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Profile Analysis of the LTPP SPS-9P Site in Arizona

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16. Abstract

This report characterizes the longitudinal profiles of five pavement sections within the Arizona Specific Pavement Studies 1 project throughout their service life. This project was built and monitored as part of the Long-Term Pavement Performance Study. Road profile measurements were collected on this site about once per year since the winter after it was opened to traffic. This study analyzed the profiles in detail by calculating their roughness values, examining the spatial distribution of roughness within them, viewing them with post-processing filters, and examining their spectral properties. These analyses provided details about the roughness characteristics of the road and provided a basis for quantifying and explaining the changes in roughness with time, as well as linking profile properties to each section's maintenance history and observations of surface distress.

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INTRODUCTION

This report provides the results of profile and roughness analyses for a Long-Term Pavement Performance (LTPP) Specific Pavement Studies 9P (SPS-9P) site in Arizona. This was a pilot site, and it was designed to compare Superpave mix performance with that of the agency standard mix. (*1*)

The construction report provides details about the project, and key items are excerpted here. (*1*) The test pavements were constructed on northbound U.S. Highway 93 in Mohave County, Arizona from October 1992 through August 1993. This is the same location as Arizona's SPS-1 project. The SPS-9P project includes five test sections. (See Table 1.) These include an agency standard mix (A901), two sections of Superpave Level 1 mixtures with 1 in (25 mm) maximum aggregate (A902, A903), and two sections of Superpave Level 1 mixtures with 3/4 in (19 mm) maximum aggregate (0902, 0903). The structure of all sections includes a granular base about 4 in thick, and 7 in of asphalt concrete placed in three lifts.

Table 1. Arizona SPS-9P Descriptions.

Section	Mix Description
A901	Agency Standard, 3/4 in (19 mm)
0902	Superpave Level 1, 3/4 in (19 mm)
A902	Superpave Level 1, 1 in (25 mm)
0903	Superpave Level 1, 3/4 in (19 mm)
A903	Superpave Level 1, 1 in (25 mm)

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

PROFILE DATA SYNCHRONIZATION

Profile data were collected over the entire Arizona SPS-9P site on ten dates, listed in Table 2. Each visit at the site took place during a visit of the SPS-1 site at the same location. Note that the visit numbers in Table 2 correspond to visit numbers for a companion report about the SPS-1 site, and that some visits of the SPS-1 site did not produce any profile measurements on SPS-9P test sections. Raw profile data were available for all ten visits. In each visit, a minimum of seven repeat profile measurements were made.

Data Extraction

Profiles of individual test sections were extracted directly from the raw measurements. This was done for two reasons. First, profiles were collected in visits 03 through 09 at a 0.98 in sample interval and in visits 11 and 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*)

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

Visit	Date	Time	Repeats	Section				
				A901	0902	A902	0903	A903
01	27-Jan-1994	—	9					
02	27-Feb-1995	12:45	9					
03	23-Jan-1997	09:54-12:50	9					
04	08-Apr-1998	13:50-15:31	7					
05	04-Dec-1998	10:40-12:16	7					
06	17-Nov-1999	09:26-11:06	7					
07	19-Dec-2000	11:26-13:31	9					
09	20-Feb-2002	10:41-14:25	9					
11	09-Mar-2004	16:18-16:40	9					
11	10-Mar-2004	11:29-13:34	9					
13	27-Mar-2006	12:43-16:12	9					

In visits 02 through 07, 09, 11 and 13 measurements of section A901, 0902 and A902 were made within long profiles that also included SPS-1 test sections. Sections 0903 and A903 were typically covered in a subsequent set of runs on the same date. The exception was visit 11, where sections 0903 and A903 were measured on the previous day.

The raw data were used to synchronize all of the profiles to each other through their entire history. Three clues were available for this purpose: (1) the site layout from the construction report, (2) event markers in the raw profiles from the start and end of each section, and (3) automated searching for the longitudinal offset between repeat measurements.

Cross Correlation

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

The procedure is based on a customized version of cross correlation. (*3*) In this procedure, a "basis" measurement is designated that is considered to have the correct longitudinal positioning. A "candidate" profile is then searched for the longitudinal offset that provides the highest cross correlation to the basis measurement. A high level of cross correlation requires a good match of profile shape, the location of isolated rough spots, and overall roughness level. Therefore, the correlation level is often only high when the two measurements are synchronized. When the optimal offset is found, a profile is extracted from the candidate measurement with the proper overall length and endpoint positions. For the rest of this discussion, this process will be referred to as *automated synchronization*.

For this application, cross correlation was performed after the IRI filter was applied to the profiles, rather than using the un-filtered profiles. This helped assign the proper weighting to relevant profile features. In particular, it increased the weighting of short-wavelength roughness that may be linked to pavement distress. This enhanced the effectiveness of the automated synchronization procedure. The long-wavelength content within the IRI output helped ensure that the longitudinal positioning was nearly correct, and the short-wavelength content was able to leverage profile features at isolated rough spots to fine-tune the positioning.

Synchronization

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

1. Establish a basis measurement for each section from visit 06.

    This was done using the event markers from a raw measurement. The first repeat measurement of each section was used for this purpose. Visit 06 was selected because it included event markers near the expected locations for each test section. All of the sections were assumed to begin at the appropriate event marker, and continue for 500 ft.

2. Automatically synchronize the other eight repeats from visit 06 to the basis set.
3. Automatically synchronize the measurements from the previous visit to the current basis set.
4. Designate the previous visit as the current visit.
5. Replace the basis set with a new set of synchronized measurements from the first repeat of the current visit.
6. Repeat steps 3 through 5 until visit 01 is complete.

Visits 07 through 13 were synchronized using steps 3 through 6, but going forward in time.

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

Table 3. Selected Repeats, Section A901.

Visit	Repeat Numbers					Composite Correlation
02	2	3	5	7	8	0.845
03	2	3	4	7	8	0.887
04	1	2	3	4	6	0.847
05	1	2	3	6	7	0.876
06	1	2	4	5	6	0.891
07	1	2	7	8	9	0.910
09	1	2	3	4	5	0.909
11	1	3	4	7	9	0.813
13	2	4	6	7	8	0.848

Table 4. Selected Repeats, Section 0902.

Visit	Repeat Numbers					Composite Correlation
01	1	2	5	7	8	0.894
02	2	3	4	5	9	0.936
03	3	4	6	7	8	0.919
04	1	2	3	6	7	0.852
05	1	2	3	5	7	0.923
06	2	3	5	6	7	0.940
07	2	4	5	7	8	0.941
09	3	4	5	8	9	0.928
11	2	3	7	8	9	0.949
13	2	3	4	5	9	0.949

Table 5. Selected Repeats, Section A902.

Visit	Repeat Numbers					Composite Correlation
01	2	4	6	7	8	0.897
02	3	5	6	7	8	0.953
03	4	5	7	8	9	0.934
04	1	2	5	6	7	0.939
05	1	2	3	5	7	0.955
06	2	3	5	6	7	0.956
07	1	3	6	7	9	0.970
09	2	3	4	7	8	0.957
11	1	3	5	7	8	0.969
13	2	3	5	7	9	0.970

Table 6. Selected Repeats, Section 0903.

Visit	Repeat Numbers					Composite Correlation
03	5	6	7	8	9	0.946
04	1	2	3	4	5	0.877
05	1	2	3	4	7	0.928
06	2	3	4	5	6	0.949
07	3	4	6	8	9	0.952
09	1	2	4	5	6	0.955
11	3	4	5	6	9	0.759
13	1	2	5	6	7	0.756

Table 7. Selected Repeats, Section A903.

Visit	Repeat Numbers					Composite Correlation
03	1	5	7	8	9	0.963
04	2	4	5	6	7	0.916
05	2	3	4	5	7	0.932
06	1	2	3	6	7	0.949
07	1	3	5	6	7	0.964
09	1	4	5	7	8	0.939
11	2	3	4	5	8	0.891
13	4	5	6	8	9	0.896

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 7 provide an appraisal of the agreement between profile measurements for each visit of each section. When two profiles produce a correlation level above 0.82, their IRI values are expected to agree within 10 percent most (95 percent) of the time. Above this threshold, the agreement between profiles is usually acceptable for studying the influence of distresses on profile. When two profiles produce a correlation level above 0.92, they are expected to agree within 5 percent most of the time. Above this threshold, the agreement between profiles is good. Correlation above 0.92 often depends on consistent lateral tracking of the profiler, and may be very difficult to achieve on highly distressed surfaces. Note that the IRI values provided in this report will be the average of five observations, which will tighten the tolerance even further.

Overall, the majority of the groups of measurements listed in Tables 3 through 7 exhibited good or better correlation, and most of them exhibited acceptable correlation. Any group of repeat measurements that produced a composite correlation level below 0.82 was investigated using filtered plots, and they are discussed here.

Section A901, Visit 11: Correlation was diminished by sinusoidal chatter in the profiles.

Section 0903, Visits 11 and 13: Correlation was significantly diminished by a large number of narrow downward spikes in the profiles, particularly on the right side.

SUMMARY ROUGHNESS VALUES

Figures 1 through 5 show the left and right IRI values for each pavement section over their monitoring period. This includes up to twenty summary IRI values; two per visit over up to ten visits. The figures show the IRI values versus time in years. In this case, "years" refers from the number of years between the measurement date and the date that the site was opened to traffic, which was August 1, 1993. Fractions of a year are estimated to the nearest day.

To supplement the plots, Appendix A lists the IRI, Half-car Roughness Index (HRI), and Ride Number (RN) of each section for each visit. These roughness values are the average of the five repeat measurements selected in the data quality screening. Keep in mind that these are not necessarily the same five repeat measurements selected for the LTPP Level E database. Appendix A also provides the standard deviation of IRI over the five repeat measurements. This helps identify erratic roughness values that are the result of transverse variations in profile caused by surface distresses.

Figures 1 through 5 provide a snapshot of the roughness history of each pavement section. The remainder of this report is devoted to characterizing the profile content that made up the roughness, and explaining the profile features that contributed to roughness progression.

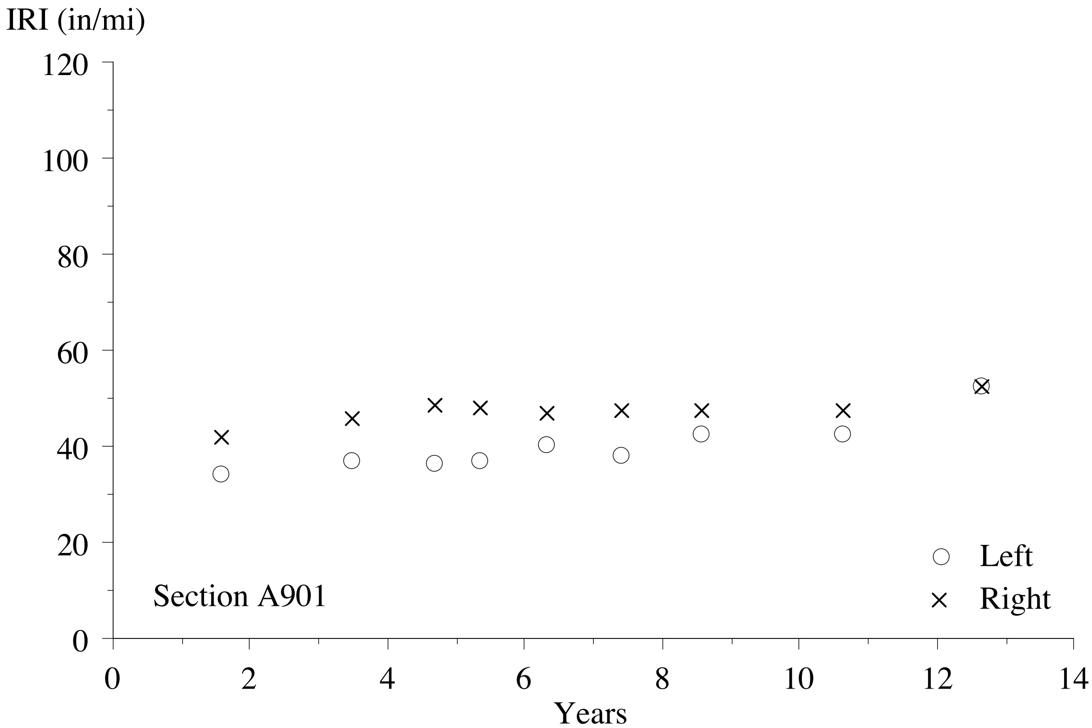

Figure 1. IRI progression, section A901.

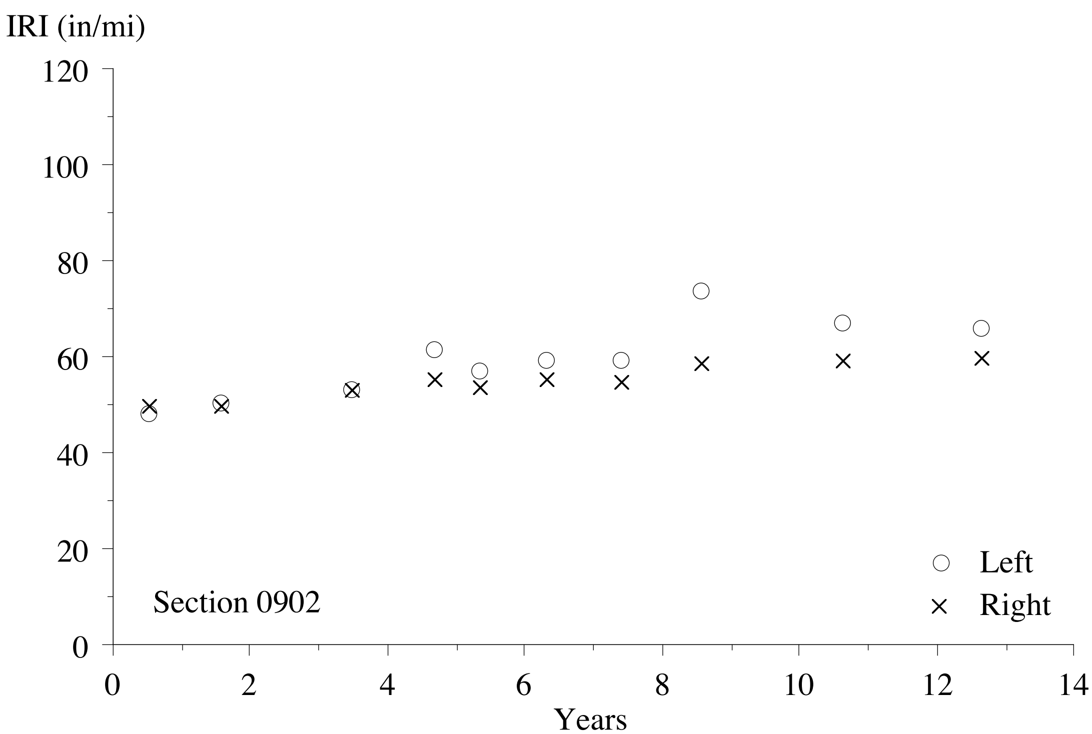

Figure 2. IRI progression, section 0902.

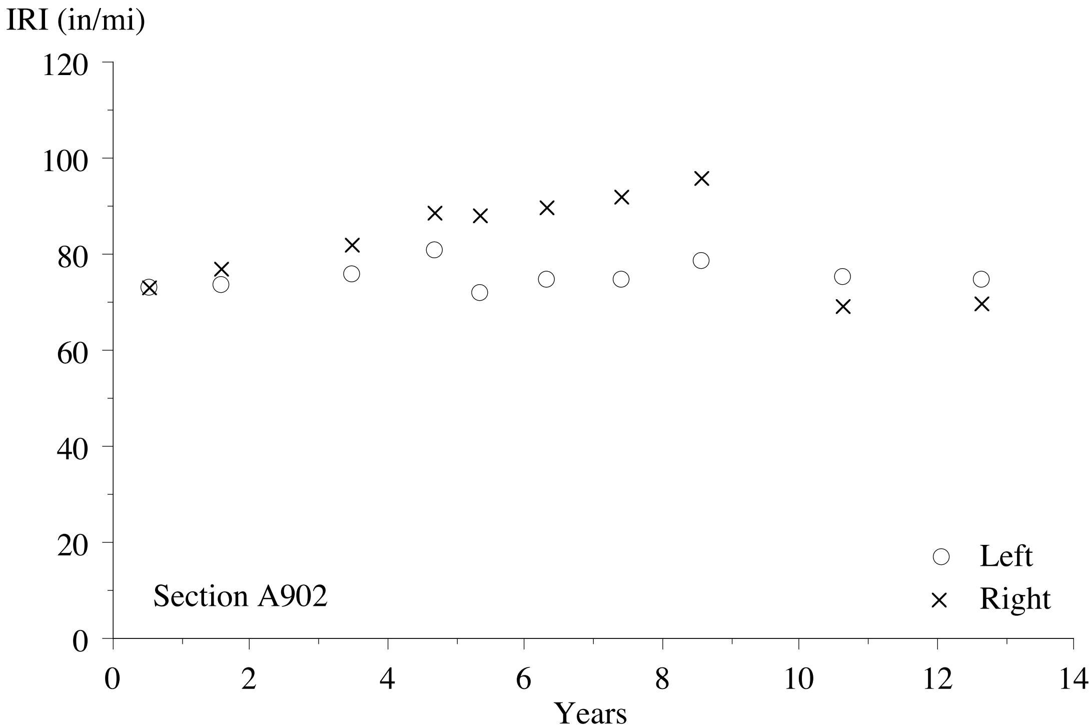

Figure 3. IRI progression, section A902.

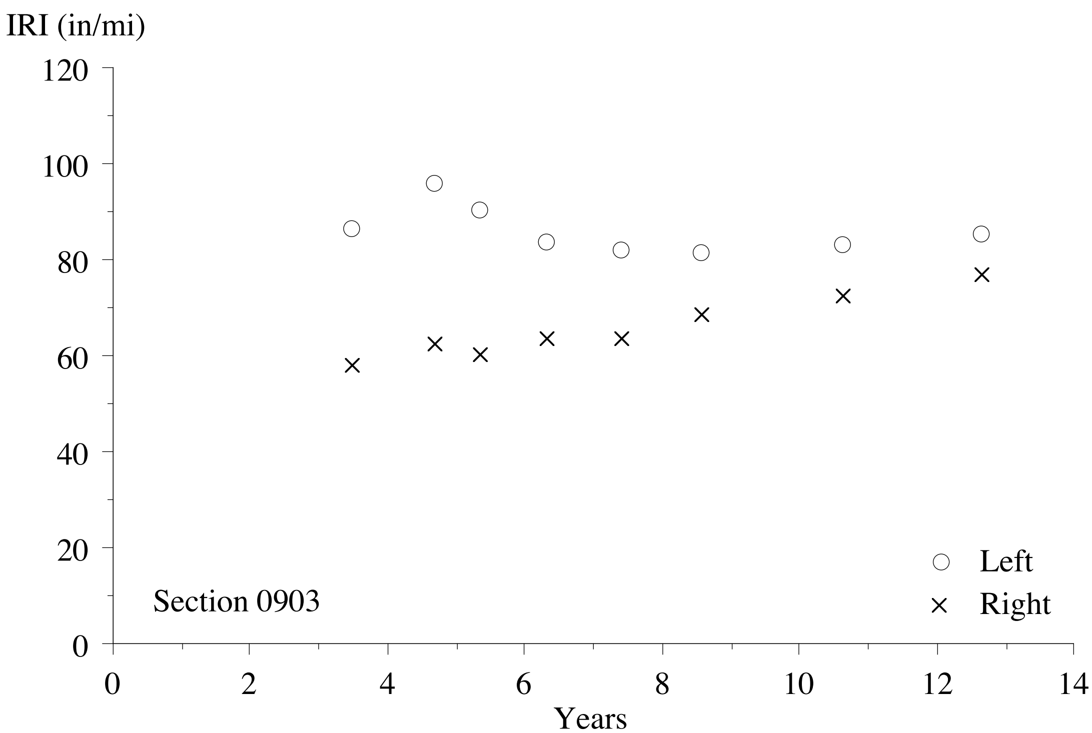

Figure 4. IRI progression, section 0903.

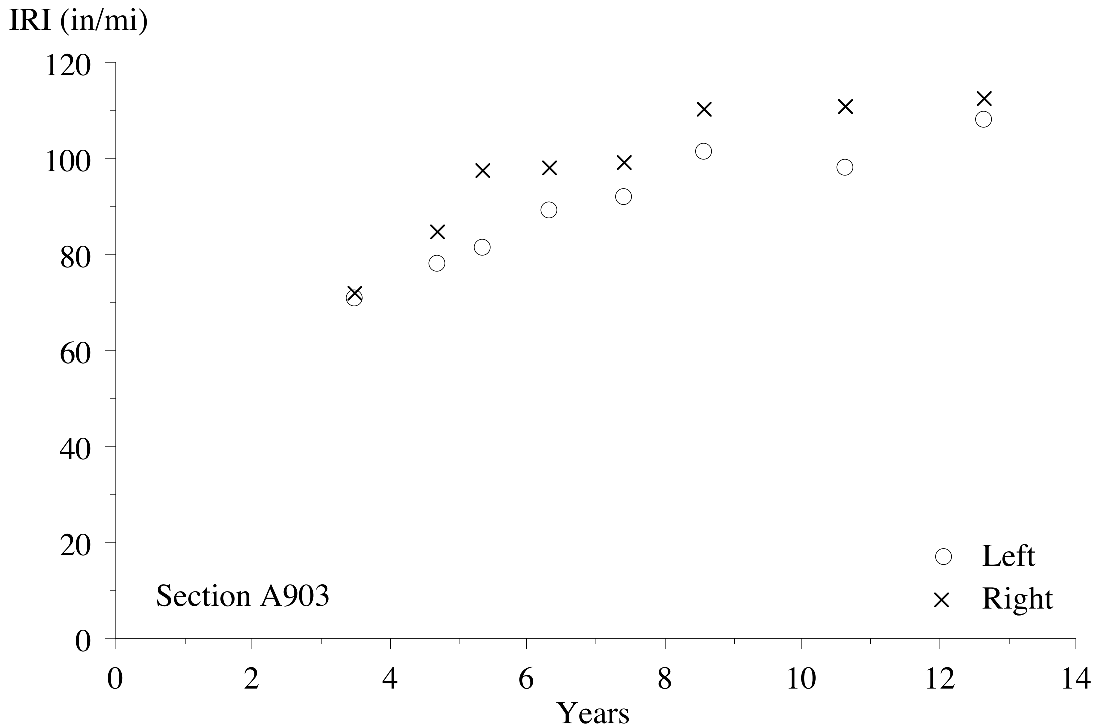

Figure 5. IRI progression, section A903.

PROFILE ANALYSIS TOOLS

This section of the report describes analysis techniques that were used to study the profile characteristics of each pavement section, and their change with time. These tools help study roughness, roughness distribution, and roughness progression of each section, including concentrated roughness that may be linked to pavement distress. The discussion of each analysis and plotting method is rather brief. However, all of the methods listed here are described in detail elsewhere. *(4)*

Summary Roughness Values

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

Elevation Profile Plots

A simple way to learn about the type of roughness that exists within a profile is to view the trace. However, certain key details of the profile are often not as obvious in a raw profile trace as they may be after the profile is filtered. Three types of filtered plots were inspected for every visit of every section:

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

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

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

These filters were used to screen the profiles for changes with time and special features of interest. The terms “long”, “medium”, and “short” are relative, and in this case pertain to the relevant portions of the waveband that affects the IRI. The long wavelength portion of the profile was typically very stable with time. However, the long wavelength profile plots of every section changed somewhat between visit 09 and 11. This was not caused by a change in the surface characteristics of the section. Rather, it was caused by a change in profiler make, and the associated change in filtering practices.

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

Filtered profile plots also helped to characterize the effects of maintenance operations. For example, a slurry seal was applied to two of the sections in May 2002 (between visit 09 and 11). In most cases, this caused a complete change to the short wavelength profile plots and a significant change to the medium wavelength profile plots.

In addition to filtered plots, every profile was viewed in its raw form. This helped reveal noteworthy features that did not necessarily affect the IRI, but helped establish a link between surface distress and profile properties. Two examples of this were: (1) narrow downward spikes in the profiles caused by raveling, and (2) several densely-spaced dips in the left profile on section A901 caused by surface damage in the wheelpath.

Roughness Profile

A roughness profile provides a continuous report of road roughness using a given segment length. (*5*) Instead of summarizing the roughness by providing the IRI for an entire pavement section, the roughness profile shows the details of how IRI varies with distance along the section. It does this by displaying the IRI of every possible segment of given baselength along the pavement, using a sliding window.

A roughness profile displays the spatial distribution of roughness within a pavement section. As such, it can be used to distinguish road sections with uniform roughness from sections with roughness levels that change over their length. Further, the roughness profile can pinpoint locations with concentrated roughness, and provide an estimate of the contribution of a given road disturbance to the overall IRI.

In this work, roughness profiles were generated and viewed using a baselength of 25 ft. That means that every point in the plot shows the IRI of a 25-ft long segment of road, starting 12.5 ft upstream and ending 12.5 ft downstream. Any location where a peak occurs in the roughness profile that is greater than or equal to 2.5 times the average IRI for the entire section is considered an area of *localized roughness*. All areas of localized roughness are discussed in the detailed observations by identifying them, listing their severity, and describing the underlying profile features that caused them.

Power Spectral Density Plots

A power spectral density (PSD) plot of an elevation profile shows the distribution of its content within each waveband. An elevation profile PSD is displayed as mean square elevation versus wave number, which is the inverse of wavelength. PSD plots were calculated from the slope profile, rather than the elevation profile. This aided in the interpretation of the plots, because the content of a slope PSD typically covers fewer orders of magnitude than an elevation PSD.

A PSD plot is generated by performing a Fourier transform on a profile (or in this case, a slope profile). The value of the PSD in each waveband is derived from the Fourier coefficients, and represents the contribution to the overall mean square of the profile in that band.

The slope PSD plots provided a very useful breakdown of the content within a profile. In particular, the plots reveal: (1) cases in which significant roughness is concentrated within a given waveband, (2) the type of content that dominates the profile (e.g., long, medium, or short wavelength), (3) the type of roughness that increases with time, and (4) the type of roughness that is stable with time.

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

Distress Surveys and Maintenance Records

Once the analysis and plotting described above were completed, all of the observations were compared to the manual distress surveys performed on each section. Manual distress surveys were available for each section starting in February 1995, and covering six dates over the monitoring history. These were performed using LTPP protocols by technicians certified to perform distress surveys. The surveys provided a means of relating profile features to known distresses.

Observations of changes in profile properties were also compared to maintenance records. In particular, sealing of cracks affected the presence and shape of narrow dips on one section, and the application of a slurry seal affected the short and medium wavelength content within the profiles on two sections.

DETAILED OBSERVATIONS

This section reports key observations from the roughness index progression, PSD plots, filtered elevation profile plots, roughness profiles and distress surveys. In many cases, similar behavior was noted for multiple sections. These observations are repeated under the heading of every section where it is appropriate. However, changes in profile properties with time that were caused by changes in profiler make or model are not discussed here. These observations are summarized at the end of the report.

Section A901, Right

Roughness: The IRI increased steadily from 42 to 53 in/mi over visits 02 through 13.

Elevation profile plots: The short, medium, and long wavelength elevation profile plots were very consistent throughout the monitoring period, with the exception of the area from 360 to 430 ft from the start of the section. In this area, the medium wavelength profile plots changed significantly with each visit. A bump appears in all visits from 360 to 410 ft from the start of the section that is over 0.4 in high. The transition into and out of the bump both became harsher (i.e., sharper) with time.

Roughness profiles: The roughness profiles changed very little with time over the first 360 ft of the section. In the last 140 ft of the section, the roughness increased aggressively with time, and by visit 13 the area centered 413 ft from the start of the section qualified as localized roughness. The localized roughness there was caused by the trailing end of the long bump, which is a sharp slope break by visit 13.

Distress and maintenance history: Very little distress was recorded for this section, even in later visits.

Section A901, Left

Roughness: The IRI increased steadily from 35 to 53 in/mi over visits 02 through 13.

Elevation profile plots: The unfiltered elevation profile plots included two areas with strong periodic chatter about 250 to 280 ft and 440 to 465 ft from the start of the section in some repeat measurements from all visits. The chatter usually appeared as a series of narrow dips about 0.1 in deep and 0.7 ft apart. (In many areas, the chatter approximated a sinusoid.) In visits 04 and 11, many of the repeat measurements included the chatter in the locations above, as well as most of the first half of the section. Figure 6 shows an example of the chatter (and its "hit-or-miss" nature) from visit 04.

The later visits included a bump in the profile from about 402 to 410 ft from the start of the section. It grew in severity with time, and was nearly 0.2 in high by visit 13. In visit 13, unlike other visits, this bump was preceded by another one that was as severe.

Roughness profiles: The roughness was very evenly distributed throughout the section in visits 02 through 05. The roughness of the first 380 ft of the section was consistent throughout the monitoring history. This indicates that the chatter observed in the profiles did not affect the IRI much. (If it had, the roughness in the first half of the section would have escalated in visits 04 and 11.)

All of the increase in roughness in the later visits took place in the last 120 ft of the section, and most of it was concentrated around 410 ft from the start of the section.

This was caused almost entirely by the bumps mentioned above. By visit 13, an area of localized roughness was centered 410 ft from the start of the section with a peak value of nearly 200 in/mi in the roughness profile.

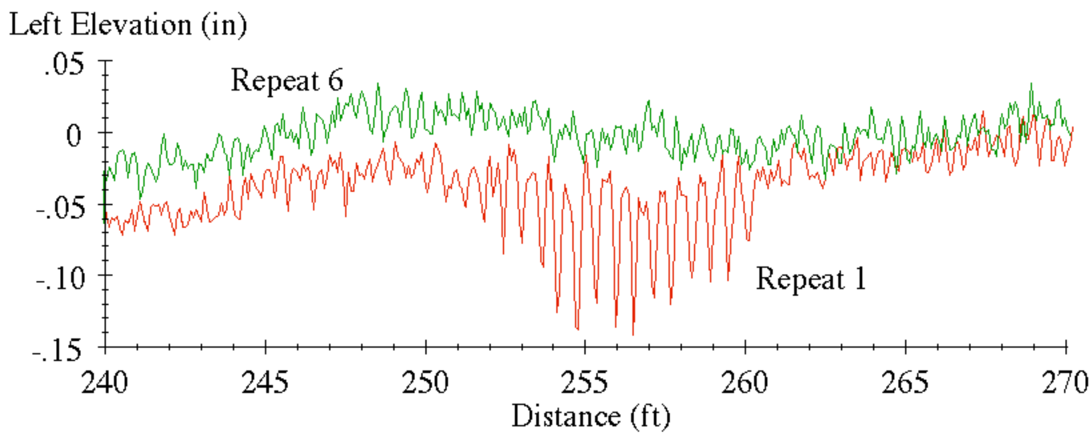

Figure 6. Periodic chatter found in the left side profiles from section A901.

PSDs: All of the PSD plots included a peak at a wavelength of about 0.6 ft.

Distress and maintenance history: Very little distress was recorded for this section, even in later visits. Nothing in the distress histories explains the bump that caused the localized roughness. Note that a large transverse crack was noted in March 2006 that did appear as a bump in the visit 13 profiles about 44 ft from the section start, but it did not affect the IRI much.

The chatter in the profile corresponds to a narrow scuff that runs along the left wheelpath over most of the section, but runs off to the edge near the end. It is present in the photos, and appears as a long series of indents about a third the width of the lane edge stripe. (See Figure 7.)

Figure 7. Pavement scuff in the left wheelpath.

Section 0902, Right

Roughness: The IRI increased steadily from 50 to 60 in/mi.

Elevation profile plots: The elevation profile plots were very consistent throughout visits 01 through 09, with the exception of some developing roughness in the medium wavelength range. The elevation profiles in the medium and short wavelength ranges had changed significantly between visits 09 and 11, such that the shape and severity of most features was often totally different between visits. However, the elevation profiles were extremely consistent in all ten repeat measurements from visits 11 and 13. In visits 11 and 13, the feature that stood out most was a bump 0.1 in high and 6 ft wide from 78 to 84 ft from the start of the section. Three other small disturbances were found in the short wavelength elevation profile plots 162, 208 and 451 ft from the start of the section.

Roughness profiles: The roughness was distributed evenly across the section in visits 01 through 09, and the roughness profiles were fairly consistent with each other for those visits. The visit 11 roughness profiles were significantly different from those of visit 09. Roughness profiles from visits 11 and 13 were very consistent with each other, and included one area of localized roughness and another area where localized roughness was developing. The first was at the bump 78 to 84 ft from the start of the section. This caused a peak in the roughness profile of about 210 in/mi. The second rough area appeared about 450 ft from the start of the section with a peak value of up to 120 in/mi.

Distress and maintenance history: A slurry seal coat was applied in May 2002. This accounts for the major change in medium and short wavelength content between visits 09 and 11. Nothing in the distress surveys explains the localized roughness found 78 to 84 ft and 450 ft from the start of the section. Distress surveys from April 2005 and March 2006 included a significant number of cracks that did not appear to add roughness to the profiles.

Section 0902, Left

Roughness: The IRI followed an increasing trend from 48 in/mi in visit 01 to 66 in/mi in visit 13. The section was roughest in visit 09 with an IRI value of 74 in/mi.

Elevation profile plots: No rough features stood out in the short wavelength roughness plots in visits 01 through 06. In visit 07, a dip up to 0.4 in deep and about 0.5 ft long appeared 213.5 ft from the start of the section. It was not present in any other visit. Visit 09 profiles included several shallow bumps that did not appear in profiles from visits 07 or 11. The medium and short wavelength elevation profile plots were very similar in all ten repeats from visits 11 and 13, but those plots were very different from visit 09. In particular, the short wavelength plots were much smoother in visits 11 and 13 than in visit 09.

Roughness profiles: Roughness was distributed fairly evenly throughout the section in visits 01 through 07, except that the area from 160 to 260 ft from the start of the section was about twice as rough as the rest. The narrow dip 213.5 ft from the start of the section was not severe enough to produce localized roughness. The shallow bumps and extra short wavelength roughness in visit 09 caused it to be rougher than previous visits over the last three quarters of the section. In visits 11 and 13, some areas of the section were rougher than others, but no localized roughness was found. The highest peak in the roughness profile was caused by a rise in pavement elevation of about 0.25 in over 5 ft of pavement starting about 61 ft from the start of the section.

Distress and maintenance history: A slurry seal coat was applied in May 2002. This accounts for the major change in medium and short wavelength content between visits 09 and 11. Nothing in the distress surveys explains the narrow dip found in visit 07 or the shallow bumps found in visit 09.

Section A902, Right

Roughness: The IRI increased steadily from 73 to 96 in/mi in visits 01 through 09, then reduced to 69-70 in/mi in visits 11 and 13.

Elevation profile plots: The elevation profile plots were somewhat consistent in visits 01 through 09. The profiles from visits 11 and 13 were very consistent with each other. However, they were not at all similar in the short wavelength range to profiles from previous visits, and were markedly different in most locations in the medium wavelength range.

Roughness profiles: Visit 01 through 09 profiles included severe localized roughness centered about 260 to 265 ft from the start of the section. This was caused by a sharp change in slope at the bottom of a long (> 100 ft), deep (> 1 in) dip. The dip included a high level of short wavelength roughness at and near its lowest point. Overall, the dip caused a peak in the roughness profile of 240-280 in/mi. In visits 11 and 13, the dip caused a much lower level of peak roughness (150-160 in/mi).

The roughness profiles showed that the roughness progressed across most of the section in visits 01 though 09. The roughness profiles also showed that the roughness was not particularly evenly distributed along the section in visits 11 and 13, with higher roughness found 60 to 100 ft from the start of the section, about 410 ft from the start of the section, and at the bottom of the long dip described above.

Distress and maintenance history: A slurry seal coat was applied in May 2002. This accounts for the change in medium and short wavelength content between visits 09 and 11. Crack sealing was performed on this section in May 2001, but no major change in the profiles seemed to occur.

Distress surveys from April 2005 and March 2006 show significant transverse cracking, but no strong effect (e.g., dips) was found in the profiles.

Section A902, Left

Roughness: The IRI ranged from 73 to 81 in/mi without an increasing trend. The highest value occurred in visit 04.

Elevation profile plots: The elevation profile plots were somewhat consistent in visits 01 through 09. The most noteworthy feature of the profiles was a set of narrow dips that appeared 355 to 400 ft from the start of the section in visits 05 through 09. These dips were usually well repeated within a given visit, but they did not always appear in the same place in every visit.

The profiles from visits 11 and 13 were very consistent with each other. However, they were not at all similar in the short wavelength range to profiles from previous visits, and were markedly different in most locations in the medium wavelength range. The profiles from visits 11 and 13 included a bump about 0.25 in high and 0.5 ft long that was 87.5 ft from the start of the section, and a bump 0.2 in high that ranged from 406 to 414 ft from the start of the section. Neither of these features were found in previous visits.

Roughness profiles: Visit 01 through 09 profiles included localized roughness centered about 260 to 265 ft from the start of the section. This was caused by a sharp change in slope at the bottom of a long (> 100 ft), deep (> 1 in) dip. It caused a peak in the roughness profile of 170-230 in/mi.

In visits 11 and 13, the two bumps described above caused peaks in the roughness profile of over 120 in/mi, but they were not severe enough to be classified as localized roughness. The long dip that has caused localized roughness in visits 01 through 09 was still present, but it was not as severe.

Distress and maintenance history: A slurry seal coat was applied in May 2002. This accounts for the change in medium and short wavelength content between visits 09 and 11. Nothing in the distress surveys explains the two bumps noted in visits 11 and 13. Crack sealing was performed on this section in May 2001, but no major change in the profiles seemed to occur.

Section 0903, Right

Roughness: The IRI increased steadily from 58 to 77 in/mi over visits 03 through 13.

Elevation profile plots: The elevation profile plots were very consistent throughout visits 03 through 09, with the exception of some developing roughness in the medium wavelength range. Profiles from visits 11 and 13 were also very similar to previous visits in the long and medium wavelength range, and somewhat similar in the short wavelength range. However, unfiltered plots from visits 11 and 13 included a high density of narrow downward spikes up to 0.3 in deep that appeared throughout the section. The spikes rarely appeared in the same location in more than one or two of the repeat measurements.

Roughness profiles: The roughness was not particularly evenly distributed along the section, but no areas of localized roughness were found. The growth in roughness was not isolated to one area.

Distress and maintenance history: A very high level of distress was recorded in April 2005 and May 2006. This includes fatigue with water bleeding and pumping, and raveling along the entire right wheelpath. Cracking and raveling, which are confirmed by the photos, explain the narrow downward spikes dispersed throughout the profiles from visits 11 and 13.

Section 0903, Left

Roughness: The IRI followed an unusual trend with time. It was 87 in/mi in visit 03, 96 in/mi in visit 04, 91 in/mi in visit 05, and 82 to 85 in/mi over the rest of the visits.

Elevation profile plots: The elevation profile plots were fairly consistent throughout visits 03 through 05. Profile plots in the long, medium, and short wavelength ranges were very consistent in visits 06 through 13. However, profiles from visits 11 and 13 included narrow downward spikes up to 0.5 in deep that appeared throughout the section. The spikes often appeared in the same location in more than one of the repeat measurements. Note that fewer spikes appeared in the left side profiles than on the left, and the spikes that did appear were often in more than one repeat measurement. Figure 8 shows the density and shape of the spikes over 100 ft of the section in visit 13. In some locations, the spikes appear in only one repeat measurement of the five, but in others the spikes appear in multiple repeats.

Roughness profiles: The roughness was not particularly evenly distributed along the section, such that the middle third was the roughest. No areas of localized roughness were found. Although visits 03 through 05 were the roughest, the roughness profiles did not change much over the monitoring period.

PSD Plots: Significant content was isolated near a wavelength of 40 ft.

Distress and maintenance history: A very high level of distress was recorded in April 2005 and May 2006. This includes fatigue with water bleeding and pumping, and raveling along the entire right wheelpath. Cracking and raveling, which are confirmed by the photos, explain the narrow downward spikes dispersed throughout the profiles from visits 11 and 13.

Section A903, Right

Roughness: The IRI increased from 72 in/mi in visit 03 to 113 in/mi in visit 13. In visits 05 through 07, the IRI held at 98-99 in/mi, and in visits 09, 11 and 13 the IRI held at 111-113 in/mi.

Elevation profile plots: Profiles did not change much over visits 05 through 07. Unfiltered profiles from visits 11 and 13 included several downward spikes throughout the length of the section that appeared in only one repeat measurement in some locations, and up to three locations in others. With the exception of the spikes, the profiles from visits 09, 11 and 13 were consistent with each other.

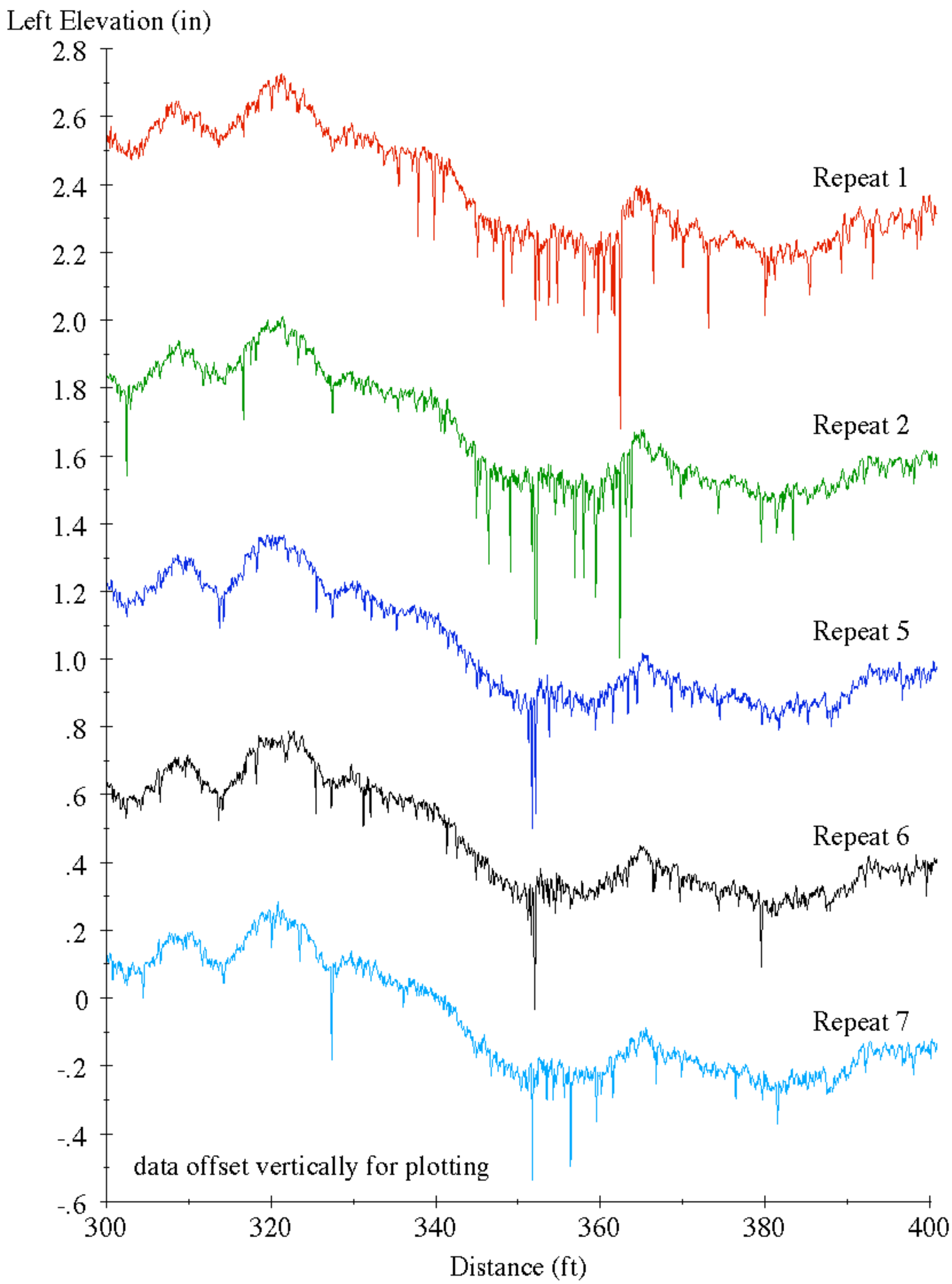

Figure 8. Narrow downward spikes in visit 13 of section 0903.

Roughness profiles: Localized roughness was detected about 70 ft from the start of the section, which caused a peak in the roughness profile of 180-240 in/mi over the monitoring period. The roughness was caused by a sharp change in slope about 60 ft from the start of the section at the bottom of a long dip.

In visits 03 through 13, the progression in roughness was very evenly distributed along the section. That is, when roughness increased, it increased equally along the section. The roughness profiles from visits 11 and 13 were very similar to those of visit 09. This is because the spikes in the profiles from visits 11 and 13 were not numerous or severe enough to add significant roughness.

Distress and maintenance history: A very high level of distress was recorded in April 2005 and May 2006. This includes fatigue with water bleeding and pumping, and raveling along the entire right wheelpath. Cracking and raveling, which are confirmed by the photos, explain the narrow downward spikes dispersed throughout the profiles from visits 11 and 13.

Section A903, Left

Roughness: The IRI increased steadily from 71 in/mi in visit 03 to 108 in/mi in visit 13.

Elevation profile plots: The medium and long wavelength elevation plots were fairly consistent in visits 03 through 07. However, the short wavelength elevation plots became rougher over time, and seemed to grow in roughness most between visits 06 through 09.

Unfiltered elevation profile plots revealed several features that affected the roughness. In visit 09, a dip less than 1 ft long and up to 0.5 in deep appeared 45 ft from the start of the section. The dip was not detected in visit 11. It was detected in visit 13 in two of the five repeat measurements, where it was nearly an inch deep. A less severe dip also appeared 57 ft from the start of the section in two of the five repeat measurements from visit 09.

Profiles from visits 11 and 13 included several downward spikes throughout the length of the section that were rarely in the same location in more than one repeat measurement.

Roughness profiles: No localized roughness was found in any visit, although the roughness was not particularly evenly distributed along the section. The growth in roughness was not confined to any particular area.

Distress and maintenance history: A very high level of distress was recorded in April 2005 and May 2006. This includes fatigue with water bleeding and pumping, and raveling along the entire left wheelpath. Cracking and raveling, which are confirmed by the photos, explain the narrow downward spikes dispersed throughout the profiles from visits 11 and 13. Nothing in the distress measurements explains the dip 45 ft from the start of the section.

SUMMARY

This section provides a summary of important observations from each section within the Arizona SPS-9P 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 1 through 5), 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.

A slurry seal coat was applied to sections 0902 and A902 in May 2002. On both sections, the seal coat modified the short wavelength content of the profiles significantly. Often, the net result was temporary smoothing of narrow dips that appeared at cracks and raveling. On both sections, the medium wavelength content of the profiles was also altered. This usually meant that high and low points within the medium wavelength profile plots occurred in roughly the same places, but with altered shape and severity.

The slurry seal coat reduced the IRI on both sections. The change was largest on the right side of section A902, where the IRI reduced by 27 in/mi. The change occurred because the right side profiles often included a higher level of narrow dips caused by cracking that was submerged after seal coat was placed.

Placement of the seal coat also improved the relationship between the right and left profiles by eliminating narrow dips and uncorrelated short wavelength content. This is demonstrated by the fact that the difference between the HRI and MRI reduced from 27 percent to 14 percent on section 0902 and from 25 percent to 10 percent on section A902.

Profiles from sections 0903 and A903 in visits 11 and 13 included several downward spikes that often appeared in only one or two repeat measurements of each location. These were caused by cracking and raveling, which covered both wheelpaths. The spikes were more prevalent in the right wheelpath. The spikes did not appear to affect the IRI significantly.

Significant raveling was also recorded on both sections before visit 09, but visit 09 profiles did not include the downward spikes. The explanation may be the change in profiler height sensor footprint. (*6*) Profiles were measured in visits 11 and 13 by an International Cybernetics Corporation MDR 4086L3 profiler. These include height sensors with a footprint diameter of about 1.5 mm. In visits 03 through 09, profiles were measured using K.J. Law T-6600 profilers, which used a height sensor with a footprint that was 38 mm wide and 6 mm long.

The change in profiler make in late 2002 affected the long wavelength content of the profiles on every test section. This is because the newer profiler used a high-pass filter that eliminated a little more of the profile content than the previous device. This had no probable effect on the measurement of localized roughness or the study of narrow bumps and dips caused by distress. However, it did confound the study of the true effect caused by the slurry seal coat, since the device change and application of the seal coat both occurred between visits 09 and 11.

Another minor device effect within the profiles was peaks in the PSD plots with no pavement-related explanation. In visits 01 and 02 (measured by the K.J. Law DNC 690) most PSD plots from the left side included a strong peak at a wavelength of 2.5 ft. In visits 03 through 09 (K.J. Law T-6600) all profiles from the left and right side included a peak in their spectral content at a wavelength somewhere between 0.35 and 0.65 ft and another at a wavelength of double the first.

The rest of this report provides a summary of the most important observations made about each test section. The summaries are extracted from the Detailed Observations section of this report. To help provide context for the summary statements below, Figure 9 shows the range of left and right IRI for each section. Note that the highest IRI value for some of the sections did not occur in the final visit. (See Appendix A or Figures 1 through 5.)

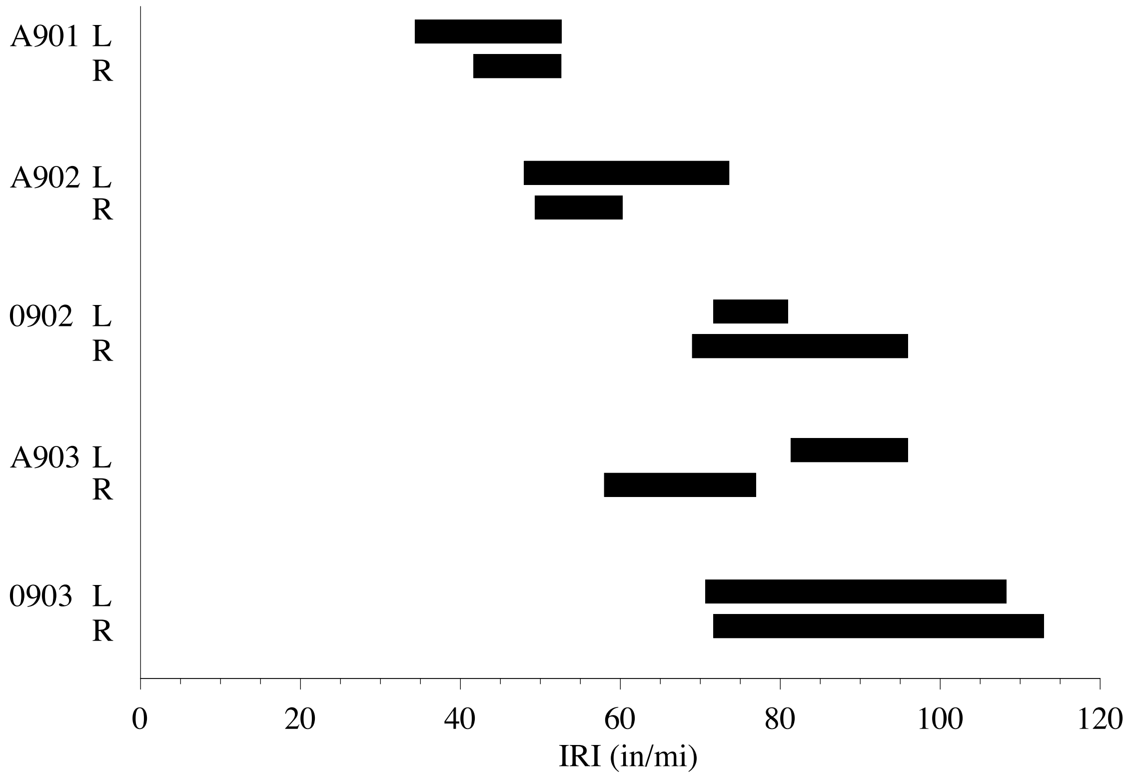

Figure 9. Summary of IRI ranges.

Section A901: The left side profiles included two patches of sinusoidal chatter in all visits, and included the chatter over the first half of the section in visits 04 and 11. This affected the look of the profiles tremendously, but it did not affect the IRI much. A bump appeared about 400 ft from the start of the section that become rougher with time, and caused localized roughness by visit 13.

Section 0902: The short and medium wavelength roughness was altered by the application of a slurry seal coat in May 2002, and the roughness of the right side was significantly reduced. Localized roughness was found on the right side in visits 11 and 13 at a bump 0.1 in high from 78 to 84 ft from the start of the section. A severe narrow dip 0.5 ft long and 0.4 in deep was found 213.5 ft from the start of the section in visit 07 only. No corresponding distress was noted.

Section A902: The short and medium wavelength roughness was altered by the application of a slurry seal coat in May 2002, and the roughness of the right side was significantly reduced. A long, deep dip from about 205 to 320 ft from the start of the section increased the roughness of the section significantly. It appeared on both sides, but it was much more harsh in the right side profiles. The feature that affected the roughness most was the change in slope at the deepest part of the dip, and the short wavelength roughness there. Note that the dip registered a much lower level of concentrated roughness on the right side after the seal coat.

Section 0903: This section was covered with significant signs of fatigue over the entire surface by the end of the monitoring period. The profiles from visits 11 and 13 included a large number of narrow downward spikes. The location and severity of the spikes was not well correlated between repeat measurements. These were caused by cracking and raveling. No localized roughness was found on the section.

Section A903: This section was covered with significant signs of fatigue over the entire surface by the end of the monitoring period. The profiles from visits 11 and 13 included a large number of narrow downward spikes. The location and severity of the spikes was not well correlated between repeat measurements. These were caused by cracking and raveling. Localized roughness was detected about 70 ft from the start of the section because of a sharp change in slope at the bottom of a long dip centered 10 ft upstream.

REFERENCES

1. Nichols Consulting Engineers, Chtd, "Construction Report on Site 040900/04A900." (1997) 25 p.
2. Evans, L. D. and A. Eltahan, "LTPP Profile Variability" *Federal Highway Administration Report FHWA-RD-00-113* (2000) 178 p.
3. Karamihas, S. M., "Development of Cross Correlation for Objective Comparison of Profiles." *International Journal of Vehicle Design*, Vol. 36, Nos. 2/3 (2004) pp. 173-193.
4. Sayers, M. W. and S. M. Karamihas, "Interpretation of Road Roughness Profile Data." *Federal Highway Administration Report FHWA/RD-96/101* (1996) 177 p.
5. Sayers, M. W., "Profiles of Roughness." *Transportation Research Record 1260* (1990) pp. 106-111.
6. Perera, R. W. and S. D. Kohn, "Quantification of Smoothness Index Differences Related to LTPP Equipment Type." *Federal Highway Administration Report FHWA-HRT-05-054* (2005).

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 225 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 0.773. This is an unusually large difference between HRI and MRI . Note that a better linear fit was found without forcing a zero intercept. A simple linear fit produced a slope of about 0.711 and an intercept of about 4.6 in/mi.

RN has shown a closer relationship to road user opinion than the other indexes. (*3*) As such, it may help distinguish the segments from each other by ride quality. Further, the effect on RN may help quantify the impact of that distress on ride when a particular type of distress dominates the roughness of a section. In particular, a very low RN value coupled with moderate IRI values indicates a high level of short wavelength roughness, and potential sensitivity to narrow dips and measurement errors caused by coarse surface texture.

Table A-1 provides the roughness values. The tables also list the date of each measurement, and the time in years since the site was opened to traffic. Negative values indicate measurements that were made before rehabilitation.

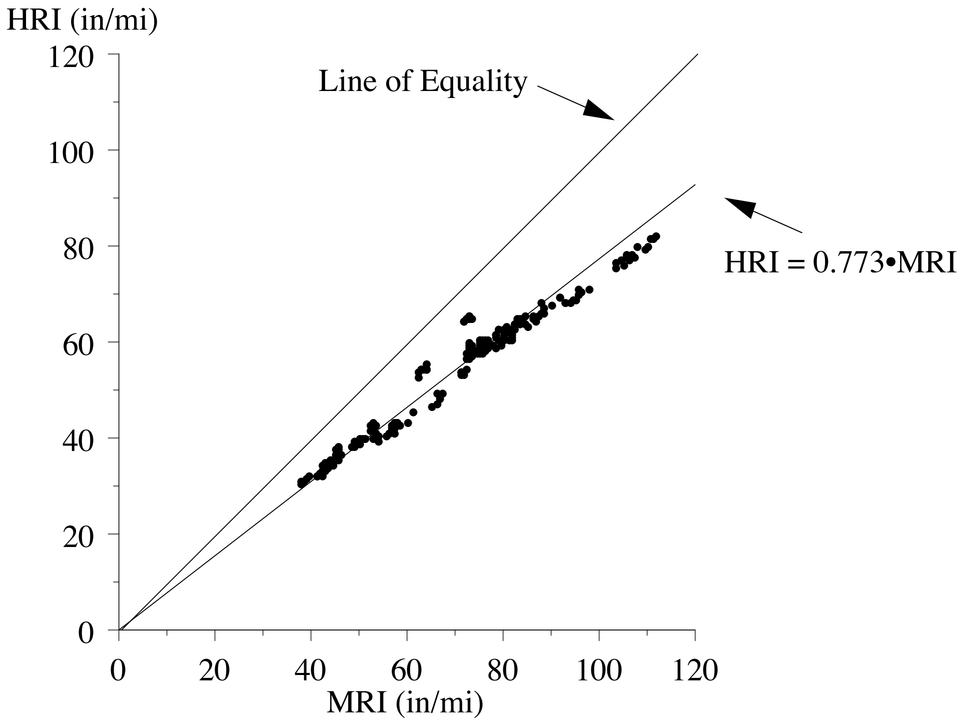

Figure A–1. Comparison of HRI to MRI.

Table A-1. Roughness Values.

Section	Date	Years	Left IRI (in/mi)		Right IRI (in/mi)		MRI (in/mi)	HRI (in/mi)	RN
			Ave	St Dev	Ave	St Dev			
0902	27-Jan-94	0.49	48	1.0	50	0.6	49	39	4.05
0902	27-Feb-95	1.57	50	0.9	50	0.6	50	40	4.10
0902	23-Jan-97	3.48	53	0.6	53	0.3	53	41	3.96
0902	8-Apr-98	4.68	62	2.9	55	1.3	59	43	3.70
0902	4-Dec-98	5.34	57	0.8	54	1.3	56	41	3.77
0902	17-Nov-99	6.29	59	0.7	56	0.5	57	43	3.84
0902	19-Dec-00	7.38	59	0.9	55	0.3	57	43	3.77
0902	20-Feb-02	8.56	74	0.9	59	1.0	66	48	3.50
0902	10-Mar-04	10.61	67	0.7	59	1.0	63	54	3.75
0902	27-Mar-06	12.65	66	0.5	60	1.2	63	54	3.75
0903	23-Jan-97	3.48	87	0.9	58	0.4	73	57	3.85
0903	8-Apr-98	4.68	96	3.0	63	0.5	79	61	3.48
0903	4-Dec-98	5.34	91	1.0	61	0.6	76	59	3.58
0903	17-Nov-99	6.29	84	0.9	64	0.7	74	58	3.65
0903	19-Dec-00	7.38	82	0.4	64	0.7	73	58	3.61
0903	20-Feb-02	8.56	82	0.3	69	0.9	75	59	3.42
0903	9-Mar-04	10.60	83	2.3	73	2.8	78	60	3.13
0903	27-Mar-06	12.65	85	3.2	77	2.2	81	63	2.95

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			
A901	27-Feb-95	1.57	35	1.6	42	0.7	38	31	4.27
A901	23-Jan-97	3.48	37	0.4	46	0.6	41	32	4.23
A901	8-Apr-98	4.68	37	0.7	49	0.3	43	34	4.10
A901	4-Dec-98	5.34	37	0.6	48	0.4	43	34	4.16
A901	17-Nov-99	6.29	40	0.6	47	1.1	44	35	4.17
A901	19-Dec-00	7.38	38	0.9	48	0.3	43	34	4.24
A901	20-Feb-02	8.56	43	0.8	48	0.3	45	37	4.16
A901	10-Mar-04	10.61	43	0.7	48	1.0	45	37	3.98
A901	27-Mar-06	12.65	53	0.9	53	0.7	53	43	3.80
A902	27-Jan-94	0.49	73	1.1	73	1.0	73	60	3.70
A902	27-Feb-95	1.57	74	1.1	77	0.9	76	60	3.75
A902	23-Jan-97	3.48	76	2.0	82	1.7	79	61	3.65
A902	8-Apr-98	4.68	81	2.1	89	1.4	85	64	3.39
A902	4-Dec-98	5.34	72	0.5	88	1.8	80	60	3.57
A902	17-Nov-99	6.29	75	1.6	90	1.3	83	64	3.52
A902	19-Dec-00	7.38	75	0.6	92	1.1	84	65	3.51
A902	20-Feb-02	8.56	79	0.8	96	1.1	87	66	3.45
A902	10-Mar-04	10.61	75	0.1	69	0.8	72	65	3.76
A902	27-Mar-06	12.65	75	0.9	70	0.4	73	65	3.75
A903	23-Jan-97	3.48	71	0.7	72	0.6	71	54	3.73
A903	8-Apr-98	4.68	78	1.5	85	1.9	82	62	3.38
A903	4-Dec-98	5.34	82	1.4	98	2.5	90	69	3.34
A903	17-Nov-99	6.29	90	1.5	98	1.9	94	69	3.36
A903	19-Dec-00	7.38	92	1.2	99	1.1	96	70	3.31
A903	20-Feb-02	8.56	101	1.1	111	1.5	106	77	2.99
A903	9-Mar-04	10.60	98	2.9	111	1.7	105	78	2.90
A903	27-Mar-06	12.65	108	1.1	113	1.3	111	81	2.71

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.