4.6	83	74	4.01
0507	15-Jan-92	1.59	112	5.1	69	2.4	91	79	3.91
0507	22-Feb-93	2.70	107	1.8	66	2.3	86	76	3.93
0507	03-Feb-97	6.64	112	1.5	69	0.2	90	77	3.84

Table A-1 (cont). Roughness Values.

Section	Date	Years	Left IRI (in/mi)		Right IRI (in/mi)		MRI	HRI	RN
			Ave	St Dev	Ave	St Dev	(in/mi)	(in/mi)	
0507	09-Dec-97	7.49	115	3.8	69	1.9	92	78	3.78
0507	11-Dec-98	8.50	111	1.5	67	0.9	89	77	3.83
0507	11-Nov-99	9.41	111	1.7	68	1.3	90	77	3.85
0507	01-Dec-00	10.47	114	0.6	70	0.2	92	80	3.82
0507	15-Nov-01	11.43	110	0.5	68	0.8	89	77	3.85
0507	04-Nov-02	12.39	122	1.8	76	0.9	99	84	3.64
0507	06-Feb-04	13.65	119	1.7	71	1.3	95	81	3.69
0507	14-Dec-04	14.51	104	1.1	63	1.1	84	75	3.81
0507	24-Mar-06	15.78	113	1.4	71	0.7	92	80	3.66
0508	05-Feb-90	-0.35	93	5.0	113	3.9	103	83	2.72
0508	21-Sep-90	0.27	64	0.5	54	0.8	59	54	4.27
0508	22-Feb-93	2.70	65	0.6	55	0.5	60	54	4.21
0508	03-Feb-97	6.64	65	0.4	58	1.0	62	54	4.14
0508	09-Dec-97	7.49	67	1.0	58	0.7	62	54	3.98
0508	11-Dec-98	8.50	65	0.3	59	0.4	62	55	4.05
0508	11-Nov-99	9.41	68	0.2	60	0.4	64	56	4.11
0508	01-Dec-00	10.47	71	0.2	62	0.2	66	59	4.04
0508	15-Nov-01	11.43	72	0.5	63	0.5	67	59	3.89
0508	04-Nov-02	12.39	76	0.9	63	0.4	70	60	3.73
0508	06-Feb-04	13.65	78	1.2	69	0.6	74	64	3.57
0508	14-Dec-04	14.51	78	1.1	68	0.6	73	64	3.55
0508	24-Mar-06	15.78	90	1.1	77	0.9	84	71	3.25
0509	05-Feb-90	-0.35	171	5.1	141	5.5	156	130	2.18
0509	21-Sep-90	0.27	69	0.5	61	1.7	65	59	4.15
0509	22-Feb-93	2.70	72	0.9	65	0.6	68	61	4.06
0509	03-Feb-97	6.64	79	0.4	74	0.5	77	68	3.72
0509	09-Dec-97	7.49	87	1.0	78	1.4	83	73	3.45
0509	11-Dec-98	8.50	98	1.4	100	1.5	99	89	2.88
0509	11-Nov-99	9.41	123	1.2	108	0.4	115	102	2.49
0509	01-Dec-00	10.47	141	1.4	127	2.6	134	120	2.20
0509	15-Nov-01	11.43	173	1.5	166	5.0	169	147	1.78
0509	04-Nov-02	12.39	188	11.1	141	12.7	164	141	1.94
0509	06-Feb-04	13.65	203	7.6	200	12.2	202	175	1.62
0509	14-Dec-04	14.51	168	18.5	246	15.2	207	177	1.59
0509	24-Mar-06	15.78	249	3.1	246	15.7	248	209	1.28
0559	05-Feb-90	-0.35	146	13.4	121	2.3	134	106	2.61
0559	22-Feb-93	2.70	71	0.8	79	0.4	75	68	3.94
0559	03-Feb-97	6.64	71	1.2	81	0.3	76	67	3.91
0559	09-Dec-97	7.49	77	1.4	81	1.1	79	70	3.81
0559	11-Dec-98	8.50	76	0.7	79	0.9	78	69	3.86
0559	11-Nov-99	9.41	75	0.8	81	0.5	78	69	3.88
0559	01-Dec-00	10.47	76	0.3	83	0.5	79	71	3.83
0559	15-Nov-01	11.43	80	0.7	83	0.4	82	72	3.67
0559	04-Nov-02	12.39	77	0.7	87	1.2	82	71	3.57
0559	06-Feb-04	13.65	84	0.7	83	0.9	83	71	3.47
0559	14-Dec-04	14.51	87	1.0	86	0.7	86	74	3.37
0559	24-Mar-06	15.78	103	1.0	96	1.0	99	84	2.88
0560	05-Feb-90	-0.35	113	22.9	146	11.9	130	106	2.70
0560	22-Feb-93	2.70	60	0.9	50	0.6	55	44	4.14
0560	03-Feb-97	6.64	61	0.5	56	1.8	58	47	3.99

Table A-1 (cont). 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			
0560	09-Dec-97	7.49	63	0.7	57	5.1	60	49	3.84
0560	11-Dec-98	8.50	62	0.9	75	2.0	68	54	3.65
0560	11-Nov-99	9.41	68	0.3	74	3.7	71	52	3.54
0560	01-Dec-00	10.47	69	0.9	83	2.2	76	58	3.40
0560	15-Nov-01	11.43	74	0.8	102	1.7	88	66	3.08
0560	04-Nov-02	12.39	84	2.1	89	5.9	86	64	2.96
0560	06-Feb-04	13.65	89	0.3	97	3.1	93	67	2.80
0560	14-Dec-04	14.51	69	1.5	116	8.9	93	73	3.07
0560	24-Mar-06	15.78	99	2.9	152	3.9	125	92	2.17

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.

Appendix B: Detailed Observations

This appendix provides detailed observations from the roughness trends, profiles and distress surveys of each section within the Arizona SPS-5 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.

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 displayed using a baselength of either 10 ft (called a *very short interval roughness profile*) or 25 ft (called a *short interval roughness profile*) unless otherwise specified. An area has localized roughness when the short interval roughness profile 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 few of the profiles were dominated by periodic content.

Section 0501

<u>Roughness</u>: The right side of the lane was much rougher than the left. This section was taken out of the study after three visits, and no significant change in roughness occurred during that time. The average HRI for each visit was about 20 percent lower than the MRI. This is a larger difference than was observed on most other sections. This may signify the presence of localized roughness that appears in only one side of the lane.

<u>PSD</u>: The PSD plots were typical for asphalt pavement. They did not change significantly with time.

<u>Filtered Profiles</u>:

<u>Long Wavelengths</u>: The long wavelength content of the profiles was very consistent through time.

<u>Medium Wavelengths</u>: The medium wavelength elevation plots were not consistent throughout the four visits. In addition, the profiles were not very repeatable within a given visit. Nevertheless, the overall roughness level appeared to be about the same in each profile.

<u>Short Wavelengths</u>: The short wavelength elevation plots were not very consistent between visits or very repeatable within a given visit. The exception was the appearance of some narrow dips throughout the left side profile.

<u>Roughness Profile</u>: A very short interval roughness profile shows that the section includes multiple areas of localized roughness. However, the locations where localized roughness appears was rarely the same in multiple visits.

Distress Surveys: The manual distress surveys recorded block cracking, alligator cracking, and pumping in both wheel paths. This explains the difficulty with repeatability and consistency with time.

Section 0502

Roughness: Rehabilitation decreased the IRI of the left side by 9 percent and the IRI of the right side by 56 percent. The left side IRI was quite high after rehabilitation, and grew at an inconsistent rate over the next 16 years. The left IRI showed a total increase of about 118 in/mi. The right side IRI grew at an faster rate, and increased a total of nearly 160 in/mi.

The HRI was 11 percent below the MRI just after rehabilitation. This gap grew steadily to 25 percent by visit 13. The increasing difference between HRI and MRI indicates a lesser relationship between features in the left and right profiles, and may signify the presence of localized roughness or distress that appears in only one side of the lane.

PSD: The PSD plots for visits 00 and 01 showed a similar level of roughness for wavelengths greater than 30 ft, but major changes for wavelengths smaller than 30 ft.

Both the left and right PSDs include roughness that is concentrated at wavelengths near 10.9 ft. While this periodic roughness is present for the right side profile, it is a dominant portion of the roughness in the left side profile. (See Figure 13.) In fact, it appears that concentrated roughness in the waveband between 8 and 13 ft is responsible for the high IRI values after rehabilitation on the left side.

For the right profile, the PSD does not change from visit 01 through 12 for wavelengths greater than 30 ft, but the range for wavelengths below 30 ft increases steadily with time. For the left profile, the PSD also does not change from visit 01 through 12, with the exception of a steady increase in the range for wavelengths below 7 ft. (See Figure 13.) It is possible that roughness in the wavelength range from 7-30 ft also increases with time. However, the high content in the range from 8-13 ft overshadows the progression.

Filtered Profiles:

Long Wavelengths: After rehabilitation, the long wavelength content of the profiles was consistent through time. A slight change occurred between visits 09 and 10. This was caused by the change in profiler make, and the associated difference in high-pass filtering techniques. Rehabilitation also changed long wavelength elevation traces, but some aspects of the very long wavelength content were still visible.

Medium Wavelengths: The periodic content within the left side profiles dominated the content within the medium wavelength profile plots. The periodic content was also visible in the right side profiles, as was other roughness. The right side profiles showed a progression in localized rough features (dips) throughout the monitoring history. These features appear more clearly in short wavelength elevation traces and un-filtered plots.

The elevation profile in the medium wavelength roughness range after rehabilitation was not at all similar to the profile before rehabilitation.

Short Wavelengths: Before rehabilitation (visit 00) the profiles included narrow dips, less than 2 ft wide and 0.05-0.25 in deep, throughout the section. These dips did not appear with a regular spacing.

Over the monitoring history of the section, localized roughness gradually appeared and grew in severity at several locations on each side of the lane. These were usually narrow (1-2 ft wide) dips that eventually grew to depths of up to 0.3 in on the left side of the lane and up to 0.4 in on the right side of the lane. By visit 13, more than 50 dips appeared on each side of the lane that increased the roughness of the section.

Roughness Profile: The left side was twice as rough over the first 300 ft of the section than the last 200 ft. This is because the first 300 ft of the section included periodic roughness with a wavelength that varied from 8 to 13 ft and amplitude of as much as high as 0.1 inches. The last 200 ft did not. The roughness was distributed relatively equally along the right side of the section, with the exception of increased roughness in the last 100 ft of the section in visit 13.

No localized roughness appeared in the short interval roughness profile. A very short interval (10 ft) roughness profile showed that the progression in overall roughness was due entirely to the increase in severity of the dips described above.

Distress Surveys: The manual distress measurements showed an increase in cracking on the section throughout its entire monitoring history. By 2002, it appeared that cracking covered the entire section. This explains the aggressive but unsteady increase in roughness, the frequent occurrence of narrow dips within the profiles, and the relative lack of repeatability between runs.

Section 0503

Roughness: Rehabilitation decreased the IRI of the left side by 34 percent and the IRI of the right side by 56 percent. The MRI grew at an increasing rate over the next 16 years, and increased by nearly 67 in/mi.

PSD: The PSD plots show very little change in content for the wavelength range from 30 to 150 ft on either side from visits 01 through 13. On the right side, the wavelength range shorter than 30 ft became steadily rougher over the monitoring history of the section. On the left side, the wavelength range shorter than 15 ft grew steadily in roughness.

PSD plots for visits 00 and 01 were somewhat similar in the wavelength range above 30 ft, but the profiles themselves were not necessarily similar over this entire range. (This is because the distribution of roughness within certain wavebands was roughly the same, but that does not necessarily indicate agreement between the profiles.) Rehabilitation significantly reduced spectral content for wavelengths below 15 ft.

Filtered Profiles:

Long Wavelengths: After rehabilitation, the long wavelength content of the profiles was very consistent through time. Rehabilitation also changed long wavelength elevation traces, but some aspects of the very long wavelength content were still visible, particularly on the left side.

Medium Wavelengths: The elevation profile in the medium wavelength roughness range after rehabilitation was not at all similar to the profile before rehabilitation.

Some features of the medium wavelength elevation profiles were similar throughout the monitoring history of the section after rehabilitation. However, the roughness did appear to increase with time. In particular, several dips seemed to grow in depth over the last five visits. These features appear more clearly in short wavelength elevation traces and un-filtered plots.

Short Wavelengths: Before rehabilitation (visit 00) the left profile included narrow dips, less than 2 ft wide and 0.05-0.25 in deep, throughout the section. These dips did not appear with a regular spacing, and were rarely evident in the right side profile.

Over the monitoring history of the section, short-duration rough features gradually appeared and grew in severity in at several locations on each side of the lane. These were usually narrow (1-2 ft wide) dips that eventually grew to depths of up to 0.5 in on the left side of the lane and up to 0.8 in on the right side of the lane. On the left side, the dips appeared 107 ft, 129 ft, 144 ft, 170 ft, 187 ft, 213 ft, 231 ft, 250 ft, 283 ft, 308 ft, 341 ft, 359 ft, 393 ft, 417 ft, 437 ft, 447 ft, and 461 ft from the start of the section. On the right side, the dips appeared 19 ft, 43 ft, 56 ft, 77 ft, 97 ft, 144 ft, 171 ft, 187 ft, 212 ft, 219 ft, 232 ft, 249 ft, 282 ft, 308 ft, 340 ft, 359 ft, 376 ft, 397 ft, 415 ft, 434 ft, 446 ft, 463 ft, and 483 ft from the start of the section. Most of the dips first appeared is visits 04 or 05, and grew in severity over the rest of the monitoring history. The exception was the dip in the left side profile at 107 ft, which was relatively severe through the entire post-rehabilitation history of the section.

A swatch of rough pavement appears in the right profile 414-446 ft from the start of the section in visits 10. It is not nearly as rough in visits 11 through 13.

Roughness Profile: A very short interval (10 ft) roughness profile shows that the progression in overall roughness is due entirely to the increase in severity of the dips described above. A short interval (25 ft) roughness profile shows that on the right side of the lane the roughness is distributed relatively equally along the section. On the left side, increased roughness exists in the later visits from 100-330 ft.

Isolated roughness (not severe enough to qualify as localized roughness) appeared on the left side 107 ft from the start of the section in visits 01 through 13. This area stood out, because the dip was somewhat wider than the other dips, and it appeared much sooner than the others. The distress survey recorded an area of localized distress in the same location on the left side of the lane.

Distress Surveys: All of the dips listed above appear in locations where manual distress measurements reported transverse cracking. Although all of the dips correspond to transverse cracks in the distress survey, not all transverse cracks caused significant roughness in the profile measurements. Note that other sections, such as 0505, 0508, and 0559 also included dips at transverse cracks. However, the dips that occurred at cracks in this pavement section were typically much deeper, and progressed in roughness much more aggressively. The swatch of rough profile on the right side from 414-446 ft corresponds to a large area of cracking.

Section 0504

Roughness: Rehabilitation increased the IRI of the left side by 4 percent and decreased the IRI of the right side by 49 percent. The MRI changed very little (11 in/mi) over the next 14 years, then increased 10 in/mi between visit 12 and 13. For all visits after rehabilitation, the left IRI is about 26-38 in/mi higher than the right IRI.

PSD: The PSD plots show very little change in content for the wavelength range from 3 to 150 ft on either side from visits 03 through 12, but an increase in content shorter than 10 ft between visit 12 and 13. On the right side, very little similarity exists in spectral content between visits 00 (before rehabilitation) and 01 (after rehabilitation). On the left side, some portions of the PSD plot for visits 00 and 01 were similar, but the profiles themselves were not. (This is because the distribution of roughness within certain wavebands was roughly the same, but that does not necessarily indicate agreement between the profiles.)

Both the left and right PSDs include roughness that is concentrated at wavelengths near 12 ft. This periodic roughness is a major portion of the roughness in the left side profile. It is also a significant source of roughness in the right side profile. In fact, it appears that concentrated roughness in the waveband between 8 and 13 ft is responsible for the left to right difference in IRI.

Filtered Profiles:

Long Wavelengths: After rehabilitation, the long wavelength content of the profiles was very consistent through time. Rehabilitation caused major changes in long wavelength roughness.

Medium Wavelengths: Only minor changes in medium wavelength roughness occurred from visits 01 through 13. The elevation profile in the medium wavelength roughness range after rehabilitation was not at all similar to the profile before rehabilitation.

The periodic content within the profiles, described above, dominated the content within the medium wavelength profile plots. In the right side profile, the amplitude of this roughness ranges from 0.04 to 0.12 in. Over much of the section, it appeared that the periodic roughness on the left side of the pavement was more than twice as severe as the right, and lagged the right side by up to 1.5 ft. The rolling process may have caused this roughness, but it would require a roller with a drum diameter of about 3.8 ft. In photo 27 from the construction report, it appears that this is possible. (*1*)

Short Wavelengths: Before rehabilitation (visit 00) the left and right profiles included narrow dips, less than 2 ft wide and 0.04-0.20 in deep, throughout the section. These dips were 3-25 ft apart, and often appeared in the same location on both sides of the lane. Rehabilitation eliminated the dips.

In most locations, short wavelength elevation plots did not change significantly over the monitoring history of the section. Upper harmonics of the 8-13 ft wavelength content and associated periodic roughness dominated the content of the plots.

Over the monitoring history of the section, roughness gradually appeared 64 ft, 108 ft, 147 ft, 190 ft, 313 ft, 362 ft, 397 ft and 498 ft from the start of the section. These were all either narrow (up to 3 ft wide) dips or narrow dips preceded by a small swell. These first began to appear in visit 04, and grew in severity with time. Their severity grew the most between visit 12 and 13.

Roughness Profile: Roughness was distributed uniformly throughout the section. A very short interval (10 ft) roughness profile showed that the roughness at the dips mentioned above was not significant when compared to the periodic roughness that existed over the length of the section until visit 13.

Distress Surveys: The dip locations listed above correspond to transverse cracks recorded in the 5-Dec-2005 distress survey. Every transverse crack recorded on that date produced a dip in the profile except one.

Section 0505

Roughness: Rehabilitation decreased the IRI of the left side by 46 percent and the IRI of the right side by 56 percent. The MRI grew at a slightly increasing rate over the next 16 years, and increased a total of 45 in/mi.

PSD: The PSD plots show very little change in content for the wavelength range from 15 to 150 ft in visits 01 through 13. However, the roughness at wavelengths below 15 ft steadily increased with time. PSD plots for visits 00 and 01 were similar in the wavelength range above 15 ft, but the profiles themselves were not similar for all wavelengths over 15 ft. (This is because the distribution of roughness within certain wavebands was roughly the same, but that does not necessarily indicate agreement between the profiles.) Rehabilitation significantly reduced spectral content for wavelengths below 15 ft.

Filtered Profiles:

Long Wavelengths: After rehabilitation, the long wavelength content of the profiles was very consistent through time. Rehabilitation caused only minor changes in the profile elevation plots over the long wavelength range.

Medium Wavelengths: The elevation profile in the medium wavelength roughness range after rehabilitation was not at all similar to the profile before rehabilitation.

Medium wavelength elevation profiles did not agree very well between visits. Further, rough features rarely showed steady growth in severity with time.

Short Wavelengths: Before rehabilitation (visit 00) the left and right profiles included narrow dips, less than 2 ft wide and 0.05-0.30 in deep, throughout the section. These dips were 3-25 ft apart, and often appeared in the same location on both sides of the lane. Rehabilitation eliminated the dips.

Over the monitoring history of the section, dips gradually appeared and grew in severity in at least twelve locations on each side of the lane. These were usually narrow (1-2 ft wide) dips or wider depressed areas of pavement (i.e., dense groups of narrow dips). Some dips appeared as early as visit 04. Others did not appear until visit 11.

Patches of narrow dips appeared in the profiles of visit 09. These looked like "chatter" in the traces that covered large areas of the profile, especially in the second half of the section. The chatter was either not present or less severe in later visits.

Although the "chatter" in the profiles often appeared as very short wavelength content, they increased the IRI.

Roughness Profile: The second half of the section was somewhat rougher than the first half on the right side in visits 09 and 11. Placement and severity of peaks within the very short interval (10 ft) roughness profile was not as consistent for this section as others within the SPS-5 experiment.

Distress Surveys: Distress measurements indicated a tremendous amount of cracking that began to appear before visit 04. By visit 09, the cracking had consumed large areas of pavement, including major portions of both wheel paths. Between visits 09 and 10 (May, 2002), the cracks were sealed.

The cracking history explains many of the observations listed above. Cracking caused the growth in short wavelength roughness over. This section exhibited slight degradation in profile repeatability and inconsistency in placement of roughness, as compared to other sections within the SPS-5 site. This is because of the "hit-or-miss" nature of large areas of cracking within each wheel path. The profiler only measures two narrow tracks, and does not experience precisely the same cracks, or the same aspects of each crack, equally in each pass. On the other hand, the overall IRI values were consistent between runs, and the growth in IRI was, for the most part, steady. This is because the cracking covered a wide area of the lane, so the profiler was likely to experience about the same level of cracking in each pass, even if the roughness did not always appear in consistent locations.

The rate of increase in IRI slowed somewhat between visits 09 and 10. The crack sealing that was performed between these visits probably reduced the apparent roughness of the cracking.

Section 0506

Roughness: Rehabilitation reduced the IRI of the left side by 32 percent and the IRI of the right side by 51 percent. The MRI showed a modest increase (11 in/mi) over the next 14 years, then a steeper increase (27 in/mi) over the next 2 years.

PSD: The PSD plots show very little change in content for the wavelength range from 2 to 100 ft on either side over visits 01 through 11, but increased in content for wavelengths shorter than 10 ft afterward. PSD plots for visits 00 and 01 were similar in the wavelength range above 20 ft, but the profiles themselves were not. (This is because the distribution of roughness within certain wavebands was roughly the same, but that does not necessarily indicate agreement between the profiles.) Rehabilitation significantly reduced spectral content for wavelengths below 20 ft.

Filtered Profiles:

Long Wavelengths: After rehabilitation, the long wavelength content of the profiles was very consistent through time. Rehabilitation also changed long wavelength elevation traces, but a few aspects of the very long wavelength content were still visible.

Medium Wavelengths: Only minor changes in medium wavelength roughness occurred from visits 01 through 13. The elevation profile in the medium wavelength roughness range after rehabilitation was not at all similar to the profile before rehabilitation.

Short Wavelengths: Before rehabilitation (visit 00) the left and right profiles included narrow dips, less than 2 ft wide and 0.05-0.15 in deep, throughout the section. These dips were 3-25 ft apart. They often appeared in the same location on both sides of the lane, but were much more prevalent within the left profile. Rehabilitation eliminated the dips.

Over the monitoring history of the section, roughness gradually appeared and grew in severity at some locations: ~132 ft on the right side, ~317 ft on both sides, ~369 ft on the right side and ~419 ft on both sides. Narrow (1-2 ft wide) dips that were 0.10-0.25 in deep caused the roughness. These began to appear in visit 09, and many of them grew in severity over the rest of the monitoring period. By visit 13, narrow dips appeared in both the left and right side profiles 22 ft, 50 ft, 89 ft, 133 ft, 164 ft, 218 ft, 250 ft, 278 ft, 317 ft, 369 ft and 419 ft from the start of the section.

Roughness Profile: A very short interval roughness profile shows that a few of the short-wavelength rough features on the section contributed to the roughness progression. For example, Figure B–1 shows the right roughness profile near a dip with gradually increasing severity. The roughness increases steadily with time at this location. Note that the roughest 10-ft segment that includes the dip increases in severity from 140 in/mi to 524 in/mi from visit 01 through visit 13. Over this interval, the dip grew to a depth of 0.5 in and a width of 3 ft. This would have an impact of over 7 in/mi on the overall roughness of the section.

Distress Surveys: All of the narrow dips listed above occurred in locations where distress surveys indicated the presence of transverse cracks.

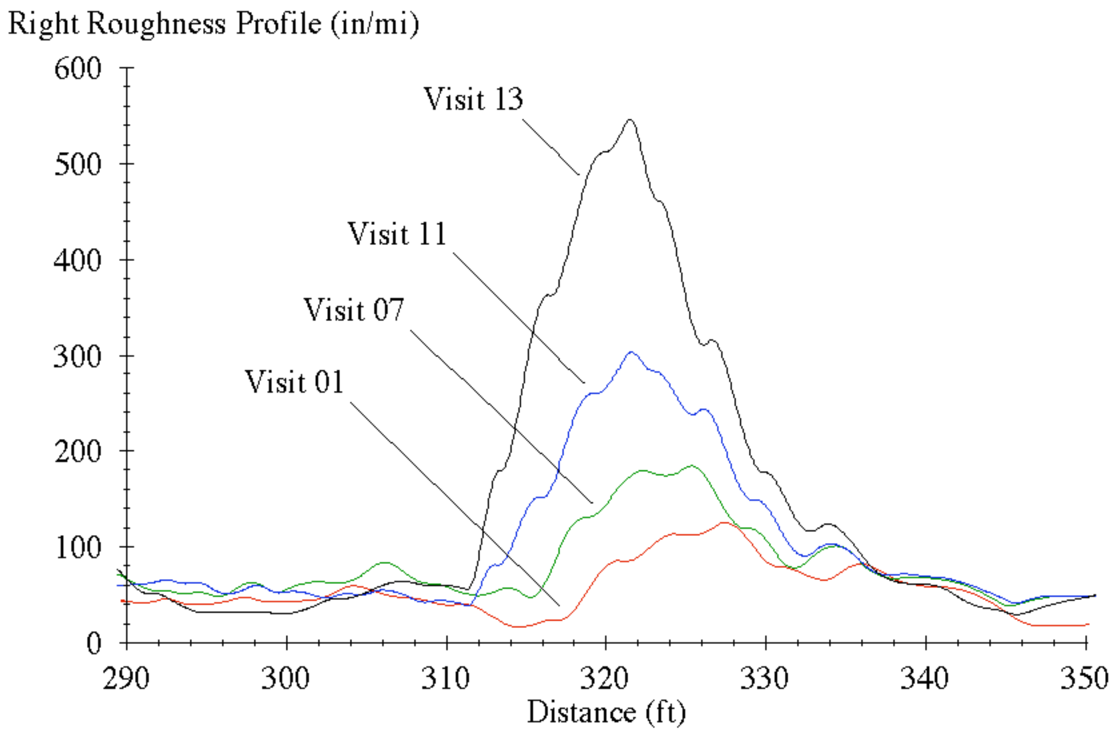

Figure B–1. Roughness profile of section 0506, 10-ft baselength.

Section 0507

Roughness: Rehabilitation reduced the IRI of the left side by 7 percent and the IRI of the right side by 50 percent. The MRI showed a modest, but inconsistent, increase (11 in/mi) over the next 16 years. For all visits after rehabilitation, the left IRI is about 40-47 in/mi higher than the right IRI.

PSD: The PSD plots show very little change in content for the wavelength range from 5 to 150 ft on either side over the 16 years after rehabilitation. On the right side, very little similarity exists in spectral content between visits 00 (before rehabilitation) and 01 (after rehabilitation). On the left side, some portions of the PSD plot for visits 00 and 01 were similar, but the profiles themselves were not. (This is because the distribution of roughness within certain wavebands was roughly the same, but that does not necessarily indicate agreement between the profiles.)

Both the left and right PSDs include roughness that is concentrated at wavelengths near 12 ft. While this periodic roughness is significant for the right side profile, it is a major portion of the roughness in the left side profile. In fact, it appears that concentrated roughness in the waveband between 8 and 13 ft is responsible for the left to right difference in IRI.

Filtered Profiles:

Long Wavelengths: After rehabilitation, the long wavelength content of the profiles was very consistent through time. Rehabilitation caused major changes in long wavelength roughness.

Medium Wavelengths: Only minor changes in medium wavelength roughness occurred from visits 01 through 13. The elevation profile in the medium wavelength roughness range after rehabilitation was not at all similar to the profile before rehabilitation.

The periodic content within the profiles, described above, dominated the content within the medium wavelength profile plots. Over much of the section, it appeared that the periodic roughness on the left side of the pavement was more than twice as severe as the right, and lagged the right side by about 1.5 ft. The rolling process may have caused this roughness, but it would require a roller with a drum diameter of about 3.8 ft. In photo 27 from the construction report, it appears that this is possible. *(1)*

Short Wavelengths: Before rehabilitation (visit 00) the left and right profiles included narrow dips, less than 2 ft wide and 0.05-0.10 in deep, throughout the section. These dips were 3-25 ft apart, and often appeared in the same location on both sides of the lane. Rehabilitation eliminated the dips.

Short wavelength elevation plots did not change significantly over the monitoring history of the section through visit 12. Upper harmonics of the 8-13 ft wavelength content and associated periodic roughness dominated the content of the plots. In visit 13, a bump appeared about 70 ft from the start of the section that was 0.25 in high on the left side and 0.15 ft high on the right.

Roughness Profile: Roughness was distributed uniformly throughout the section. The bump that appeared in visit 13 did not affect the roughness significantly.

Distress Surveys: No significant localized roughness existed within the section that could be linked to distress. The distress surveys listed few cracks, although a crack was recorded about 70 ft from the start of the section.

Section 0508

Roughness: Rehabilitation reduced the IRI of the left side by 31 percent and the IRI of the right side by 51 percent. The MRI showed only a modest increase (25 in/mi) over the next 16 years.

PSD: The PSD plots show very little change in content for the wavelength range from 4 to 150 ft on the left side for visits 01 through 09, then an increase in roughness for wavelengths shorter than 6 ft between visits 09 and 10. The right side PSD plots do not agree as well as the left, but are consistent in the wavelength range from 10 to 150 ft for visits 01 through 13. The right side PSD plots also show steadily increasing roughness for wavelengths shorter than 6 ft. Very little similarity exists in spectral content between visits 00 (before rehabilitation) and 01 (after rehabilitation).

Filtered Profiles:

Long Wavelengths: Rehabilitation also caused major changes in long wavelength roughness, but the very long wavelength content was not altered much in the second half of the section.

Medium Wavelengths: Only minor changes in medium wavelength roughness occurred from visits 01 through 13. The elevation profile in the medium wavelength roughness range after rehabilitation was not at all similar to the profile before rehabilitation.

Short Wavelengths: Before rehabilitation (visit 00) the left and right profiles included narrow dips, ~2 ft wide and 0.05-0.30 in deep, throughout the section. These dips were 5 ft or more apart, and appeared to have uniform spacing over some parts of the section. Rehabilitation eliminated the dips. Narrow dips did not begin to appear again until visit 08. These were all either narrow (up to 2 ft wide) dips, narrow dips preceded by a small swell, or small (0.1 in) downward steps. None of these dips appeared to correspond to localized roughness that existed before rehabilitation.

Roughness Profile: Very short interval roughness profiles showed that few of the dips within the section added significantly to the roughness progression. Although they were easily detected in the profile, most of these features caused very little overall roughness. Two exceptions were the dips on the left profile that appeared about 15 ft and 427 ft from the section start.

Distress Surveys: All of the dips found in profiles from the later visits appeared near locations where distress surveys indicated the presence of transverse cracks. The transverse cracking at these locations was either detected by the distress survey in the same year that evidence of them first appeared in the profiles, or a year or two earlier. Thus, it was typical to see evidence of the cracking in the profiles for visits 09 through 13, but rarely in visits 01 through 06. (The distress survey in November, 1997 found very few cracks.) Note that many cracks were listed in the distress survey that did not cause a dip in the corresponding profile.

Section 0509

Roughness: Rehabilitation decreased the IRI of the left side by 59 percent and the IRI of the right side by 57 percent. The MRI grew at an increasing rate over the next 16 years, and increased 183 in/mi.

PSD: Rehabilitation, performed between visits 00 and 01, greatly reduced the roughness for wavelengths below 15 ft, and changed the content at wavelengths above 15 ft. After rehabilitation, the PSD plots show an aggressive growth in roughness for wavelengths below 30 ft. The content for wavelengths above 30 ft was steady with time.

Filtered Profiles:

Long Wavelengths: After rehabilitation, the long wavelength content of the profiles was somewhat consistent through time. Rehabilitation changed the long wavelength elevation plots for this section, but many of the very long wavelength traits survived the overlay.

Medium Wavelengths: The elevation profile in the medium wavelength roughness range after rehabilitation was not at all similar to the profile before rehabilitation.

Medium wavelength elevation profiles showed a progression in rough features (dips) throughout the monitoring history. These features appear more clearly in short wavelength elevation traces and un-filtered plots.

Short Wavelengths: Before rehabilitation (visit 00) the profiles included narrow dips less than 3 ft wide and 0.05-0.35 in deep throughout the section. These dips were 3-25 ft apart and often appeared on both sides, but were relatively shallow (0.05-0.10 ft wide).

Over the monitoring history of the section, narrow dips gradually appeared and grew in severity in at least 20 locations on each side of the lane. These narrow (1-2 ft wide) dips eventually grew to depths of 0.10-0.75 in. Most of these dips first appeared in visits 04 through 06, and all appeared in visit 13. On the left side, the most severe dips appeared 13 ft, 33 ft, 52 ft, 73 ft, 95 ft, 105 ft, 115 ft, 128 ft, 145 ft, 161 ft, 176 ft, 192-195 ft, 204 ft, 214 ft, 228 ft, 244 ft, 266 ft, 286 ft, 298 ft, 342 ft, 373 ft, 401 ft, 414 ft, 433 ft, 450 ft, and 471 ft from the start of the profile. Figure 16 shows an example of one of these dips, and its progression in depth from visits 04, 07 and 11.

The dips all appeared on the right side as well. On the right side, deep dips also appeared 60 ft, 113 ft, 189 ft, 322 ft and 356 ft from the start of the profile.

Roughness Profile: A very short interval (10 ft) roughness profile shows that the progression in overall roughness is due entirely to the increase in severity of the dips described above with time. Figure 19 illustrates this for the first half of the section. Roughness at the dips progresses aggressively over time, but the roughness "between" the dips is steady.

Distress Surveys: All of the dips listed above appear in locations where manual distress measurements reported cracks. In most cases, these transverse cracks covered the entire width of the lane. Note that other sections, such as 0505, 0508, and 0559 also included dips at transverse cracks. However, the dips that occurred at cracks in this pavement section were typically much deeper, and progressed in roughness much more aggressively.

Section 0559

Roughness: Rehabilitation reduced the IRI of the left side by 51 percent and the IRI of the right side by 35 percent. The MRI showed only a modest increase (24 in/mi) over the next 16 years.

PSD: The PSD plots show an increase in roughness for wavelengths shorter than 6 ft between visits 07 and 08, and an increase in roughness for wavelengths shorter than 15 ft between visits 09 and 10. The spectral content also increased for wavelengths from 1 to 10 ft between visits 12 and 13. This was caused by localized roughness, rather than periodic roughness. Rehabilitation, performed between visits 00 and 01, greatly reduced the roughness for wavelengths below 15 ft, but caused little change in the overall level of roughness for wavelengths longer than 15 ft.

Filtered Profiles:

Long Wavelengths: Rehabilitation caused some change in long wavelength roughness, but the very long wavelength content was barely altered.

Medium Wavelengths: Only minor changes in medium wavelength roughness occurred from visits 04 through 13. The elevation profile in the medium wavelength roughness range after rehabilitation was not at all similar to the profile before rehabilitation.

Short Wavelengths: Before rehabilitation (visit 00) the left profile included narrow dips, 2-7 ft wide and 0.10-0.35 in deep, throughout the section. These dips were 5-25 ft apart, and appeared to have uniform spacing over some parts of the section. In many locations, they also appeared in the right profile, but were not as severe. Rehabilitation eliminated the dips.

Over the monitoring history of the section, roughness gradually appeared and grew in severity at several locations: (1) 70 ft, 128 ft, 150 ft, 221 ft, 291 ft 337 ft, and 427 ft on both sides, (2) 39 ft, 106 ft, 202 ft, 248 ft, 307 ft, 357 ft, 389 ft and 441 ft on the left side only, and (3) 28 ft and 108 ft on the right side only. These were all either narrow (up to 3 ft wide) dips or narrow dips preceded by a small swell. Most of these first appeared in visits 09 or 10. By visit 13, some of the dips included a downward change in elevation of up to 0.4 in from the top of the swell to the bottom of the dip.

The most severe dip occurred about 150 ft from the start of the profile on the left side. This was 5 ft wide that increased in depth throughout the monitoring history of the section until it was 0.4 in deep. Few of the dips appeared where narrow dips existed before rehabilitation.

Roughness Profile: A very short interval (10 ft) roughness profile shows that few of the rough features on the section added significantly to the roughness progression until visit 13. The dip that appeared 150 ft from the start of the section qualified as localized roughness on the left side in visit 13. (A dip on the right side that was 70 ft from the start of the section nearly qualified in visit 13.)

Distress Surveys: The dip locations listed above correspond to sealed cracks that were recorded in the distress survey on 12-Dec-2003. The localized roughness in the left profile that appears 150 ft from the start of the section is near a transverse crack (at 146-150 ft) that was observed in all distress surveys since September 1996, which was before profiler visit 04. Further, longitudinal cracking was observed in the left wheel path in distress surveys starting in December of 1999.

Section 0560

Roughness: Rehabilitation reduced the IRI of the left side by 45 percent and the IRI of the right side by 64 percent. The MRI grew at an increasing rate over the next 16 years, and increased 70 in/mi overall. The average HRI for each visit was between 19 percent and 28 percent lower than the MRI. This is a larger difference than was observed on most other sections. This indicates a lesser relationship between the left and right profile, and may signify the presence of localized roughness caused by distress that appears in only one side of the lane.

PSD: The PSD plots show very little change in content for the wavelength range from 15 to 150 ft in visits 01 through 13. However, the roughness at wavelengths below 15 ft steadily increased with time. PSD plots for visits 00 and 01 were very similar in the wavelength range above 30 ft. Rehabilitation significantly reduced spectral content for wavelengths below 15 ft.

Filtered Profiles:

Long Wavelengths: Rehabilitation did not change the long wavelength elevation plots for this section significantly. After rehabilitation, the long wavelength content of the profiles was somewhat consistent through time.

Medium Wavelengths: Medium wavelength elevation plots were similar throughout visits 03 through 11. However, on the left side, some features progressed in severity with time. On the right side, a large area of the section from 240-400 ft from the start changed properties significantly over the monitoring history, particularly from visit 07 through 11. The medium wavelength content was significantly rougher in the right side in visit 12 and 13 than in visit 11.

The elevation profile in the medium wavelength roughness range after rehabilitation was not at all similar to the profile before rehabilitation on the right side, but exhibited weak correlation to the profile before rehabilitation on the left side.

Short Wavelengths: Before rehabilitation (visit 00) the left profile included narrow dips, about 2 ft wide and 0.05-0.20 in deep, throughout the section. These dips were 5-50 ft apart. In many locations, they also appeared in the right profile, but were not as severe. Rehabilitation eliminated the dips.

For visit 03 through 13, short wavelength elevation plots were not very repeatable within a given visit. This seemed to get progressively worse throughout the monitoring history of the pavement. (This explains some of the relatively low correlation values listed in Table 13.) As such, the progression of rough features at individual locations was not consistent through time. Nevertheless, some trends were obvious. For example, "patches" of elevated short wavelength content appeared and increased in severity in the right side profile from visits 03 through 06. These appeared from 65-85 ft, 240-265 ft, 280-295 ft, and 310-345 ft. In later visits, these areas became even rougher, although the details of the profile shape from the earlier visits were not evident in the later visits. In visits 11 through 13, about half of the length of the right side profile included high short wavelength content.

Roughness Profile: A very short interval (10 ft) roughness profile shows that the areas of elevated short wavelength roughness do increase the IRI over time, particularly on the right side of the lane. However, no single area stands out as dominating the roughness of this section.

Distress Surveys: Distress surveys reported a tremendous amount of cracking that began to appear before visit 04, and became progressively more prevalent and severe throughout the rest of the monitoring history. (Some of the distress surveys also listed pumping in some areas.) The cracking often first appeared as longitudinal cracks along a wheel path and progressed to large areas of cracking in later visits.

The distress history explains many of the observations listed above. The appearance and growth of patches of short wavelength roughness over time is consistent with distress surveys. The "hit-or-miss" nature of profiling large areas of cracking also explains the relatively low correlation values for repeatability within a given visit to the site. The profiler only measures two narrow tracks, and does not experience precisely the same cracks, or the same aspects of each crack, equally in each pass. On the other hand, the overall IRI values showed a steady growth with time, and each area of the overall section seemed to grow in roughness steadily. This is because the cracking covered a wide area of the lane, so the profiler was likely to experience about the same level of cracking in each pass, even if the shape of the profile did not always appear in consistent locations.

References

1. Hossain, M., et al., "SPS-5: Rehabilitation of Asphalt Concrete Pavements. Construction Report." Arizona Transportation Research Center (1996) 380 p.