LTPP Profile Variability

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Prepared by:

ERES Consultants and Fugro-BRE
A Division of Applied Research Associates, Inc.
9030 Red Branch Road, Suite 210
Columbia, Maryland 21045

Prepared for:

Pavement Performance Division, HRDI
Federal Highway Administration
6300 Georgetown Pike
McLean, Virginia 22101-2296

Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-2296

U.S. Department of Transportation
Federal Highway Administration

FOREWORD

High quality pavement profile data are important to both the LTPP research, and highway agency pavement management systems. This report documents a study conducted to evaluate the quality and variability of the longitudinal profile data in the Long Term Pavement Performance (LTPP) database. The study focuses on LTPP profiles collected between June 1989 and October 1997. These profiles were visually reviewed for saturation spikes, lost lock, shifted starts, wrong location, out of study and other equipment-and-operator-related problems. Noted problems are identified in the report. Repair, replacement, or deletion of these files was completed in conjunction with this study. Remaining or replaced good profile data were used for analysis of variability.

T. Paul Teng, P.E.
Director
Office of Infrastructure
Research and Development

NOTICE

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Technical Consultants: Elson Spangler, Brandt Henderson, Susanne Aref, and Peter John

16. Abstract

A study has been conducted to evaluate the quality and variability of the International Roughness Index (IRI) data in the Long Term Pavement Performance (LTPP) database. All LTPP profiles collected between June 1989 and October 1997 were visually reviewed for saturation spikes, lost lock, shifted starts, wrong location, out of study, and other equipment- and operator-related problems. Noted problems are identified in the report. Repair, replacement, or deletion of these files was completed in conjunction with this study. Remaining or replaced good IRI data were used for analysis of variability.

Analysis of variance focused on the run-to-run and visit-to-visit IRI variability in the LTPP sections studied. Mean IRI values for these asphalt concrete (AC), portland cement concrete (PC), and AC/PC overlaid sections ranged from 0.5 to 4.3 m/km. Based on the upgraded data set, confidence limits were developed for expected variability between repeated profile testing runs and for the expected change in IRI between subsequent visits.

Additional analysis is also presented regarding the effects of saturation spikes, shifted profiles, and wheelpath testing location on IRI. Study was also completed on the effect of the number of runs collected at a site, the effect of moist pavement surfaces, and the results of small changes in the coefficients used to compute IRI.

Recommendations of the study address the methods used for field profile collection, office review methods, Information Management System (IMS) database design, and profile calibration.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

NOTE: Volumes greater than 1000 l shall be shown in m^3.

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

(Revised September 1993)

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LIST OF ABBREVIATIONS

AC	Asphalt concrete
ANOVA	Analysis of Variance
APC	AC overay of PC
ASTM	American Society for Testing and Materials
BWP	Both wheelpaths
CN	Construction number
COV	Coefficient of Variation
DMI	Distance Measuring Instrument
FHWA	Federal Highway Administration
GPS	General Pavement Studies
IMS	Information Management System
IRI	International Roughness Index
LTPP	Long Term Pavement Performance
LWP	Left wheelpath
MS	Microsoft
ODBC	Open Database Connectivity
PC	Portland (Cement) Concrete
QC	Quality Control
RCO	Regional Coordination Office
RCOC	Regional Coordination Office Contractor
RMSVA	Root Mean Square Vertical Acceleration
RWP	Right wheelpath
SD	Standard Deviation
SHRP	Strategic Highway Research Program
SPS	Special Pavement Studies

CHAPTER 1. INTRODUCTION

The Long Term Pavement Performance (LTPP) program has been collecting profile and International Roughness Index (IRI) information from more than 2,062 test sections since 1989 using K.J. Law 690DNC optical sensor Profilometers. Analysis of the IRI data has been limited, but with the increasing distribution of the LTPP DataPave software, this data is seeing increasing use. In an effort to confirm the quality of LTPP IRI data in the Information Management System (IMS) database and to document its variability, LTPP initiated an analysis of IRI variability in September 1997. This report documents the results of that study.

Before the data could be analyzed, the quality of the data needed to be confirmed, the single-visit and multiple-visit IRI variability needed to be evaluated, and recommendations and confidence limits needed to be developed for quality control of profile data collection. Although it was initially conceived as a small part of the analysis, the verification and upgrade of data quality became the largest effort in this analysis. During visual review, equipment- and processing-related problems were noted in 14.6 percent of the IMS profiles. Repair and upgrade of 4.5 percent of the IMS data were completed. About 4 percent of the profile runs were noted as irreparable and were deleted from the database, and nearly 2,800 runs (5.9 percent of the database) were considered questionable and are awaiting review and reprocessing or deletion by Regional Coordination Office Contractors (RCOC's).

Single-visit (run-to-run) variability among the five repeated profile runs at 152.4-m test sections has been analyzed using confirmed and upgraded IRI values (nearly 90 percent of the values in the database). This analysis included transforming the data to remove the effect of IRI level on variability. Several conclusions were drawn based on the study of the effects of pavement type, testing time, season, region, equipment type, profile initiation method, and surface roughness. Confidence limits for the expected variability between repeated runs are proposed as a result of this analysis.

Multiple-visit (visit-to-visit) variability between data collected on different dates was also studied, resulting in conclusions regarding the effect of daily and seasonal changes on IRI variability. The presence of inflection points in IRI trends was reviewed. Computed confidence intervals for the expected yearly change in IRI resulting from equipment, seasonal, wheelpath, and other random variation were also developed.

Included in this report is a summary of the data quality review findings and upgrade procedures. Analyses of the run-to-run and visit-to-visit variability are then discussed, followed by a review of other analysis activities. Confidence limits are then provided, along with recommendations for use of the results.

CHAPTER 2. DATA QUALITY REVIEW

Profile data quality in the IMS database was initially reviewed using IRI variability and slope values. This review indicated that focusing on outlier IRI values was insufficient to identify all profile quality problems. As a result, profile plotting software—originally developed for review of a small portion of select questionable profiles—was used to plot and visually review the more than 47,000 profile runs in the IMS database.

The initial statistical review of the IRI data in the IMS database indicated that the run-to-run variability in the left and right wheelpath IRI values was small. Some of these profile sets with large run-to-run variability exhibited equipment or operator problems; many others did not. In a review of the visit-to-visit IRI slopes for a given section, nearly 22 percent of the unrehabilitated test sections exhibited slopes of less than zero for the linear trend of the average IRI. This trend indicates that the pavements are becoming smoother with age (which is illogical), that there is a problem with the profile data, or possibly that unreported maintenance is occurring.

To more easily study the reasons for these trends, the Profile Viewer software was developed for reviewing and overlaying plots of measured LTPP pavement profiles. This software, described further in Appendix C, allows the operator to select and plot individual left or right wheelpath runs from single or multiple site visits. IRI values are displayed for each run, and comments from original data collection are also displayed for review.

Initially, the Profile Viewer software was intended only for review of the outlier section profiles identified in the IRI variability evaluation. However, after viewing profiles for 77 sections in 5 States and finding problems in 52 sections, it was determined that outlier searches of IRI statistics did not identify all of the data collection problems revealed in the profile review. Based on this information, the necessity of plotting and viewing all profile data was evident.

A 2.4-Gb file containing all IMS profile data was downloaded on October 7, 1997, and was split into Microsoft (MS) Access database files for review. Initially, 9,190 General Pavement Studies (GPS) profile plots were printed and visually reviewed. Then, 11,650 Special Pavement Studies (SPS) profile plots were printed. Individual color profiles for the left and right wheelpaths of all five runs from each section were visually reviewed for consistency and for the presence of equipment- or operator-related problems. In addition, color-overlaid profiles of the left and right wheelpaths for the first run from each section visit were reviewed to confirm the testing location and other discrepancies. This provided the first comprehensive review of the repeatability of the profiles in the IMS database.

Overall, the LTPP profile database appeared to have good integrity, with profiles and IRI values that reflect excellent equipment and good collection/processing methods. Many of the runs completed at one site on the same day overlay each other exceptionally well, giving the appearance of a single profile line. IRI values exhibit a steady increase in roughness between consecutive visits for many test sections. However, during the profile review, several types of questionable profile characteristics also became evident, including the following:

- Unnoted equipment-related saturation spikes.
- Partial and complete lost lock.

- Incorrect start location.
- Wrong (unknown) test location.
- Miscalibrated Distance Measuring Instrument (DMI).

Descriptions and illustrations of these questionable characteristics are provided in Appendix A. Many of these characteristics were described by RCOC profiler operators and data reviewers in the comments listed in the IMS MON_PROFILE_MASTER table, but others do not appear to have been noted during field data collection or final evaluation.

Saturation Spikes

Saturation spikes occur as an excess of light is returned to the Profilometer optical sensors, generally as reflections from the transverse pavement stripes used to mark the beginning and end of each test section. This typically results in profiles that increase in amplitude from 5 to 75 mm or more at the location of the spike. Such spikes can be flagged using the LTPP ProQual software so that they are not included in the IRI calculations. However, the spikes in the older version (ProQual 1.4) were still included in computation of the other smoothness indices.

All saturation spikes were identified and recorded in the visual review. These included both those originally edited by RCOC engineers and those identified under the current review. The presence of edited spikes was determined from an August 1998 download from the IMS database. Saturation spikes unnoted during the original review accounted for 4.9, 6.6, 1.6, and 1.6 percent (average 3.8 percent) of the site visit data in the North Atlantic, North Central, Southern, and Western Region profiles, respectively. Saturation spikes in section visit profiles were 1.8 to 11.5 times (averaging 5.2 times) more common in the left sensor than in the right for all regions.

Lost Lock

Lost lock occurs when insufficient light is returning to the optical sensors. As a result, the profile contains only information provided by the accelerometers. The resulting profile is typically very smooth for compete lost lock and choppy when lost lock is intermittent.

Significant lost lock was noted in profiles from about 3.9 percent of site visits. Rapidly intermittent lost lock accounts for about 51 percent of the noted lost lock, and occasionally intermittent or full lost lock makes up the rest. It is possible that the regular short wavelength chatter noted as rapidly intermittent lost lock could, in some cases, be the result of a loose mirror in the optical receiver or other system noise.

Regional Profilometers varied in the sensor that exhibits the most lost lock. The North Atlantic, North Central, and Western Region Profilometers were 1.2 to 2.9 times more likely to exhibit lost lock characteristics on the right sensor, while the Southern Region Profilometer had 5.3 times more lost lock on the left sensor. Lost lock characteristics were most prominent in the North Atlantic Region’s Profilometer, with 8.2 percent of its profile runs indicating significant lost lock.

There appears to have been a shift in the North Atlantic Profilometer from primarily producing lost lock in the left sensor to doing so in the right sensor around September 1994. Prior to that date, lost lock was identified in the left sensor 5.7 times more than in the right sensor. Subsequent to that date, right sensor lost lock was 8.3 times more common. This shift was noted by the RCOC, and attempts to identify and remedy the problem were taken with only limited success.

Incorrect Start Location

Occasionally, the profiles for individual runs or for a single date do not begin at the same location as the remaining test dates. This has been noted as a "shifted profile start."

Profile runs where the start location was incorrect but the spatial relation to the true start location is known are identified in the shifted start categories listed in table 3 and in Appendix G. Shifted starts, or profile runs shifted more than 5 m, are most common in the North Central (4.9 percent) and Western (7.2 percent) Regions. The estimated range of shifted profile distances in the Western Region is 5 to 53 m, with an average distance of 11 m. Western Region GPS section profile shifts averaged 33 m, and SPS sections with shifts averaged 35 m. The average GPS and SPS profile shifts for the North Central Region, where present, are 21 and 441 m, respectively. Shifted profiles for the remaining regions are evident in less than 1.2 percent of section visit profile runs.

Wrong Test Location

Several profiles in the IMS database for a single date or for consecutive dates do not match those of previous dates for the same test section. It is evident that they were collected in an unknown location different from the true section location, and they are categorized as such.

Profiles identified as being in the wrong location are different from those identified as having a shifted start location because the offset from the true section location is unknown. If the reviewers had exact knowledge of a shift in profile location, the runs were identified as being in the shifted start category. The majority of these "wrong location" runs occurred in the North Central Region, accounting for 1.2 percent of the IMS database.

Miscalibrated DMI

A miscalibrated DMI affects profiles by including too little or too much profile data in a section profile. Occasions where the DMI appears to be miscalibrated more than 1.5 m in 152.4 m have been noted.

Miscalibration of the DMI was only found to be a significant problem in the North Central Region’s profiles, with 3.1 percent of the profile runs being off by 6 to 8 m. All of these runs were completed in May 1990, April 1995, or June 1995. This indicated that an equipment problem was experienced, the calibration period was too infrequent, or the calibration test section was inadequate at those times.

Out of Study

Correspondence with RCOC personnel regarding unaccounted-for changes in section profiles between visits has identified several profiles in the IMS database that were collected after the section was declared "out of study." This is possible because test section removal from the LTPP study may occur several years after section rehabilitation, after additional profile collection and database entry have been completed.

Summary tables listing the noted characteristics related to equipment or operator problems are shown in Appendixes E through L of this report. Tables 1, 2, and 3 list the number of LTPP test section profile runs exhibiting each of these critical problems.

Table 1. Reparable profile runs in the LTPP database

Region	Total runs	RCOC noted spikes	Additional spikes	Total reparable
North Atlantic	10,011	96	486	582
North Central	14,604	185	970	1,155
Southern	10,693	0	171	171
Western	11,766	22	183	205
Total	47,074	303	1,810	2,113

Table 2. Irreparable profile runs in the LTPP database.

Region	Total runs	Lost lock	Out of study	Total irreparable
North Atlantic	10,011	821	100	921
North Central	14,604	382	70	452
Southern	10,693	542	10	552
Western	11,766	83	30	113
Total	47,074	1,828	210	2,038

Table 3. Pending profile runs in the LTPP database.

Region	Total runs	Shifted start (>10 m)	Shifted start (5-10 m)	Miscalib-rated DMI	Wrong location	Total pending
North Atlantic	10,011	105	13	0	48	166
North Central	14,604	534	188	455	366	1,543
Southern	10,693	36	7	0	9	52
Western	11,766	287	558	0	156	1,001
Total	47,074	962	766	455	579	2,762

Other Sources of Data Variability

Typically, for a single date, the five profiles from a wheelpath overlaid well for all regions. Poor profile repeatability was noted in about 10 and 30 percent of the GPS and SPS section visit profiles, respectively. It was defined as a difference in elevation for repeated runs of more than 3 mm over at least 30 percent of the test section length. Differences in the location of the measured wheelpath and equipment limitations can contribute to this vertical variability. Overall, it was identified in about 22 percent of the IMS section visit profiles. However, the variability seems to have had very little effect on IRI values and was not included in the profile problems slated for repair or deletion.

A significant amount of the noted vertical profile variations occurred in profiles collected using the new T-6600 Profilometer. Visual review of profiles collected using the 690DNC and the T-6600 indicate that good profile repeatability is more commonly obtained using the old 690DNC system.

Although not a profile problem, unreported rehabilitation noted in the review was confirmed with RCOC's in an effort to update IMS construction information. Only 115 profile runs (0.2 percent) were identified as being on a rehabilitated pavement for which the IMS construction number had not been incremented.

Summary

In summary, about 14.6 percent of the IMS profile run data exhibit equipment- or operator-related problems. Many of these profiles could be adequately repaired and replaced. The status of others is pending, requiring additional review of the available profile archives. About 4.3 percent of the IMS profile runs exhibit irreparable effects of equipment or operator problems, most notably lost lock. Table 4 categorizes these profile problems.

Table 4. Status of runs with equipment/operator problems.

Region	All problems, %	Repairable, %	Irreparable, %	Pending, %
North Atlantic	16.6	5.8	9.2	1.7
North Central	21.4	7.9	3.1	10.6
Southern	7.2	1.6	5.2	0.5
Western	11.1	1.7	1.0	8.5
All regions	14.6	4.5	4.3	5.9

Many of these questionable data were not easily identified using the quality control software and methods available at the time of collection. There was no ability to overlay profiles from a single date, nor was there an option to overlay profiles from different visit dates. Without these options, regional engineers had a limited ability to identify lost lock, spikes, early starts, and different profiles. As a result, this review is, in essence, a supplemental quality review rather than a judgment of regional data collection operations.

CHAPTER 3. PROFILE DATA QUALITY UPGRADE

To repair, replace, or delete the identified problem profile runs, the Action Plan summarized in Appendix B was developed. This plan defines criteria for acceptance and rejection of profile data. It also details the steps necessary for addressing profiles that fall within the repairable, irreparable, and pending categories. Table 5 provides an overview of the quality upgrade process and criteria. The methods used and the status of this upgrade are described in this chapter.

Table 5. Categorization of profile problem runs.

Profile problem	Repairable	Irreparable	Pending
Saturation spikes	All runs		
Lost lock		All runs	
Shifted profile (>10 m)	Replacement data available	Replacement data unavailable	Replacement unknown
Shifted profile (5-10 m)	All runs		
Miscalibrated DMI (>10 m)		All runs	
Miscalibrated DMI (5-10 m)	All runs		
Wrong location	Replacement data available	Replacement data unavailable	Replacement unknown
Unnoted rehabilitation	All runs		

Repairable Profiles

Profiles that contain saturation spikes can be repaired using the ProQual Version 2.08a software used in current LTPP profile data processing. This software allows the user to eliminate the saturation spikes from the profiles during computation of smoothness indices. As a result, computed IRI values from these reprocessed profiles can be very accurate, since only one or two data points are eliminated from the profile.

Profiles that do not begin at the correct location can also be reprocessed, using the ProQual software, when replacement data are available. Initially, all profile runs shifted more than 10 m were deleted from the IMS and reloaded if reprocessed profiles collected in the correct location were available. If profiles shifted 5 to 10 m had no available replacement data, or if the DMI was miscalibrated 5 to 10 m, the IMS profile data were extracted, comments were added, the Regional Coordination Office (RCO) quality code was reduced to 2, and the IMS profile data were reloaded.

Profiles collected at an unknown, wrong location were repaired if correct replacement data were available. For this evaluation, all such profile runs will be deleted from the analysis data set.

Unreported rehabilitation is not related to problems with the profile collection operations. However, since its identification was facilitated by the visual review of profiles, it is reported in this evaluation. Repair of this problem requires that the RCO obtain the necessary information and forms from a State or Province to incorporate the maintenance/rehabilitation informationinto the IMS database.

All profiles listed in Appendix E containing saturation spikes have been extracted from the IMS database and reprocessed without the spikes. The Profile Extractor software, described in Appendix D, was used to extract profile data and convert them to a form that can be used by the ProQual Version 2.08a software. Replacement IMS upload files, archive files, and appropriate paper files have been compiled for distribution to the RCOC's for IMS upload.

Lists of shifted profile sections, those with miscalibrated DMI values, and profiles collected in an unknown location were submitted to the Federal Highway Administration (FHWA) on February 27, 1999, for distribution to RCOC's. RCOC's were asked to replace all saturation spike profile data and, if possible, to review and replace all shifted or unknown location profiles. The RCOC's have replaced profile data for many of the shifted profiles. Profiles with miscalibrated DMI values for the North Central Region have been extracted and appropriate comments added.

Irreparable Profiles

Because of the loss or distortion of profile data input that accompanies lost lock, most such profiles are irreparable. It is possible that profiles that include rapidly intermittent lost lock could be filtered to remove those data with only a small effect on IRI. However, such efforts are not tested or have not proven to be reliable. The option of reducing the quality rating of profiles exhibiting lost lock was considered and dismissed, and in the interest of preserving database integrity, all profiles exhibiting lost lock effects have been deleted from the IMS database.

Profiles that were collected in the wrong location and profiles shifted more than 10 m, for which accurate replacement data are unavailable, are also considered irreparable. Currently, only a few such data sets have been identified, and they have been deleted from the IMS database.

Irreparable profiles in the IMS database and regional databases were deleted in stages. Initially, all profile runs exhibiting lost lock and runs that were collected in the wrong location with no available replacement data were deleted. Lists of confirmed irreparable profile runs were distributed to RCOC's in early March 1999 for deletion from the Regional Information Management System (RIMS) database. As RCOC's identified additional profile runs for which replacement data were unavailable, these were also deleted.

Pending Profiles

Although shifted profiles and profiles tested in the wrong location have been identified under this research, RCOC's were required to search their archive files to determine if accurate data were available to replace these runs. For many GPS and all SPS sections, profiles for an entire test site (which includes several test sections) were collected. In addition to the test section profiles, regional archives contain profile data collected between test sections. This sometimes contained replacement profile information for the true test site location that could be resectioned and reprocessed to replace shifted profile data with profiles from the correct location.

All profiles shifted more than 10 m were deleted from the IMS. If replacement data were prepared by the RCOC's for shifted profiles, they were reloaded into the IMS as they became available. Runs with profiles shifted between 5 and 10 m, where replacement data were unavailable, were extracted from the IMS, a comment was added, and the RCO quality code was reduced to 2. Again, lists of pending profile runs were sent to the RCOC's for review, and response and replacement were completed by September 1999.

Effect of Profile Data Upgrade

Currently, the data upgrade has consisted of reprocessing and reloading to the IMS database of 2,128 runs containing equipment-related spikes and deletion of 1,110 runs with lost lock, tested in the wrong location, or shifted more than 10 m. The effect of this upgrade on data quality can be quantified by comparing the data variability and the data trends before and after the upgrade.

<u>IRI Variability</u>

LTPP profiles are typically collected in at least five consecutive runs. The Profilometers measure surface elevations and compute IRI for the left wheelpath (LWP) and right wheelpath (RWP). An IRI for both wheelpaths (BWP) is computed as the average of the two wheelpaths. BWP IRI standard deviations of the five runs in the IMS database following the upgrade decreased 7.6 percent overall. It was assumed that reduced variability resulted from elimination of the large IRI variations associated with saturation spikes and lost lock. The coefficient of variation (COV), or percentage ratio of standard deviation to mean, also improved. A COV of 2 percent is generally considered representative of good repeatable data. The number of sections with COV values greater than 2 percent decreased by 2.8 percent with a corresponding increase in sections with COV values less than 2 percent. Figure 1 shows this effect for each wheelpath.

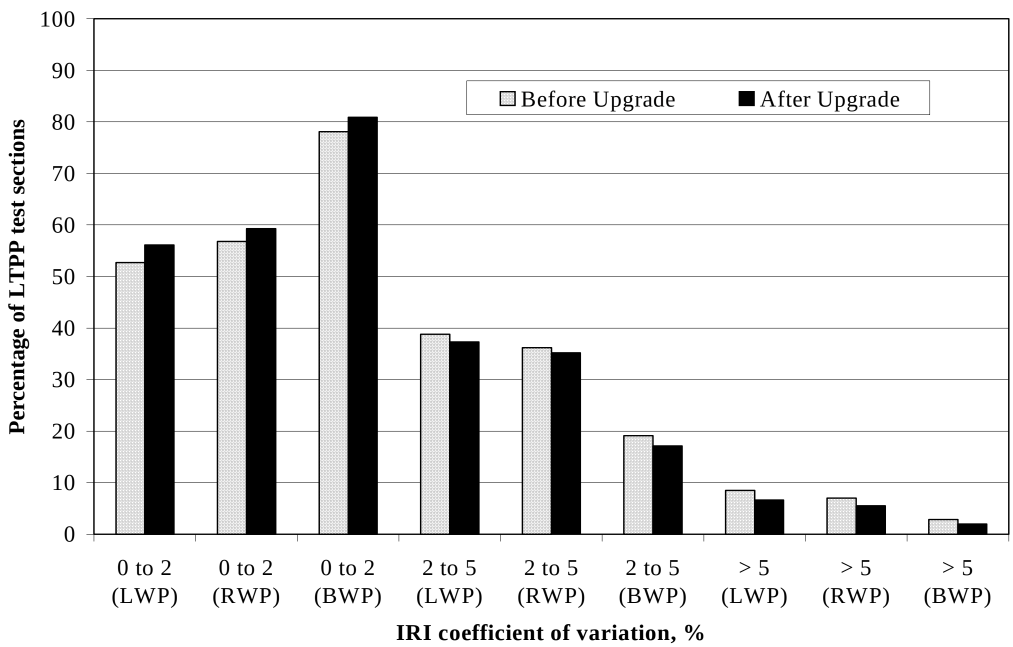

Figure 1. Effect of upgrade on IRI variability.

IRI Slope

The slope over time of the mean IRI for each wheelpath of unrehabilitated sections was also used to identify questionable IRI values and to quantify the effect of the data upgrade. The IRI slope is defined as the rate of change in average IRI across all visits. A steadily increasing rate is expected as pavement deterioration progresses. Seasonal, daily, and other testing variability can result in this rate, or change in IRI over time, being zero or less than zero. Testing in the wrong location, saturation spikes, lost lock, unreported rehabilitation, and shifted starts can also significantly change the slope, making analysis of the performance trends difficult. Prior to the data upgrade, 21.7 percent of the unrehabilitated sections having two or more visits exhibited average IRI slopes of less than zero. Following the upgrade, the improvement resulting from the data upgrade is evident, as only 15.8 percent of the sections have average IRI slopes of less than zero (see figure 2). Summaries of IRI data slopes for each region are provided in table 6. The North Atlantic Region exhibited the greatest percentage of sections with slopes of less than zero, and the Western Region has the least.

Table 6. Effect of upgrade on average IRI slope values.

Region	Percentage of sections with an IRI slope < 0	
	Before upgrade	After upgrade
North Atlantic	25.1	16.7
North Central	21.1	15.6
Southern	23.1	15.2
Western	18.5	15.9

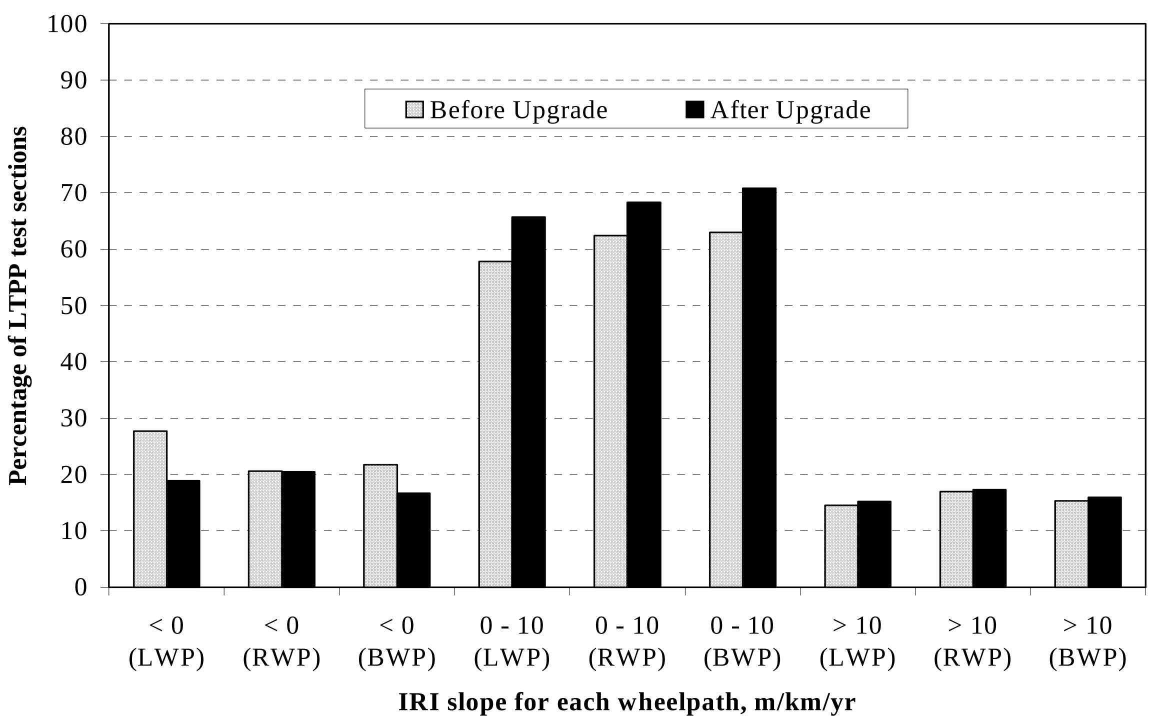

Figure 2. Effect of upgrade on IRI slopes.

CHAPTER 4. RUN-TO-RUN VARIABILITY

One main objective of this study is to identify confidence limits for IRI variability between repeated runs using Profilometer data from the LTPP database. To develop these limits, the variability of the IRI data in the database was defined. In addition, the effects of pavement type, equipment, pavement roughness, and other variables were studied. Using this variability information, effective IRI confidence limits were developed.

IRI variability was determined in three steps. First, outliers were identified using run-to-run IRI comparisons, visit-to-visit IRI trends, and visual review of profile data. If the causes of these outliers were anything other than pavement variability, they were removed from the data set. Next, using the upgraded IRI data, the run-to-run variability was identified using statistical analysis methods, data processing analysis, and field testing. Finally, confidence limits for expected variation in future profile data collection were developed. Each of these steps is described in this chapter, along with a summary of general statistics.

General Statistical Summary

The general statistical results of the variability analysis provide valuable information. COV values from visits with two or more runs in the updated data set for COV ranged from 0.0 to 32.3 percent, with mean left, right, and average IRI COV's of 2.3, 2.2, and 1.5 percent, respectively— indicative of generally good repeatable measurements. Figure 3 indicates the distribution of COV's for each wheelpath. Because the IRI from both wheelpaths is the average of the left and right wheelpath IRI's, variability is much less for the "both wheelpaths" values.

Shown in figure 4 are cumulative summaries of these COV values. About 60 percent of the left and right wheelpath IRI COV's are less than 2 percent, and more than 80 percent of the COV's for the IRI average of the two wheelpaths are less than the 2 percent currently recommended as a quality check in LTPP Directive P-6. Both wheelpath IRI COV values fall below 3.5 percent in 95 percent of the database. At least 95 percent of the left wheelpath IRI COV values are less than 5.5 percent, and about 95 percent of the right wheelpath IRI COV values are less than 5.2 percent. Figure 4 shows slightly more variation in the IRI values from the right wheelpath. This may merely illustrate the tendency of roadways to deteriorate more rapidly near the outside shoulders.

Some regional differences in run-to-run, single-visit IRI variability in terms of COV can be seen in figure 5. The North Atlantic, North Central, and Southern Region IRI data exhibit very similar ranges of COV values, with more than 80 percent of average IRI COV values being less than 2 percent. However, additional variability in the Western Region has kept the percentage of BWP IRI COV values that are less than 2 percent to only 66 percent of the data. This has resulted in more section visit data exhibiting COV values greater than 2 percent.

Visual review of the majority of the run-to-run profiles from the Western Region indicated more vertical variation, or differences in profile traces of consecutive runs. As a result, the profile runs from a single date do not typically overlay each other as well as in other regions, with a

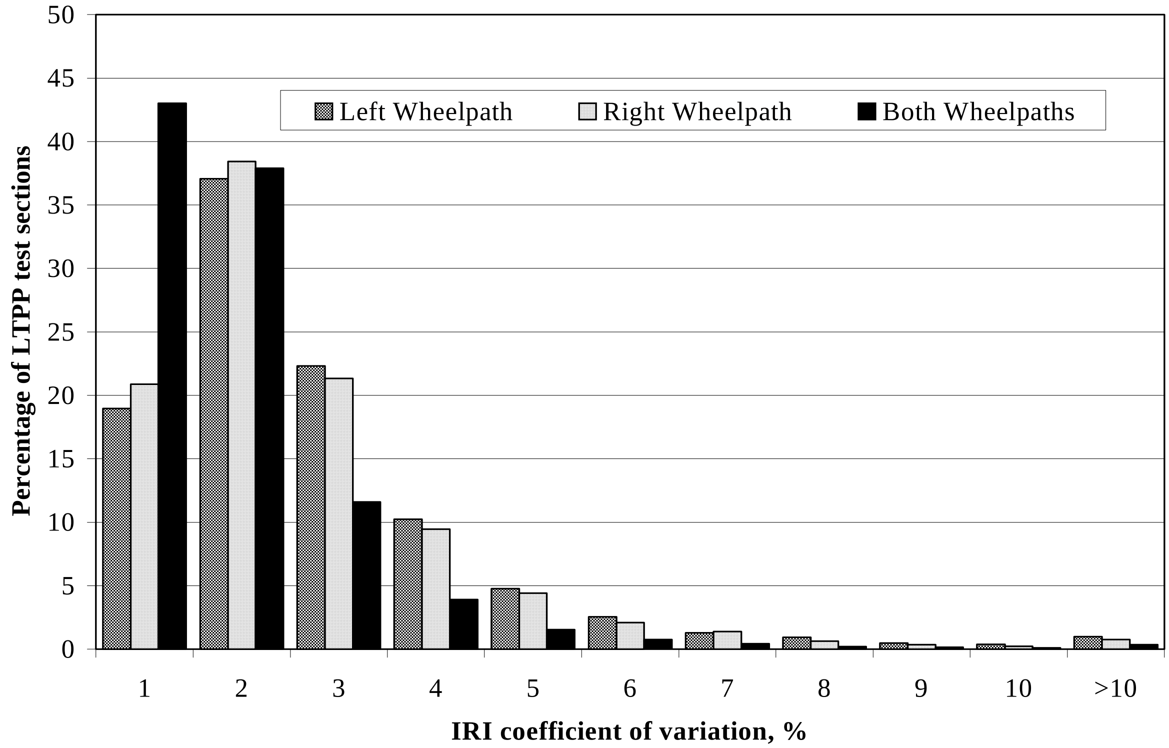

Figure 3. Histogram of IRI coefficients of variation.

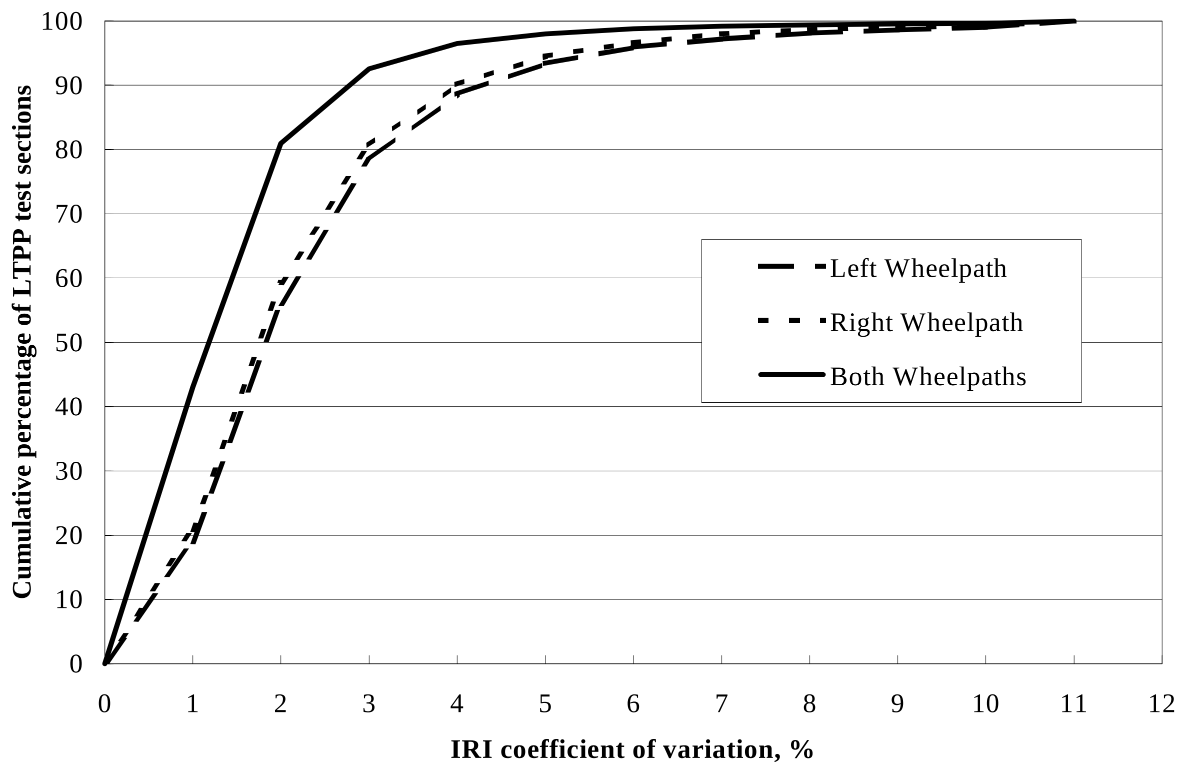

Figure 4. Cumulative IRI COVs for LTPP database.

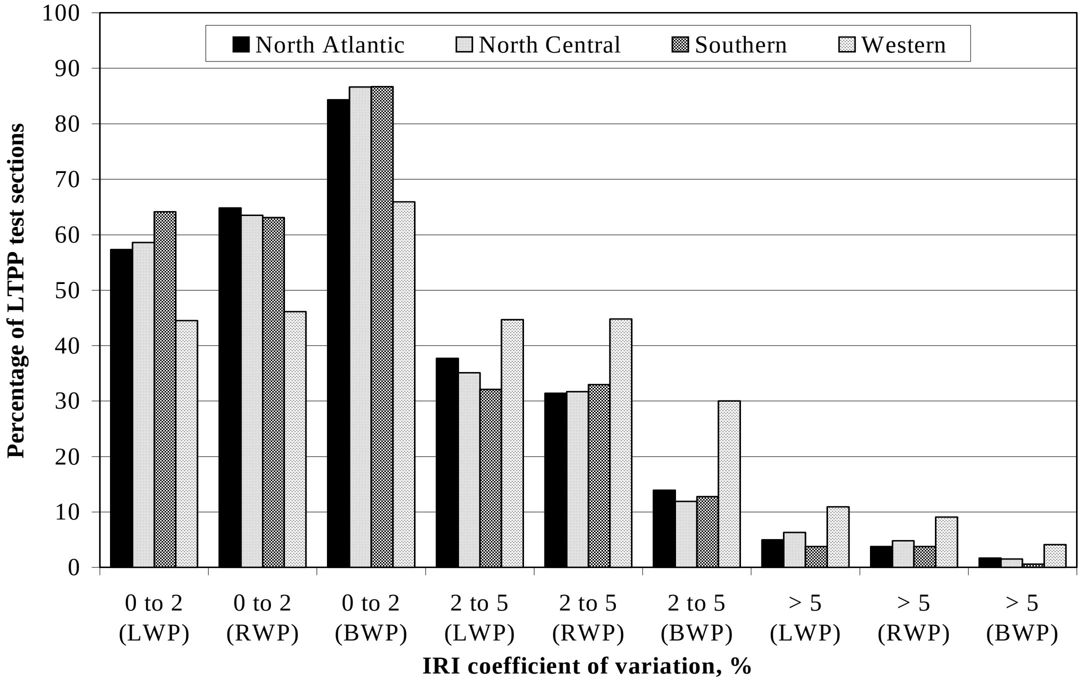

Figure 5. Regional run-to-run variability.

subsequent increase in run-to-run IRI variability. This vertical variability is sometimes attributed to a large amount of transverse pavement profile variability, variations in the collection wheelpaths, or profile collection equipment problems. Because the variability appears to be unrelated to the operator, and since the average roughness of the Western Region pavement sections is not different from other regions, it is possible that slight Profilometer equipment problems led to the additional run-to-run variability.

Also, profile runs for the SPS sections in the Western Region are shifted longitudinally from each other much more frequently than profiles from other regions. This shifting is reportedly attributable to problems with the Profilometer DMI that the Western Region Contractor worked at repairing throughout much of the data collection period.

Design of Analysis

To identify confidence limits for the collection of LTPP IRI data, a clean data set was prepared. The upgraded IRI database used in this analysis was modified from the original 1997 IMS database by deleting all runs exhibiting saturation spikes and replacing them with reprocessed data files. Also, all runs affected by lost lock, tested in the wrong location, or shifted more than 10 m from the true start location were excluded. No replacement data were available at the time of analysis for shifted runs that had been reprocessed in the correct location.

Observed interactions between roughness level and IRI standard deviation were then eliminated through data transformation, and the data were converted to a normal form. Analysis of variance was conducted using 10 fixed variables and 3 random effects. Several significant effects of these variables were observed and quantified using these models.

Data Transformation

Plots generated for the mean IRI versus the run-to-run standard deviation indicate that, as mean IRI increased, the standard deviation increased. This trend is shown in figure 6 for the GPS data. An average increase in standard deviation of 0.008 m/km for each 1 m/km change in IRI was noted for the GPS data, and an average increase of 0.013 m/km was observed for the SPS data. The increased variation at SPS sites is probably due to the difficulty encountered in maintaining the correct wheelpath on rougher sections over the longer distances required for SPS data collection.

Profilometer operators have reported this trend and its effect on quality control operations for many years. The past and current *LTPP Manual for Profile Measurements*[1-3] require Profilometer operators to more closely check profiles when the COV is greater than 2 percent. As a result of this trend, the COV was used instead of standard deviation (SD) for quality control (QC) for run-to-run IRI data. COV values exceed the 2 percent QC limit more frequently for smooth pavements than for rougher pavements. This can result in excessive review of smooth pavement profiles and possible insufficient review of rough pavement profiles.

To provide Profilometer operators with a QC statistic that is not affected by pavement roughness level, transform equations were developed. The IRI data were transformed using Box-Cox transformations with different powers for left, right, and average wheelpath data on GPS and SPS sections.

Iterative analysis was used to determine the powers λ_a, λ_l, and λ_r such that the slope of the regression of the mean and SD of the transformed variables was as close to zero as possible. Variables used in the analysis were the transformed average wheelpath IRI (tr_IRI_a), the transformed left wheelpath IRI (tr_IRI_l), and the transformed right wheelpath IRI (tr_IRI_r). Powers computed for the transformations are:

GPS: $\lambda_a = 0.38075$; $\lambda_l = 0.24665$; $\lambda_r = 0.2998$

SPS: $\lambda_a = 0.11535$; $\lambda_l = 0.08975$; $\lambda_r = 0.08715$

Each of the variables was transformed according to the following equations:

$$tr\_IRI\_a = \frac{IRI^{\lambda_a - 1}}{\lambda_a (geoIRI)^{\lambda_a - 1}} \qquad (1)$$

$$tr\_IRI\_l = \frac{IRI^{\lambda_l - 1}}{\lambda_l (geoIRI)^{\lambda_l - 1}} \qquad (2)$$

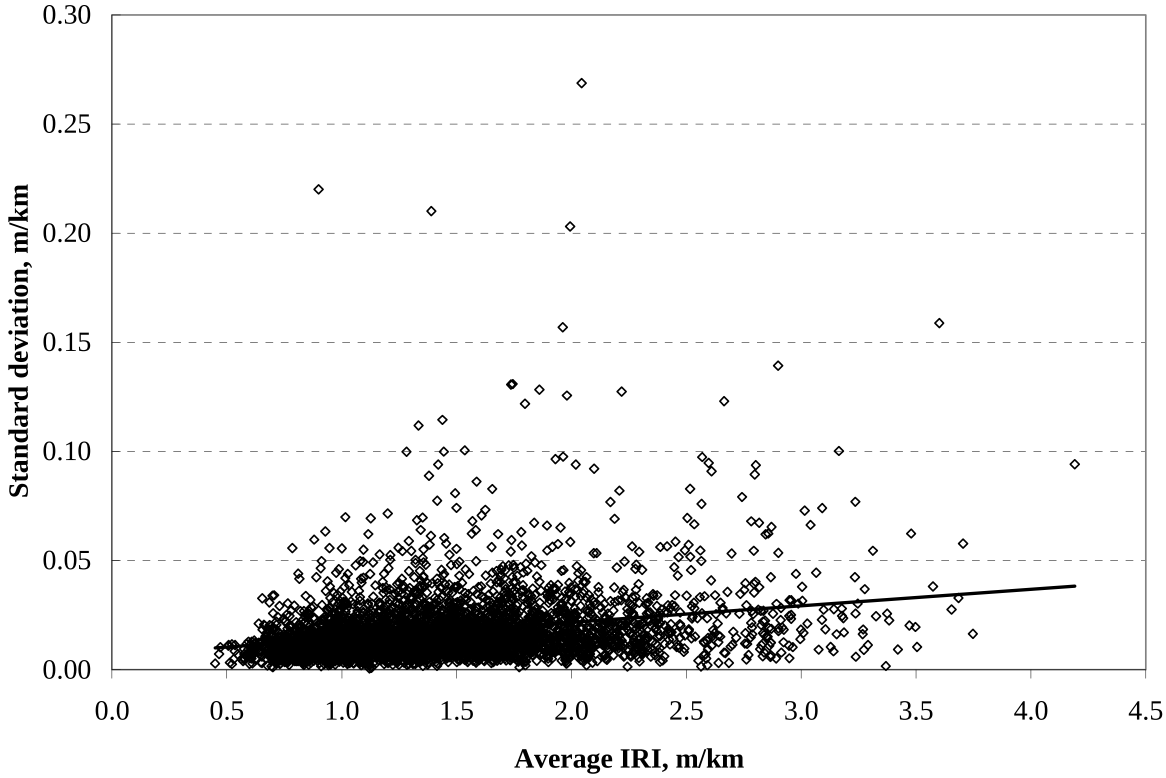

Figure 6. Relationship of IRI with standard deviation of IRI.

$$tr\_IRI\_r = \frac{IRI^{\lambda_r - 1}}{\lambda_r (geoIRI)^{\lambda_r - 1}} \tag{3}$$

Where geoIRI is the geometric mean of the IRIs and N is the number of observations:

$$geoIRI = e^{\frac{\sum \log IRI}{N}} \tag{4}$$

Even though the section type and wheelpath standard deviations are calculated from different Box-Cox transformations, these are designed to keep the resulting variables comparable. The results are typified by the relationship for average IRI of GPS sections shown in figure 7. The slope of the linear relationship for these data is 0.00005, showing no effect on standard deviation from the roughness level.

Although these transformed data can be used for quality control, histograms of the standard deviations of the transformed IRI values indicated a significant skew in the data. To allow for proper analysis of variance, the transformed IRI standard deviation data were modified with a natural log (*ln*) function to achieve a normal relationship between frequency and *ln* of the

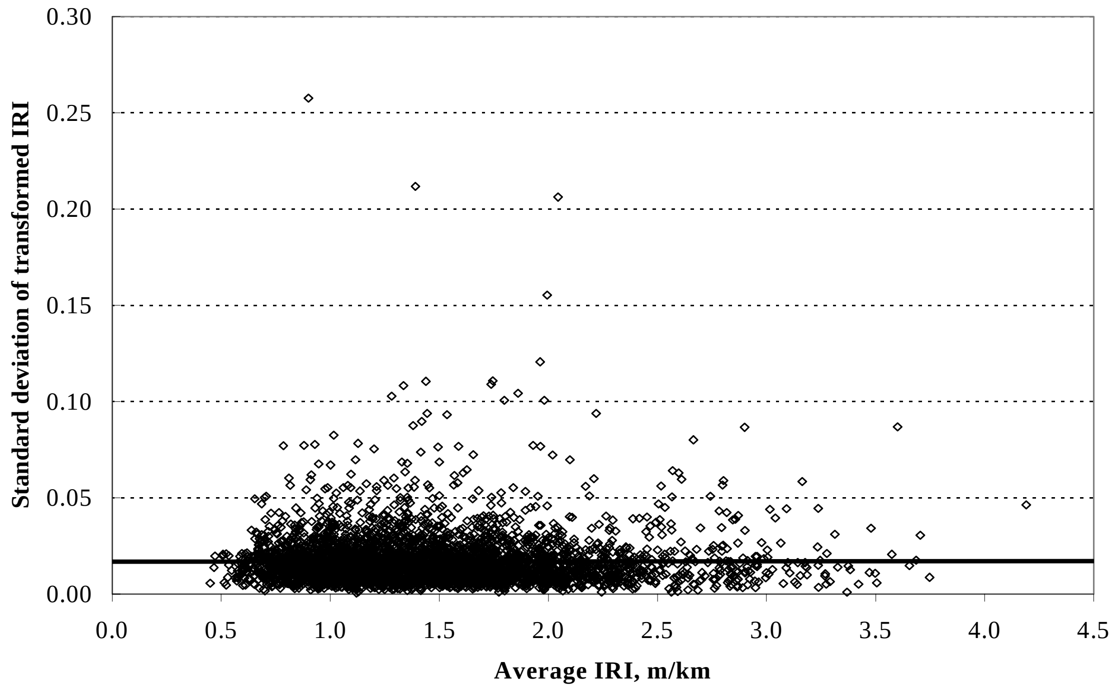

Figure 7. Transformed GPS IRI versus standard deviation.

transformed IRI standard deviation. A progression of histograms for the original, transformed, and normalized standard deviation data is shown in figures 8, 9, and 10, respectively. These normalized standard deviation data were used in the analysis of the run-to-run and visit-to-visit IRI data for this variability review.

Run-to-Run Analysis Models

The analysis of the normalized transformed IRI standard deviation data from the upgraded data set was conducted using the SAS PROC mixed utility. Random variables used in the analysis included the State, Strategic Highway Research Program (SHRP) ID, and profiler driver. Fixed variables initially included in the analysis are:

- Pavement type (AC [asphalt concrete], PC [portland cement concrete], APC [AC overlay of PC]).
- Pavement structure (AC, AC/AC, AC/PC, PC, PC/PC).
- Testing time (3 a.m. to 8 a.m., 8 a.m. to 6 p.m., and 6 p.m. to 3 a.m.).
- Season (winter, spring, summer, fall).
- Region (North Atlantic, North Central, Southern, Western).
- Equipment type (690DNC, T-6600).
- Start method (photocell, manual pendant).
- Roughness level, m/km (low [0 to 1.11], medium [1.11 to 1.56], high [>1.56]).

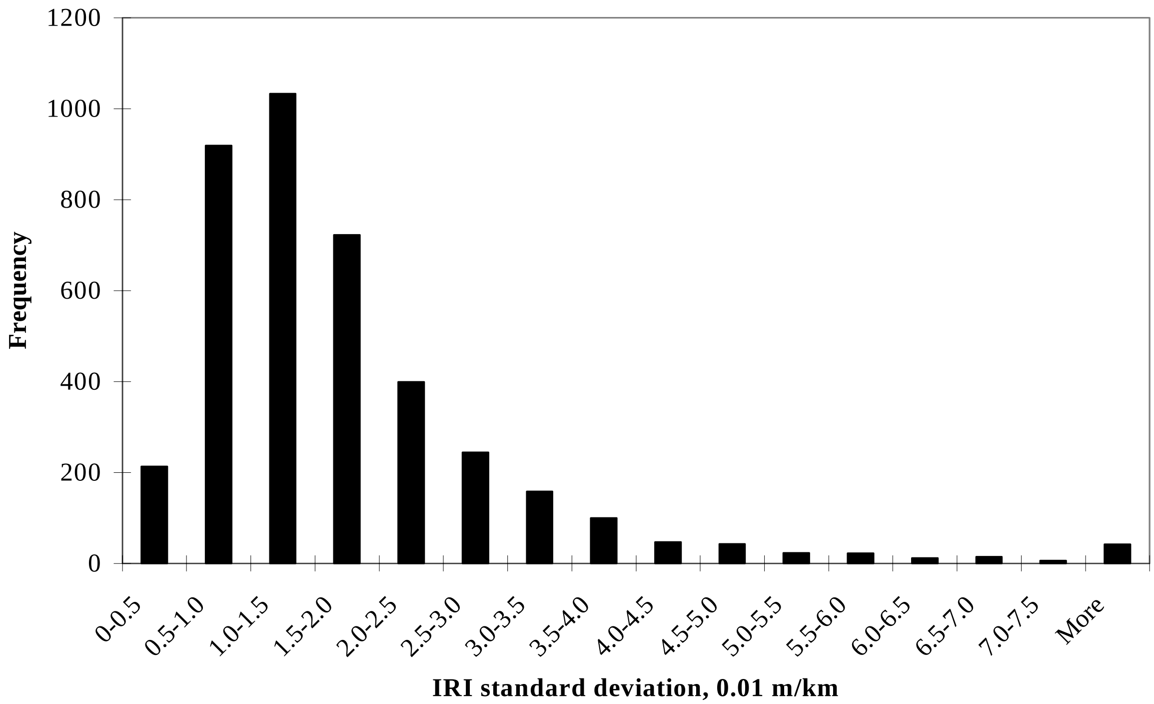

Figure 8. Histogram of GPS IRI standard deviations.

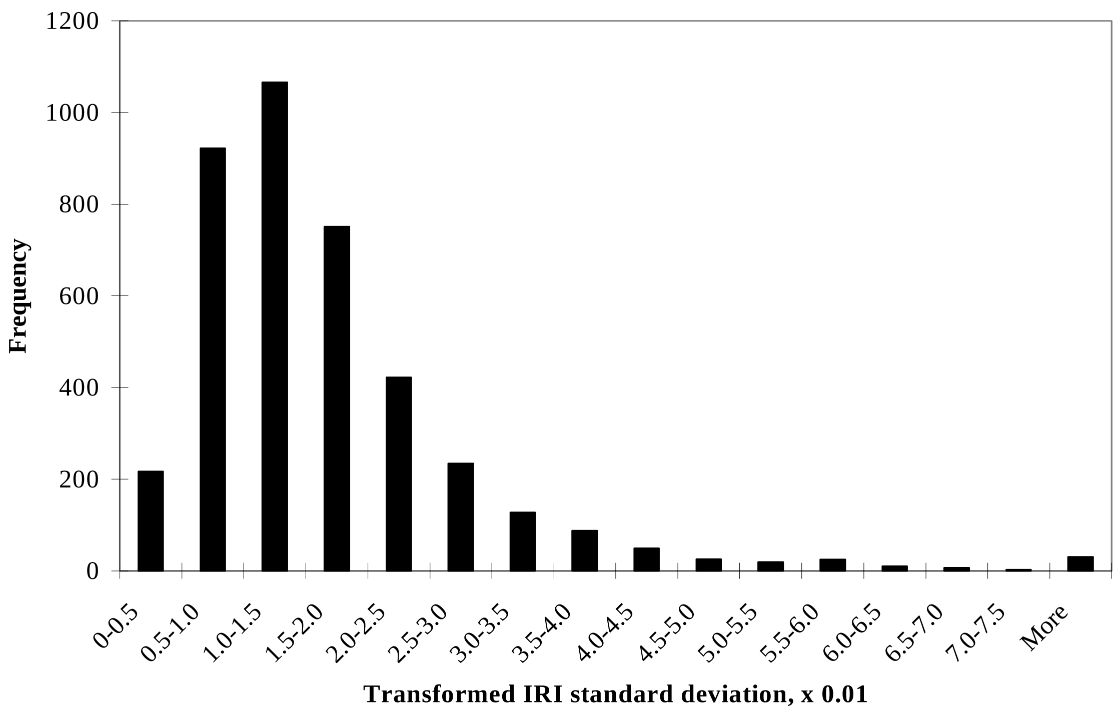

Figure 9. Histogram of GPS transformed IRI standard deviation.

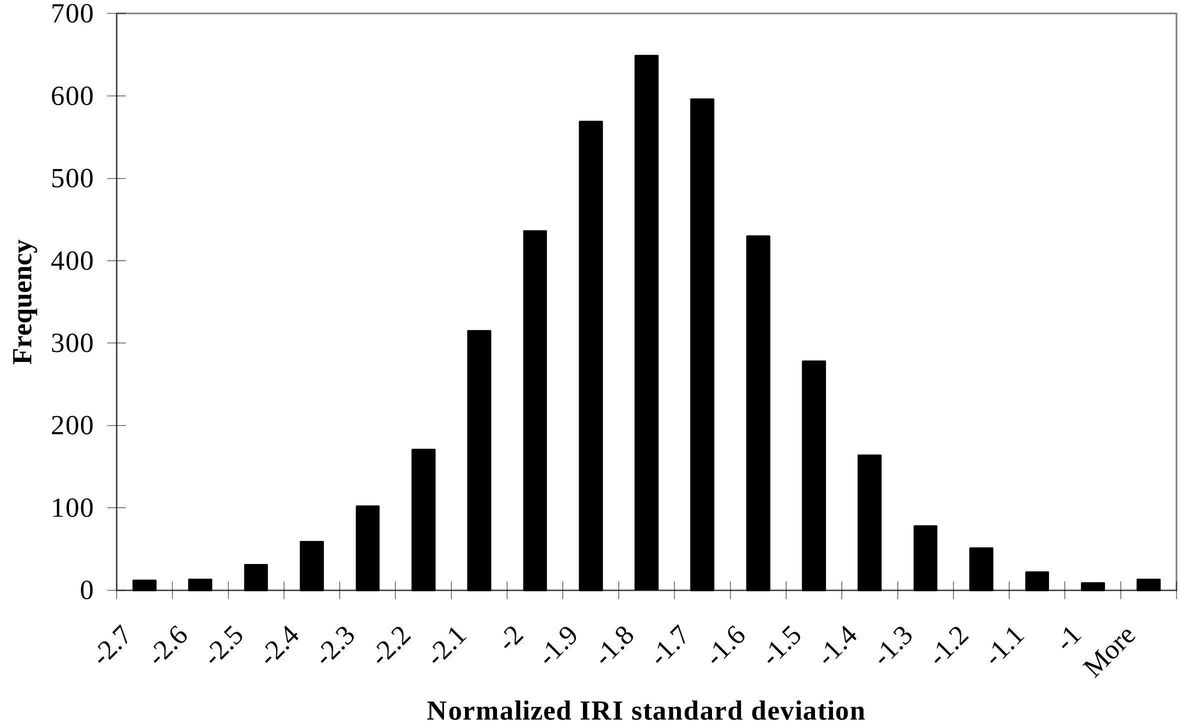

Figure 10. GPS histogram of normalized IRI standard deviation.

- Visit number (1 through 21).
- Construction number (1 through 3).

The statistical models were run initially using main effects and two- and three-factor interactions. The models were then simplified in stages, where appropriate. The resulting final models differed for GPS and SPS road segments. Results of the statistical analysis of GPS and SPS fixed effects are shown in tables 7 and 8, along with the degrees of freedom (DF) and the probability that the hypothesis of equality is true (Pr > F). The Pr > F values indicate, with 95-percent confidence, that there are significant differences in the first four GPS variables and the first eight SPS variables.

Run-to-Run Variability Results

The SPS and GPS model results indicate that differences in standard deviation for several independent variables are significant. In addition, interactions between many of these variables are significant. These independent variables include the pavement type and equipment types in GPS sections and the region, pavement structure, start method, and season for SPS sections. Significant interactions are evident between region and start method, pavement type and roughness level, region and pavement type, and season and roughness level. (All significance statements in this report, unless otherwise noted, were developed using the normalized standard deviation of the IRI for the average of the left and right wheelpaths at a 95-percent confidence level.)

Table 7. GPS statistical model results.

Main variable	Interaction with	DF	Pr > F
Pavement type		2812	0.0001
Pavement type	Roughness level	2812	0.0072
Region	Start method	2812	0.0123
Equipment type in each region		2812	0.0340
Region	Roughness level	2812	0.1641
Region		57	0.1877
Testing time		2812	0.1899
Construction number		2812	0.3169
Season		2812	0.5047
Roughness level		2812	0.6475
Region	Construction number (CN)	2812	0.8189
Start method		2812	0.8557

Table 8. SPS statistical model results.

Main effect	Interaction with	DF	Pr > F
Pavement structure	Pavement type * CN	3026	0.0001
Season		3026	0.0003
Region	Start method	3026	0.0024
Pavement type	Roughness level	3026	0.0061
Region		40	0.0144
Start method		3026	0.0222
Region	Pavement type	3026	0.0226
Pavement structure	Region * Pavement type	3026	0.0373
Season	Roughness level	3026	0.0470
Region	Season	3026	0.0496
Region	Roughness level	3026	0.0511
Pavement type	Season	3026	0.1318
Pavement type		3026	0.1498
Roughness level		3026	0.2750
Equipment type in each region		3026	0.2781
Testing time		3026	0.6428

Effect of Region

For SPS sections, there is a significant difference between regional standard deviations; however, no significant regional difference was found for GPS sections in the overall model. Summaries of the GPS and SPS transformed and normalized standard deviations for each region are shown in figure 11. According to a one-way analysis of variance (ANOVA) with least-squares means,

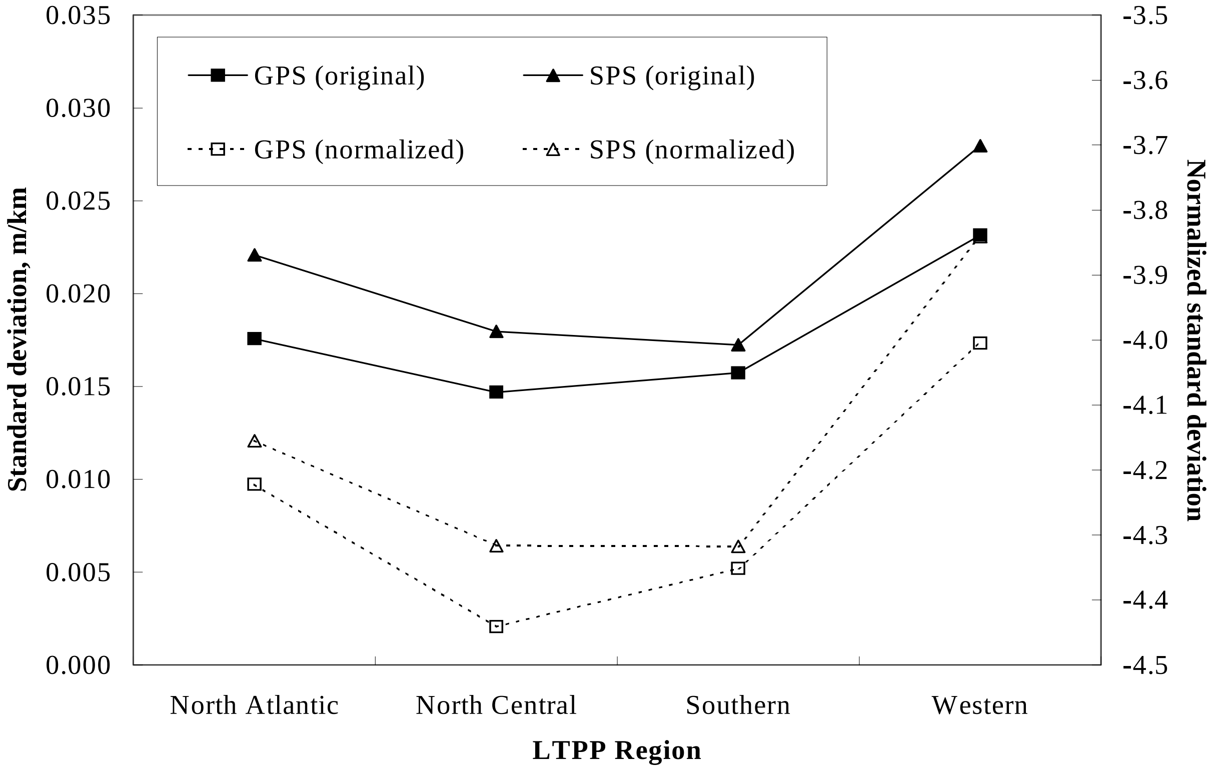

Figure 11. Regional variability for GPS and SPS sections.

the variance of Western Region SPS average IRI values is statistically greater than that of the other regions. The ANOVA is a procedure for using the variation of the components of a set of data to judge whether differences in the sample means are statistically significant. This increase in Western Region IRI values is probably the result of the problems experienced with the DMI on the Western Region's original profiler. Statistically, the least variability was found in the North Central and Southern Regions. Other effects and interactions explain the insignificance of similar trends in the GPS sections.

Effect of Pavement Surface Type

For this analysis, the LTPP pavement sections were divided by surface type into three categories—AC, APC, and PC. Figure 12 shows the variability associated with these surface types in each LTPP region. In GPS sections, the variability associated with AC and APC surfaces is statistically greater than that associated with PC surfaces. Variability for SPS sections is numerically, but not statistically, greater for the AC sections than for the PC sections.

The GPS and SPS interactions between pavement type and roughness level are indicative of the lowest variability in each roughness group occurring in AC pavements. Variances were similar for APC and PC in the low ($0 < IRI < 1.11$) and moderate ($1.11 < IRI \leq 1.56$) roughness groups, but were different for the high ($IRI > 1.56$) roughness group.

Effect of Pavement Material Structure

Information in the IMS database allows each pavement section to also be grouped by pavement material structure into five categories—AC, AC/AC, AC/PC, PC, and PC/PC. In both GPS and SPS sections, no statistical differences in variability were noted for pavement sections in these categories. The reason is illustrated in figures 13 and 14, which show no clear relationship between pavement structure and variability. Across regions for both GPS and SPS sections, the PC structures generally have the lowest IRI variability. Unrehabilitated AC sections have the greatest run-to-run variability in SPS sections, and AC overlays of PC pavements show the most GPS variability.

The SPS interactions noted between pavement material structure and the interaction of region and pavement type are caused by the close relationship between the pavement surface material and pavement material structure variables. Its significance, as well as that of pavement material structure with the interaction of pavement type and construction number, is anticipated, but is not useful for the analysis.

Effect of Equipment Differences

Each RCOC collected profiles from June 1988 to October 1996 using K.J. Law 690DNC optical-sensor Profilometers. In the fall of 1996, these profilers were replaced by K.J. Law T-6600 Profilometers with infrared sensors. The number of GPS and SPS section visits

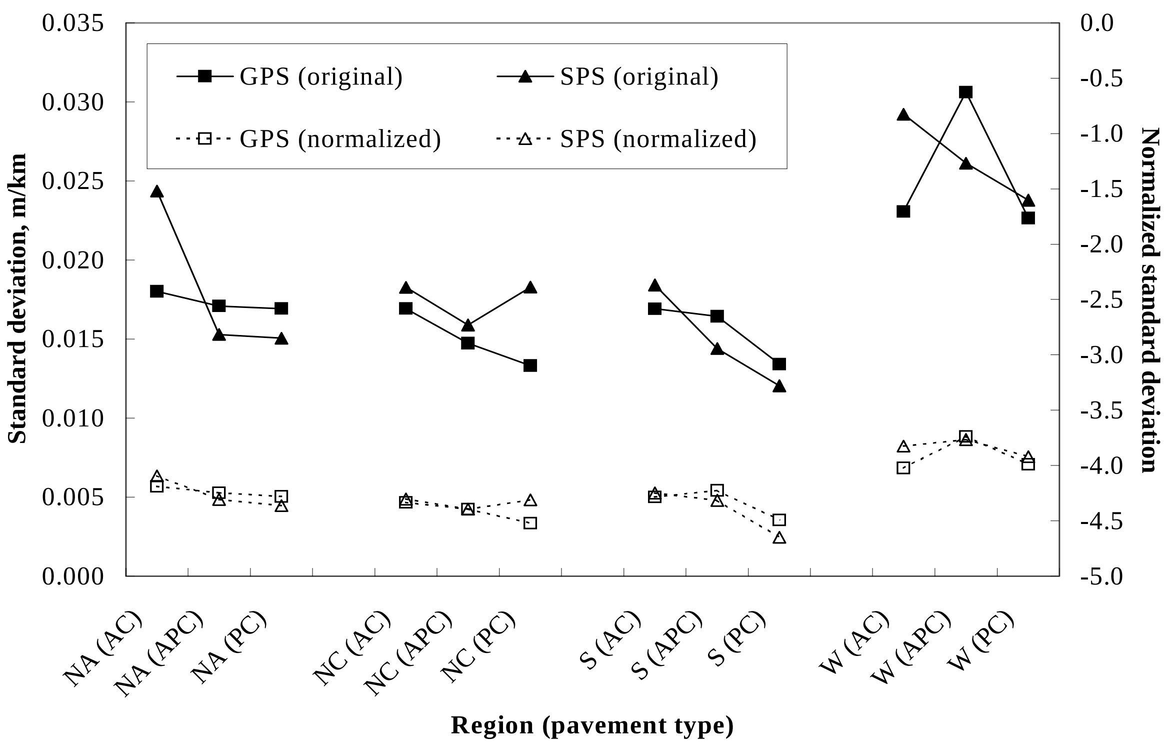

Figure 12. Variation among regional surface types.

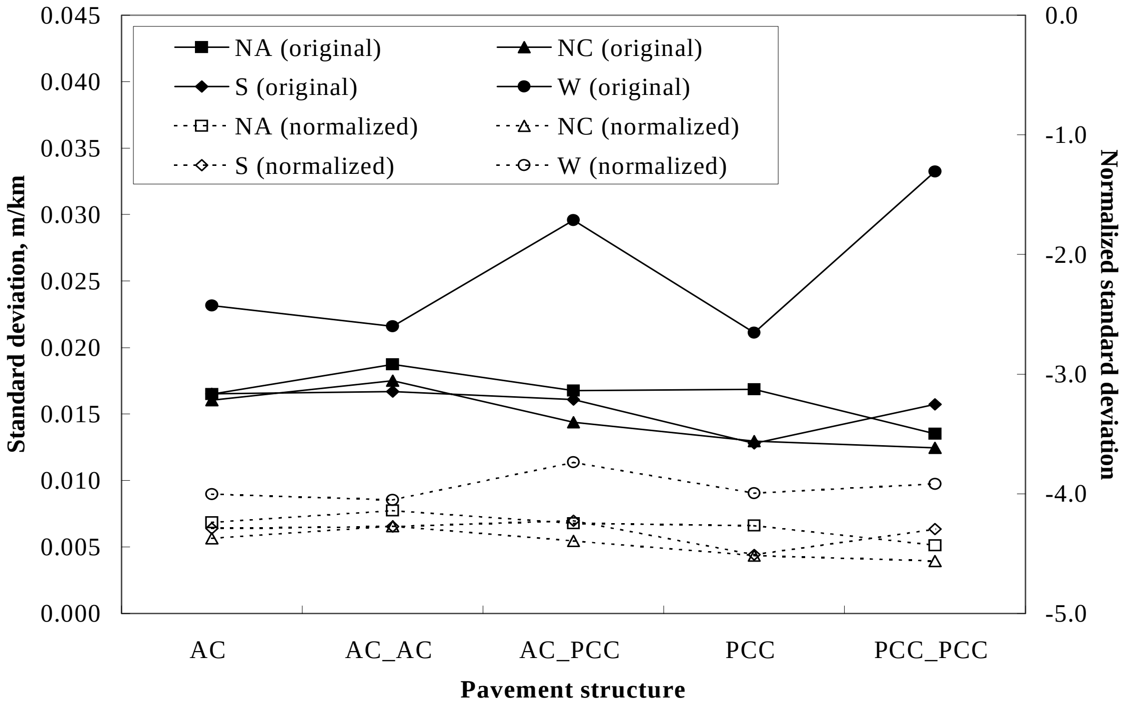

Figure 13. GPS regional IRI variability for pavement material structures.

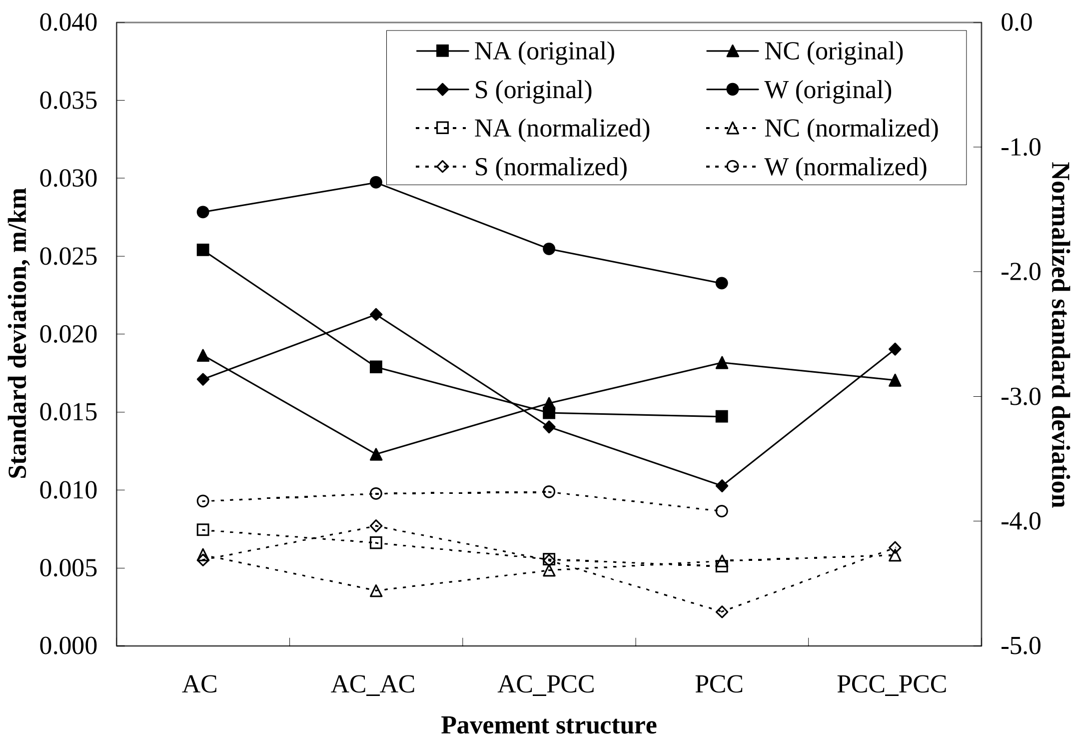

Figure 14. SPS regional IRI variability for pavement material structures.

conducted by each region is shown in table 9. Insufficient data had been collected using the T-6600 profilers in the North Central and Southern Regions to allow for statistical comparison.

Table 9. Section visits using old and new Profilometers.

Region	690DNC visits	T-6600 visits
North Atlantic	1,640	110
North Central	2,673	2
Southern	1,948	8
Western	2,022	121

Figure 15 shows the IRI variability of each piece of equipment from the four regions. The Western Region variability associated with the 78 T-6600 visits at SPS sections was significantly less than that of the 690DNC. This reduction can be related to the improved DMI repeatability in the new profiler. No difference was noted in the North Atlantic Region between equipment types based on 36 T-6600 GPS visits and 74 T-6600 SPS visits.

This equipment comparison was not conducted on results from the tests made using each type of equipment on the same site at the same time. Typically, 1 to 8 years had passed between testing with the 690DNC and the T-6600. Over this time, transverse pavement variability can change at a section, disrupting the direct comparison of variability between equipment type. Acceptance testing of the new T-6600 Profilometers has confirmed the insignificance of the difference in

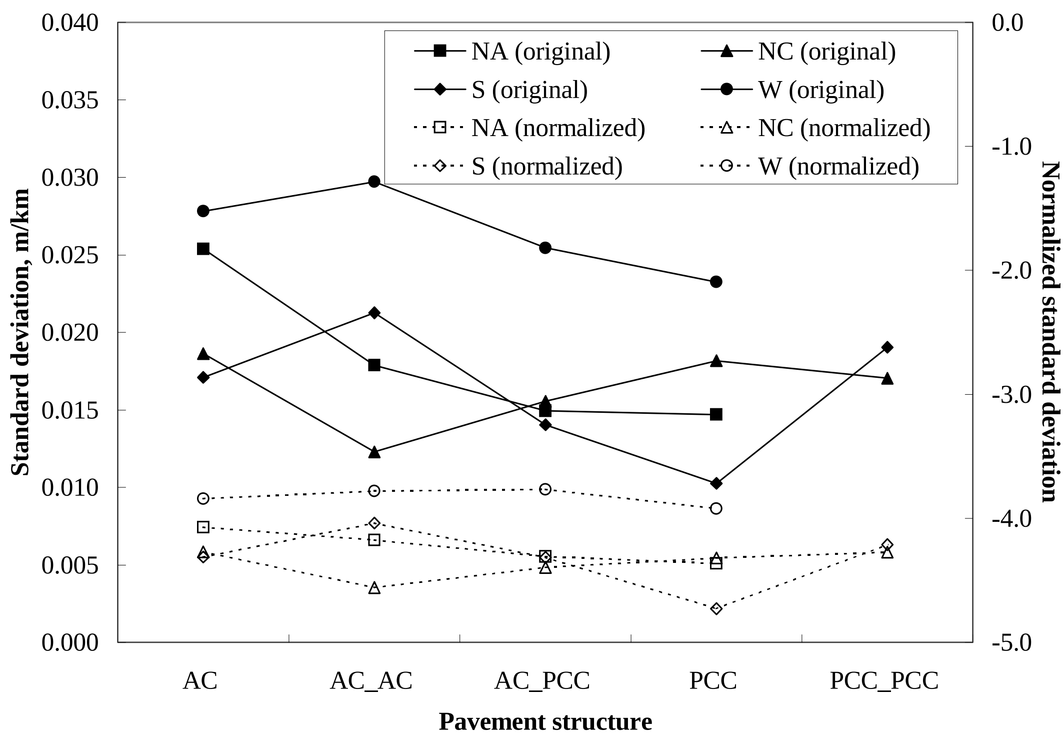

Figure 15. Variability of regional profilers.

IRI output from the two profilers on the same day at the same site. However, additional study of this comparison can be made in future analyses using the additional data collected by the T-6600 to further study similarities or differences in IRI variability.

Effect of Photocell Initiation Method

Both the 690DNC and the T-6600 were fitted with photocells for electronic initiation of data collection, and manual initiation of data collection is not currently allowed. However, between 1989 and 1991, operators collected 41 GPS and 19 SPS data sets in the North Atlantic (0 GPS, 1 SPS), North Central (29 GPS, 3 SPS), and Western (12 GPS, 15 SPS) Regions while the photocells were inoperative. Operators manually triggered the start of data collection for those sections, sometimes resulting in start location differences of more than 6 m between runs. The effect on IRI variability was significant for both GPS and SPS sections for the Western Region and for the GPS sections in the North Central Region.

Figure 16 illustrates these trends. However, because so many more visits were performed using the photocell, these data sets are quite unbalanced and not appropriate for analysis. Western Region SPS sections show the greatest increase in variability related to manual initiation, and GPS sections in the Western Region show the next greatest increase. North Central Region GPS sections show the only other significant variability increase resulting from manual profile initiation. Trends for SPS sections in the North Atlantic and North Central Regions are invalid because only one visit was collected manually in the North Atlantic Region and three were collected in the North Central Region.

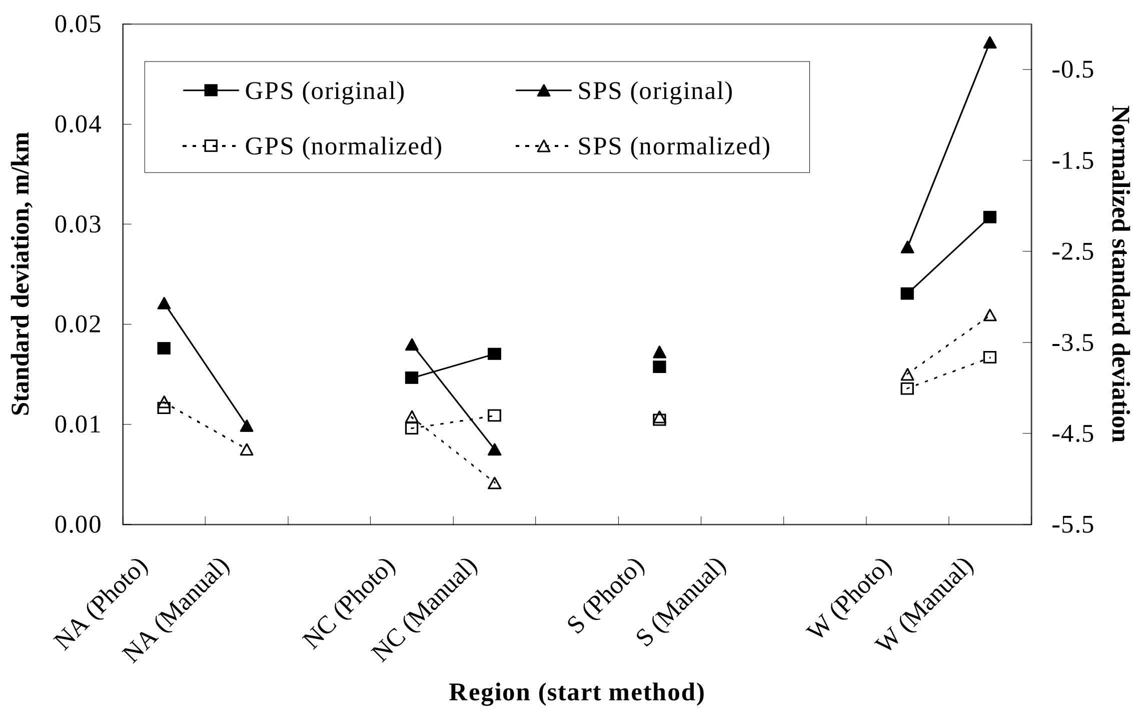

Figure 16. IRI variability from equipment start method.

Effect of Season

Especially in freezing and moist climates, the season of testing could have an important effect on variability because of the effects of pavement swelling and frost heave. Analysis of the seasonal effect was completed by dividing the year into four 3-month seasons. Winter included December, January, and February. Spring included March, April, and May, and so on.

Shown in figure 17 is a summary of the regional variability within each season. Statistically, there is no seasonal difference for GPS and SPS sections in the Southern Region. This is probably the result of not having freezing effects on pavements and base materials. The North Central Region exhibited significant differences between the spring season and the remaining seasons for SPS IRI variability. Spring provided statistically more SPS variability in the North Atlantic Region, and the winter season was more variable than the other seasons for SPS sections in the Western Region.

Overall, the variability was greater in the spring for sections with the highest level of roughness. This trend is possibly the result of a greater effect from frost heave and soil swelling on rougher pavement sections.

Effect of Time of Day

Figures 18 and 19 show the GPS and SPS variability for 10 equal time periods, beginning and ending at midnight. Although there appears to be more variability in the early morning and evening hours, this is the result of having large amounts of data in the mid-day fields and very

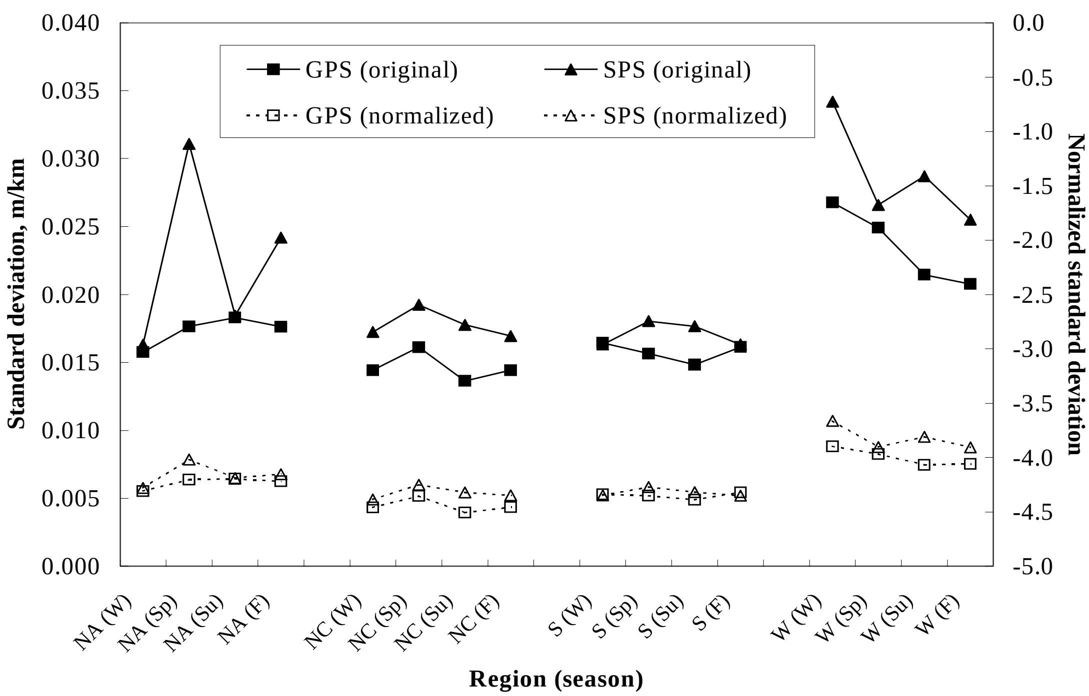

Figure 17. Seasonal effect on regional IRI variability.

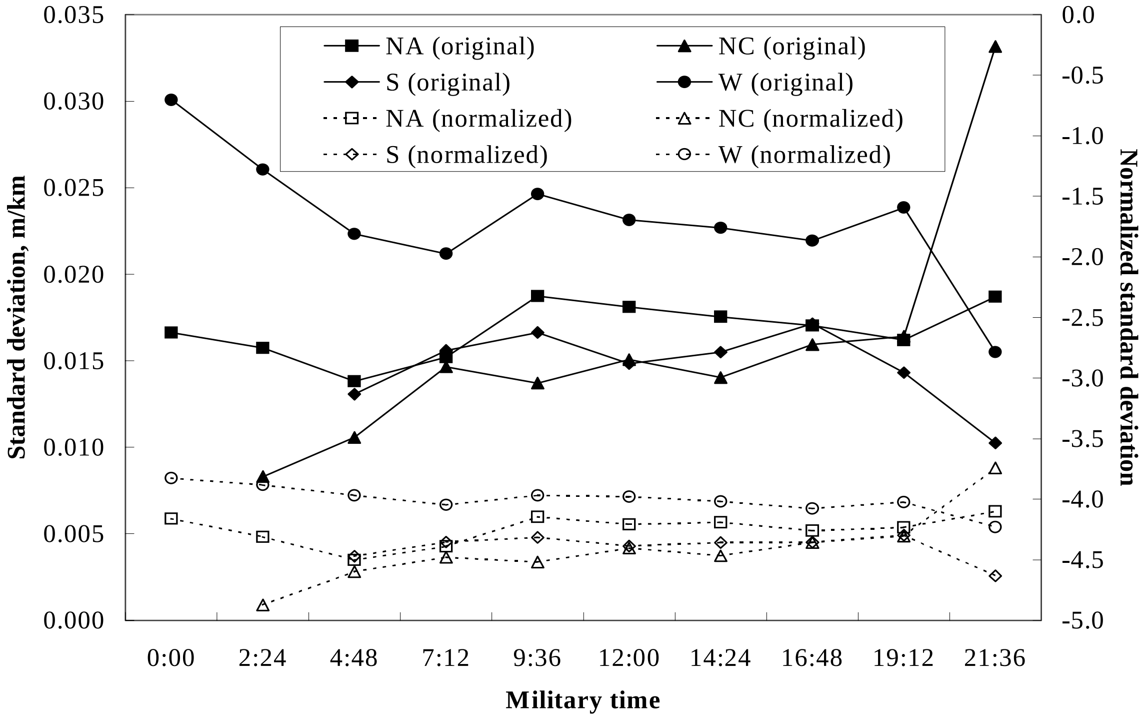

Figure 18. GPS time series IRI variability.

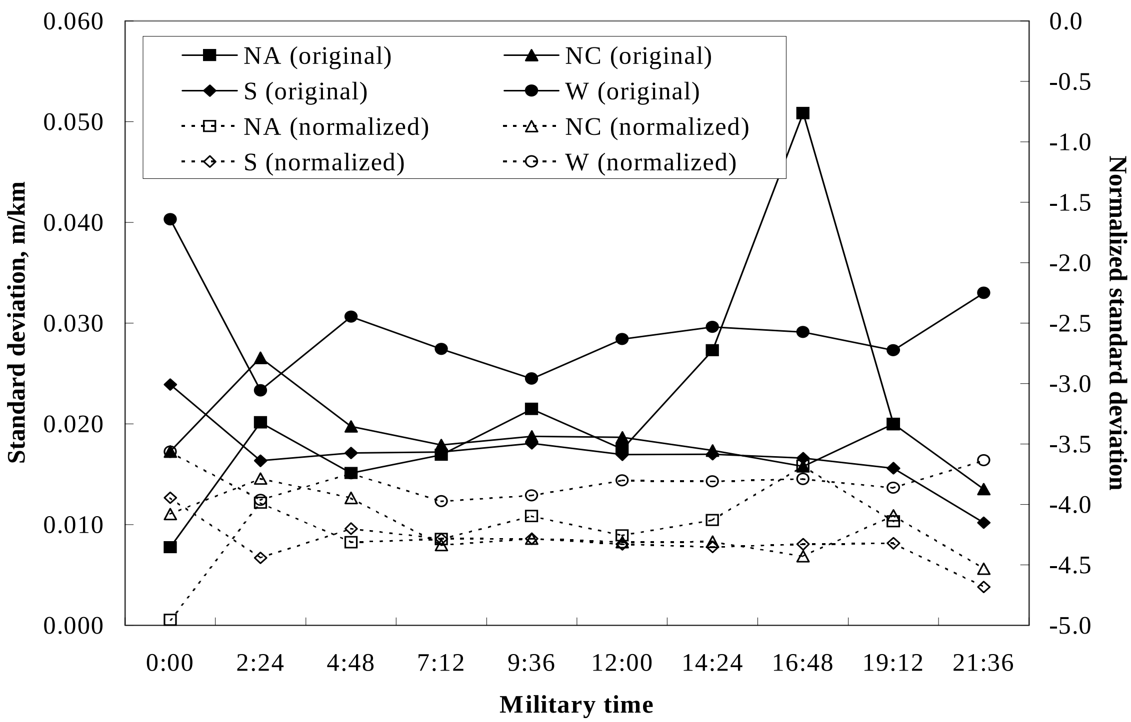

Figure 19. SPS time series IRI variability.

little data in the other fields. Analysis of this data was conducted on data from the three time periods representing different variability — 3:00 a.m. to 8:00 a.m., 8:00 a.m. to 6:00 p.m., 6:00 p.m. to 3:00 a.m. Time of day for testing had no significant effect on the variability associated with IRI data collection.

Effect of Roughness Level

To analyze the effect of pavement roughness level on variability, the GPS and SPS sections were divided into three evenly distributed categories (0 to 1.11, 1.11 to 1.56, and > 1.56 m/km). Since the IRI means for GPS and SPS sections were transformed to ensure that the level of roughness did not affect the standard deviation, no significant effect was noted as a result of roughness level. However, significant interactions were noted with pavement type and season. Also, significant, with 90-percent confidence, was an SPS interaction of roughness level with region. The reason for this last interaction is shown in figure 20. Variability was greatest in the high roughness level for the North Atlantic and Western Regions, but variability was least for the highest roughness level in the Southern Region.

The SPS interaction of roughness level with pavement type is significant in that variability is highest for the AC sections at the highest roughness level. However, at the lowest roughness level, variability is least for the AC sections. Interaction between roughness level and season was noted because the SPS variability was greater in the spring for the highest roughness level, but least in the spring for the lowest roughness level.

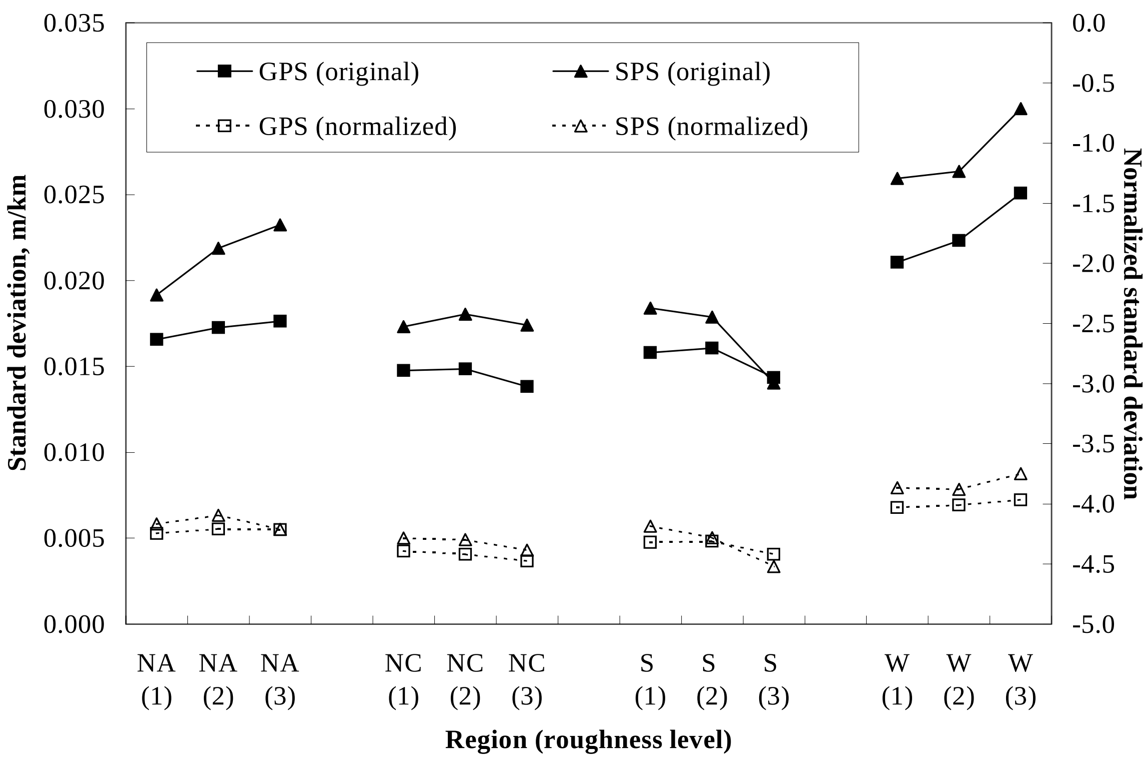

Figure 20. Regional IRI variability across roughness level.

Quality Control Implications

Currently, Profilometer operators are using a COV of 2.0 percent or greater from run-to-run as a flag for possible data problems. Operators are asked to review any profile data more closely if the limit is exceeded. This analysis has defined the run-to-run variability for SPS and GPS sections in the IMS database. An application of that information is in defining levels of variability that are within a normal limit.

Since the standard deviation of IRI data is affected by the mean IRI level, the required current practice of using a COV tends to flag very smooth pavements too frequently, and it is less stringent on rougher pavements. This analysis used a Box-Cox transform to eliminate the effect of the IRI level on standard deviation. Thus, it is possible to define a standard deviation limit that is normal across all roughness levels within the program.

Box-Cox IRI transforms can be approximated for GPS sections using the equations ($r^2 = 0.999$):

Left or Right Wheelpaths: $IRI_T = 0.0463\ IRI^3 - 0.4472\ IRI^2 + 1.9819\ IRI - 1.5899$ (5)

Average Wheelpath: $IRI_T = 0.0463\ IRI^3 - 0.4220\ IRI^2 + 1.8972\ IRI - 1.5272$ (6)

For SPS sections, the transformed IRI values can be estimated using the equations ($r^2 = 0.999$):

Left or Right Wheelpaths: $IRI_T = 0.0559\ IRI^3 - 0.5515\ IRI^2 + 2.2047\ IRI - 1.7238$ (7)

Average Wheelpath: $IRI_T = 0.0570\ IRI^3 - 0.5488\ IRI^2 + 2.2011\ IRI - 1.7209$ (8)

For each of these wheelpaths and section types, the 75-, 90-, 95-, and 99-percent confidence limits on transformed IRI standard deviations are shown in table 10. Estimated untransformed standard deviations are also shown in table 10; however, the linear relationship used in this estimate has an r^2 of 0.898. To simplify the quality checks, operators can be instructed to check all data more closely if the standard deviation of the transformed IRI data exceeds the recommended confidence limits. Figures 21 and 22 show the standard deviation of transformed GPS and SPS IRI data and several typical confidence limits. A confidence limit of 90 percent is recommended. This limit corresponds to an estimated untransformed COV for GPS sections of 2.2 percent and for SPS sections of 3.0 percent. These limits are based on the actual variability within the LTPP profile database, and they are not affected by the level of section roughness.

Table 10. Confidence limits for transformed average IRI standard deviations.

	GPS confidence limits		SPS confidence limits	
	Transformed SD	Estimated SD	Transformed SD	Estimated SD
Mean	0.017	0.018	0.021	0.022
75% level	0.022	0.022	0.026	0.027
90% level	0.032	0.033	0.040	0.042
95% level	0.040	0.042	0.053	0.058
99% level	0.061	0.068	0.087	0.101

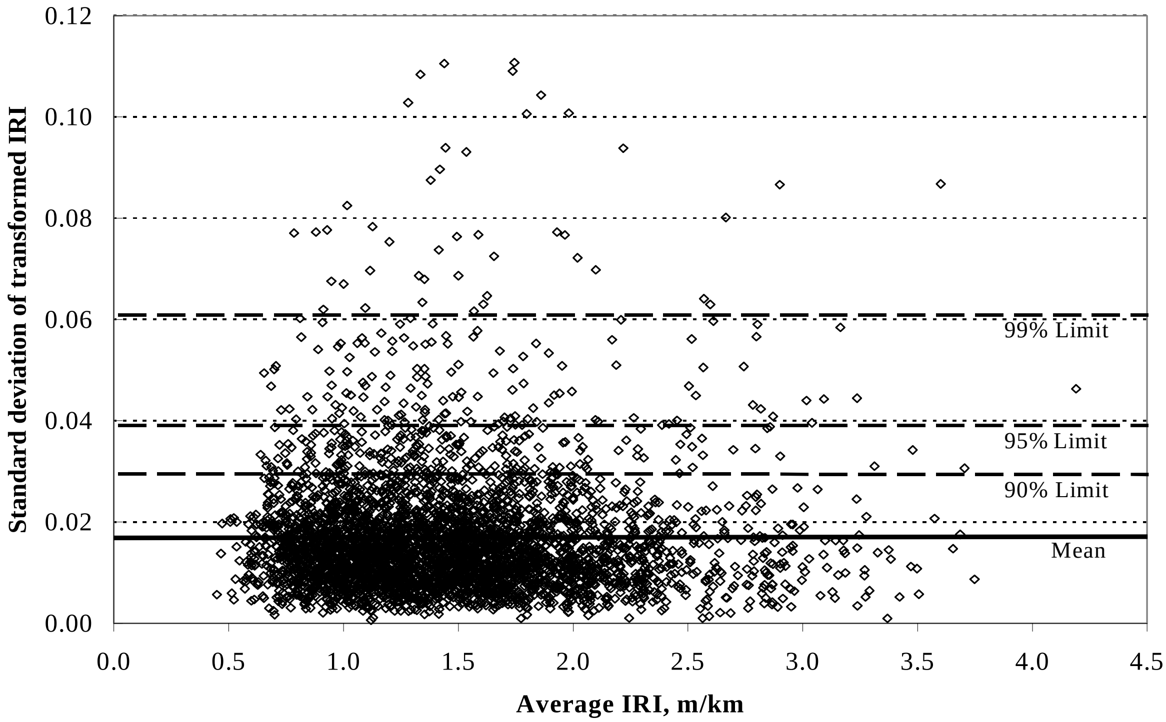

Figure 21. Confidence limits for GPS transformed IRI standard deviation.

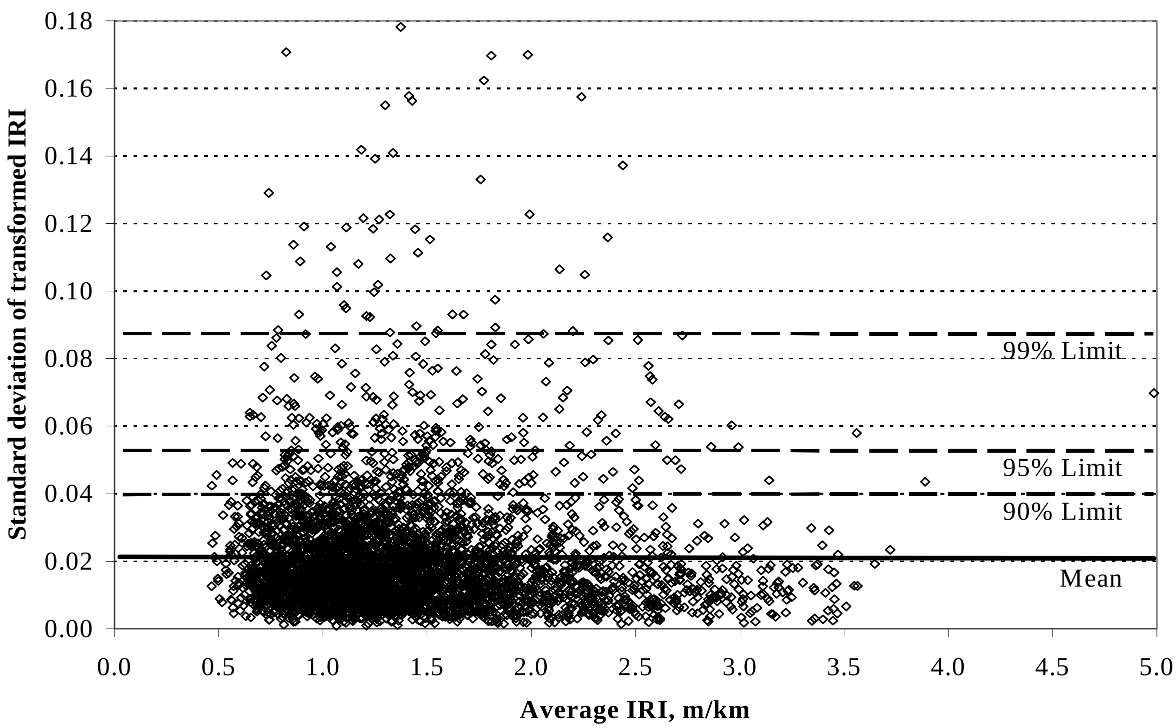

Figure 22. Confidence limits for SPS transformed IRI standard deviation.

Summary of Run-to-Run Analysis

Analysis of run-to-run variability was completed on IRI data collected between 1989 and 1997. IRI values were recomputed for runs that contained equipment-related spikes. Also, profiles that exhibited lost lock or that were shifted more than 10 m were excluded from the data set. The revised data set was transformed to eliminate the interaction between standard deviation and IRI level. In addition, the transformed IRI data were normalized using a natural log function to improve analysis accuracy.

Using main effects and two- and three-factor interactions with ANOVA analysis of the average IRI values, several key findings were identified:

- The average wheelpath run-to-run IRI variances for SPS data collected in the Western Region are significantly greater than in the other regions. This is probably related to the DMI problems reported by that region.
- Variances for the IRI of the GPS sections are not significantly different between regions. SPS data collected in the Southern and North Central Regions have the least variability. The variability associated with GPS AC and APC sections is significantly greater than that of PC sections. This may be because rutting in the wheelpaths of AC and APC sections causes differences in longitudinal profiles measured a few centimeters apart.
- SPS sections exhibit no significant variability difference between AC, APC, and PC sections, although more variability is found in the AC sections than in the PC sections.
- SPS and GPS variability of the 690DNC and the T-6600 Profilometers in the North Atlantic Region is not significantly different. The T-6600 variability in the Western Region is significantly less than that of the 690DNC. However, less than 6 percent of the data from that region was collected using the T-6600. Insufficient data are available to compare the variability in the North Central and Southern Regions' Profilometers.
- Manual triggering of data collection significantly increases the run-to-run IRI variability in all regions where a sufficient amount of data is available for analysis.
- Overall run-to-run variability is greatest in the spring for SPS sections in the North Central and North Atlantic Regions. This is possibly a result of the effect of additional moisture or thawing. Variability for SPS sections in the Western Region is statistically greatest in the winter.
- The time of day had no effect on variability for GPS or SPS sections.
- Run-to-run variation in IRI for a typical section is less than 2 percent COV. This represents very good test repeatability.
- A 90-percent confidence limit on the transformed IRI standard deviation is recommended for field quality control on the IRI average of both wheelpaths. For GPS sections, this corresponds to a transformed standard deviation value of 0.32; for SPS sections, the value is 0.40.

CHAPTER 5. VISIT-TO-VISIT VARIABILITY

Visit-to-visit IRI variability is associated with the effects of collecting profiles over time, while run-to-run variability is associated with the five profiles collected during a single site visit. Over time, the effects of daily temperature changes, seasonal changes, pavement deterioration, and other factors add additional variability to the run-to-run variability. One objective of the analysis was to define a time or roughness level inflection point where rapidly increasing pavement deterioration makes it necessary to increase the data collection frequency. The two main objectives of the visit-to-visit variability study were to define the effects of the above-stated factors and to identify confidence limits for expected change in average IRI between profile collection visits.

Inflection Point Analysis

To achieve the first objective, three approaches were taken. First, the rate at which the IRI increases with the time since construction or last rehabilitation was studied for various surface types and regions. In addition, the research team attempted to identify an inflection point in the IRI time history where the rate of yearly change significantly increases. Following on this approach, an inflection point associated with the level of roughness where more rapid IRI increases occurred was also sought. Each of these approaches failed because of the lack of an apparent inflection point or general trend toward more rapid IRI increases at higher roughness levels or pavement ages. This result indicated that, in general, the LTPP IRI data change linearly with time, inhibiting the identification of inflection point trends. However, this linear relationship helped to make it possible to achieve the two main objectives.

Time to Rapid IRI Increase

The objective of the first inflection point approach was to identify a pavement age associated with a rapid increase in the rate of IRI changes. This rate increase is important because it could indicate impending pavement failure and could be used to drive data collection scheduling or repair planning. Initially, visual analysis of the IRI data indicated that only about 99 (5 percent) of the 2,035 sections in the upgraded data set show any specific positive inflection point in the IRI time-history trend. In reality, it is debatable whether several of the sections included in this list show true inflection points. When the times between last construction or rehabilitation and these inflection points were compared, the range in time from initial reconstruction to the inflection points for each pavement type was 7 to 25 years. This is shown in figure 23. The same large range is seen in the regional data of figure 24, where the range in time from construction or last rehabilitation to the estimated inflection points was 12 to 25 years.

Even with this reduced data set, the variability in the time to rapid IRI increases is still extremely large. Thus, it is not possible to determine well-defined guidelines to trigger increasing site visit frequency or pavement maintenance based on time from last construction or rehabilitation.

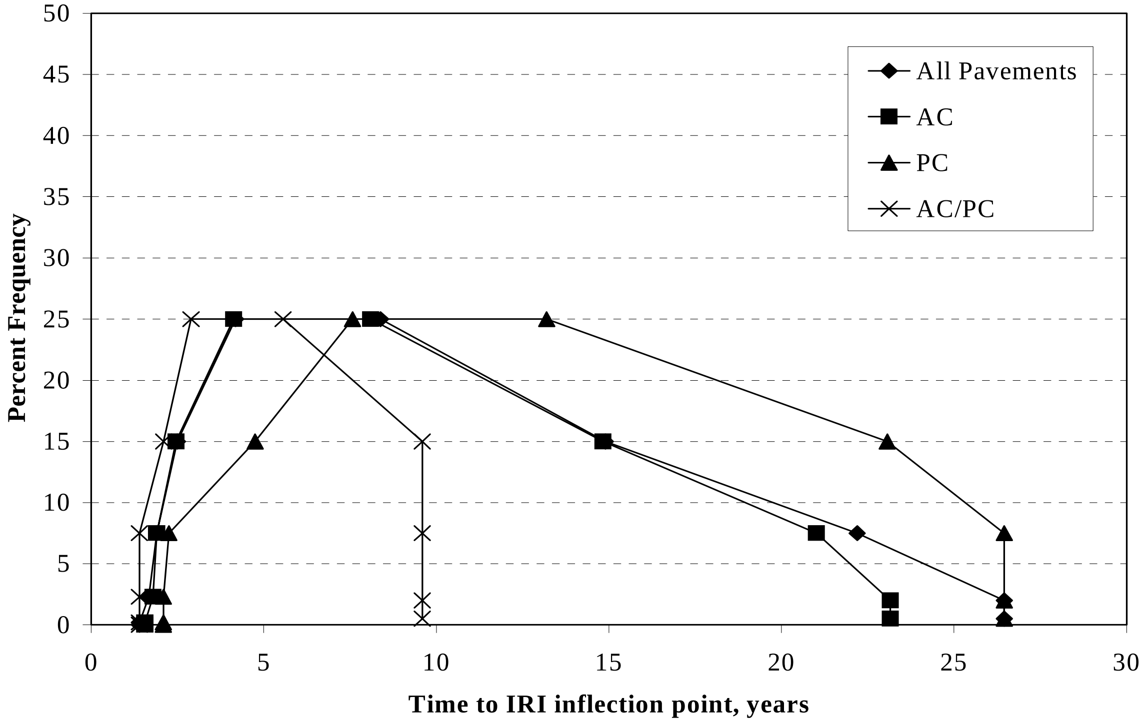

Figure 23. Histogram of IRI inflection point time by surface type.

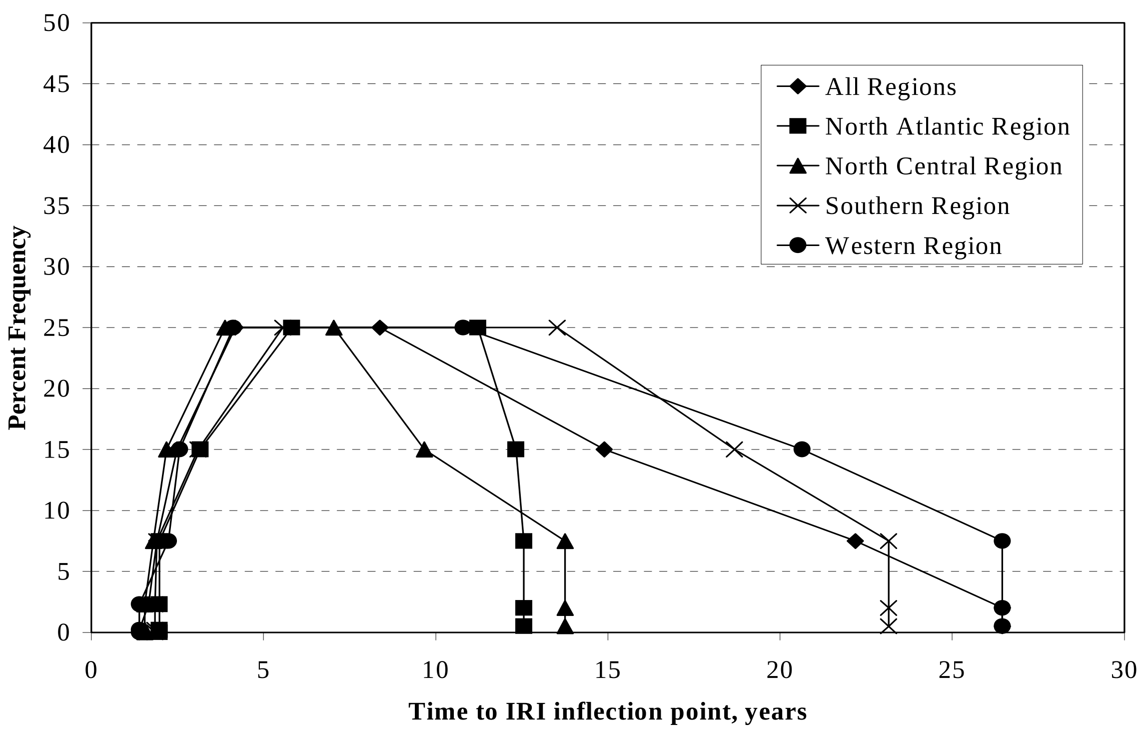

Figure 24. Histogram of IRI inflection point time by region.

IRI Time-History Slopes

Another attempted approach to finding conditions where increased testing frequency may be necessary was to identify specific overall differences in the IRI versus time slope before and after any perceived inflection point. Initially, this procedure was run on the 99 selected test sections with promising results. However, further statistical review of all sections indicated that their use was inappropriate because of the lack of statistically identifiable inflection points in the most promising data.

In the statistical review, only sites having more than three visits within a construction period and only the greatest 16 percent of IRI versus time slopes from simple linear regression were used. The response variable was the mean of the transformed IRI values. Then a quadratic polynomial was fitted for each of the identified 187 sites. Those with fewer than 4 visits prior to rehabilitation were omitted, cutting the number of sites to 116. Trends for these sections are shown in figures 25 and 26. There is obviously an increasing trend for IRI with time for most of these sections. However, there is little indication of inflection points where the rate of IRI change increases rapidly. Of these equations, 48 had negative coefficients for the second power term and 59 equations had negative coefficients for the first power term. Negative coefficients indicate a decreasing rate of change, rather than a more rapid increase.

Because of the lack of a trend indicating that the IRI increased more rapidly following a certain time in a pavement's life, this approach was abandoned. However, it is possible that such a trend does exist in pavement performance, but that the sections included in the study have not reached a deterioration level that would allow it to be identified. Another possible reason for the lack of

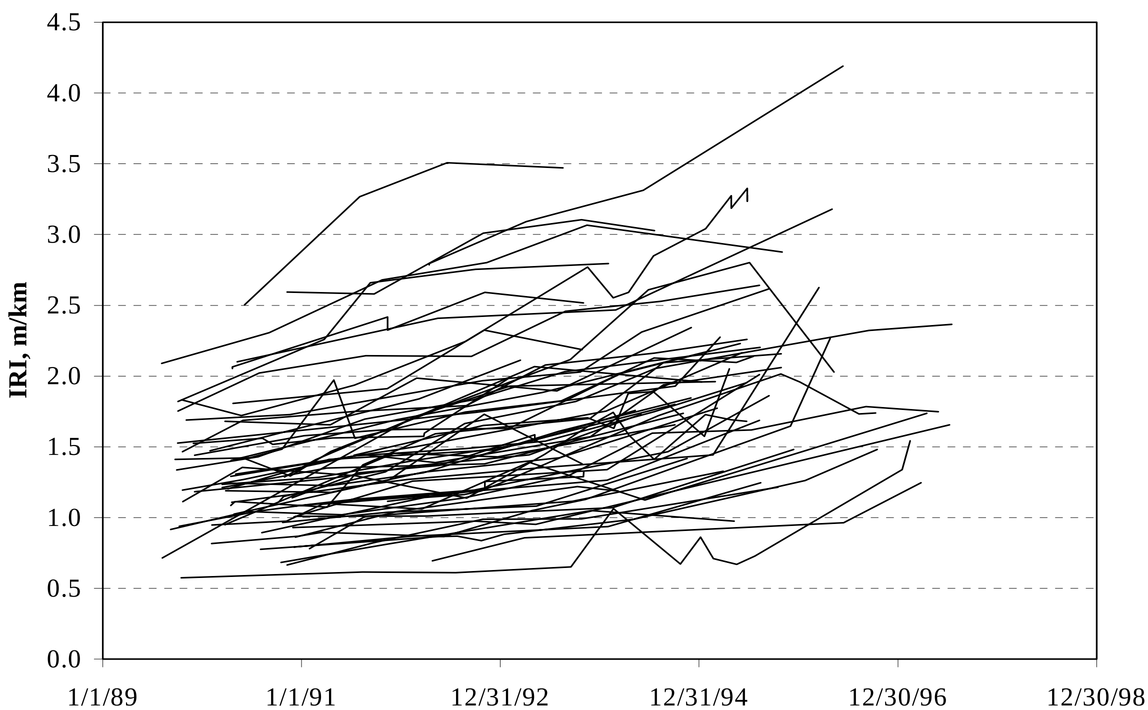

Figure 25. IRI trends for 60 selected GPS sections.

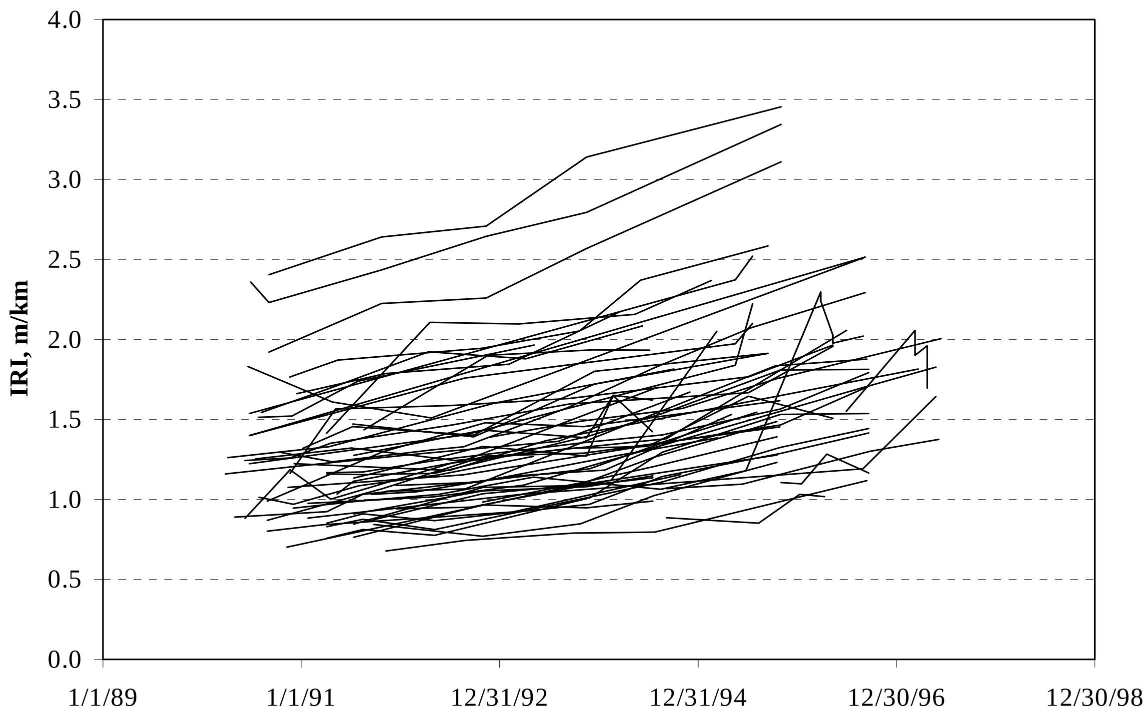

Figure 26. IRI trends for 56 SPS sections.

inflection points is that maintenance efforts have reduced the rapid increase sometimes associated with increased pavement deterioration.

IRI Roughness Level Slopes

The third approach used to identify trigger values for increased testing frequency was to find an IRI roughness level where the yearly change in IRI is significantly greater than that of lower IRI levels. This is based on the assumption that pavements deteriorate more rapidly when they get rougher.[4] To begin this analysis, the yearly change in IRI was computed using all adjacent average IRI values for sections that had more than one visit within a construction period. Figure 27 shows the resulting relationship. Because of the significant effect of short site visit intervals on an IRI rate of change, section visits that were tested less than 6 months apart were not included in the analysis. Also, 16 visits where the projected IRI was less than 0.5 m/km were eliminated because of the unreasonableness of the data. The data show a linear trend with a slope of 5.8 percent per year and a correlation coefficient (r^2) of 0.07.

These results do not indicate a significant increase in IRI at a certain level of roughness, rendering this third approach inappropriate. Although inflection points were not apparent, the linear trend between IRI level and yearly change in IRI simplified the identification of between-visit confidence limits. This trend, and the lack of change between regions and experiment types, allows for the development of confidence intervals for quality control.

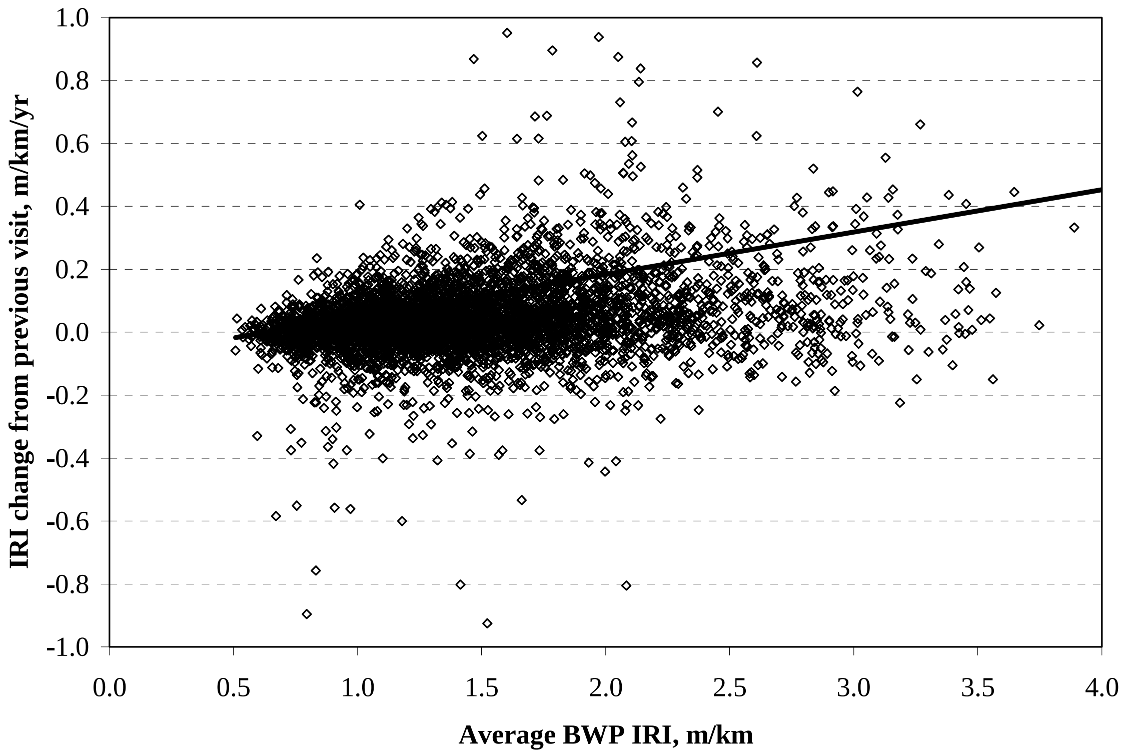

Figure 27. Change in IRI between visits.

Between-Visit Variability

Differentiating the variability associated with factors such as seasonal effects and daily temperature changes is difficult when the variability associated with wheelpath location within the data is unknown. However, seasonal and daily change effects can be isolated somewhat and evaluated within the 66 LTPP seasonal sections. These PC and AC sections were tested three or four times each year between 1992 and 1997. In many cases, the PC sections were also tested in the early morning, mid-morning, and late afternoon to identify the effects of curling on roughness. IRI values from the five runs at each of these seasonal visits provided a good estimate of these effects.

<u>Seasonal Effects</u>

Sufficient data was available from the 97 PC seasonal site visits and the 170 AC visits to provide 19 PC and 44 AC segments of 3 or 4 seasons within a year's time. Fifty-one percent of these seasonal groupings include data from four seasons. The average yearly IRI change for these groupings is 0.03 m/km, indicating that the IRI changes across the 5 to 12 months that these seasonal groups extended was not greatly related to pavement deterioration. This allowed for analysis of the effect of seasonal variability on IRI.

Within this subset of the LTPP database, the average IRI standard deviation for each visit was 0.014 m/km. This compares well with the standard deviation of the entire data set shown in figure 17. About 95 percent of these seasonal sections are from GPS sections and 80 percent of these sections are from the North Atlantic, North Central, and Southern Regions. The seasonal standard deviation compares well with the overall standard deviation of 0.013 m/km for GPS sections in these three regions, indicating that the seasonal data are representative of all data in this larger data set.

Standard deviations for the collection of the three and four seasonal visits in these yearly data sets give an indication of the effect of seasonal changes on expected IRI variability. Shown in figure 28 are the percentile rankings for the single-season and across-season standard deviations. They indicate that about 68 percent of the single-visit standard deviations are less than 0.014 m/km. IRI standard deviations between the seasons are about six times greater (0.089 m/km). The conclusion can be drawn that testing within the same season of the year should reduce the seasonally related variability by up to six times.

Daily Change Effects

FHWA has asked RCOC's to collect profiles during seasonal PC section data collection two or three times in a single day—in the early morning, mid-morning, and late afternoon. This is intended to capture the effect of slab curling on pavement roughness. The variability within a single time period versus that of an entire day provides insight into the effect of curling on IRI variability.

Data used in this comparison include IRI values from 12 seasonal GPS PC sites collected on 32 days. Multiple sets of profile testing were completed on all of these days. When the hours were

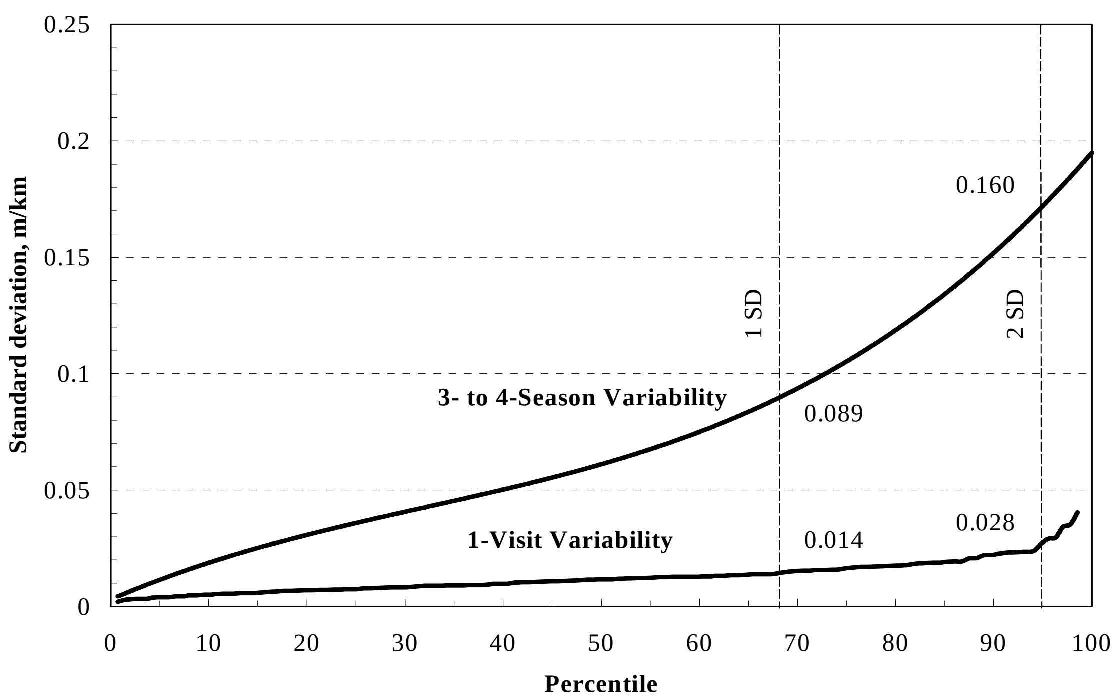

Figure 28. Seasonal effect on variability.

divided into three representative time groups (4 a.m. to 10 a.m., 10 a.m. to 3 p.m., and 3 p.m. to 10 p.m.), there remained 20 days in which two time groups were tested and 7 days when three time groups were profiled. On 5 days, the multiple sets were collected in the same time group. If only two groups were tested, one of the groups was the early morning time.

Standard deviations for the individual visits and the daily IRI values are shown in figure 29. For GPS PC sections in the entire IMS database, the average standard deviation is 0.017 m/km. In this seasonal data subset, the standard deviation is 0.019 m/km. The standard deviation for all runs collected at different times of the day is 0.047, compared to 0.019 m/km for the individual runs collected at a single time. This indicates that an increase in variability of up to 2.5 times is added to GPS PC sections when tested at different times of the day. Based on this trend, it is evident that striving to collect profiles from PC sections at the same time of day will reduce IRI variability, although not as much as by testing during the same season of the year.

Between-Visit Confidence Limits

The linear trend in IRI slope data allows, with additional analysis, the development of confidence limits for the expected change in average IRI values in consecutive visits. Differences in this change for SPS and GPS sections and for regional contractors were not statistically significant. The mean IRI slopes of the AC, PC, and APC pavement types were significantly different, requiring that confidence limit models be developed for each pavement type.

A review of the IRI slope data indicated 124 visits where the negative change in IRI between visits was greater than 0.180 m/km. These visits (2.4 percent of the data set) are outside the 90-

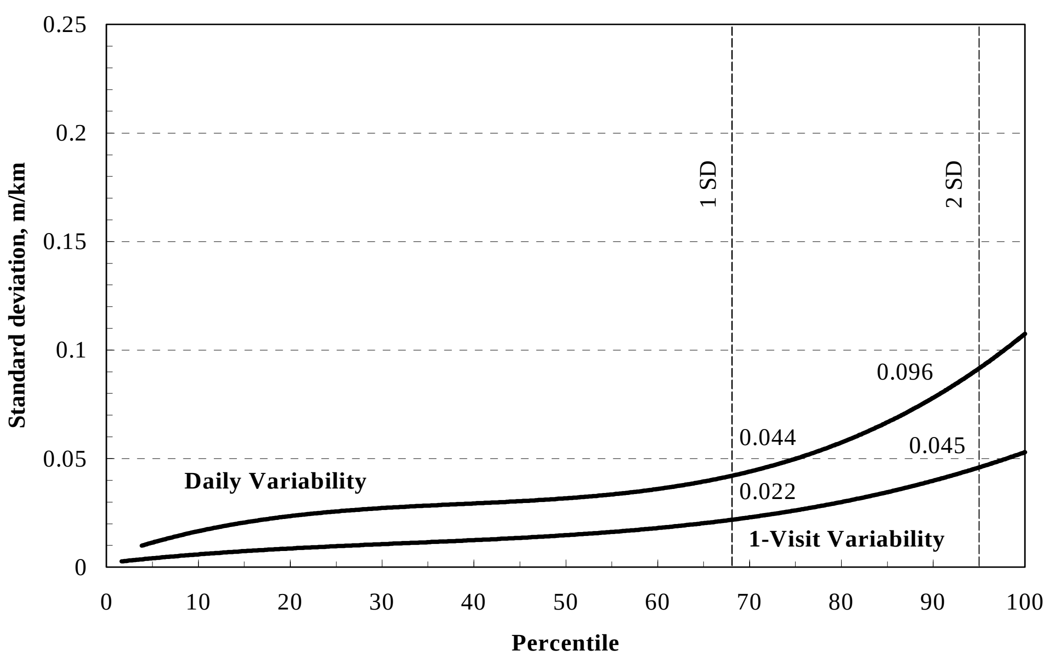

Figure 29. Daily effect on IRI variability.

percent confidence interval for yearly IRI standard deviation in the seasonal data set. Because this seasonal set includes an entire range of variability between runs, at different times of the day, and across seasons, it seemed reasonable to exclude these visits from the analysis.

For each pavement type, the IRI slopes within 0.5-m/km intervals from 0.5 to > 3.0 m/km were compared statistically. The slopes for each pavement type fell into three statistically distinct grouping intervals (according to the Duncan multiple-comparison procedure), shown in table 11. Mean and standard deviation slope values for each interval provide sufficient information to develop confidence limits for each roughness level. Data points, mean slopes, and confidence limits for AC, PC, and APC pavements are shown in figures 30, 31, and 32, respectively. These were developed using a 95-percent confidence level.

Table 11. Statistically different slopes for IRI intervals.

Grouping[1]	IRI range, m/km		
	AC	AC/PC	PC
A	0.5 to 1.5	0.5 to 1.5	0.5 to 1.5
B	1.5 to 2.5	1.5 to 2.5	1.5 to 2.5
C	>2.5	>2.5	>2.5

[1]Statistically different at 95-percent confidence level.

Formulas that can be used in quality control software or in manual quality checks are listed below for each pavement type. These models are considered accurate for AC pavements within the IRI range of 0.5 to 4.0 m/km, for PC between 0.5 and 3.5 m/km, and for APC between 0.5 and 3.0 m/km. Because of the small denominator, they are not recommended for use when the time between section tests is less than 6 months.

AC Pavements:

Upper Limit: $$IRI_E = IRI_P + \Delta T\ (0.1984\ IRI_P - 0.0273) \qquad (9)$$

Lower Limit: $$IRI_E = IRI_P + \Delta T\ (-0.0282\ IRI_P - 0.0995) \qquad (10)$$

PC Pavements:

Upper Limit: $$IRI_E = IRI_P + \Delta T\ (0.1532\ IRI_P + 0.0094) \qquad (11)$$

Lower Limit: $$IRI_E = IRI_P + \Delta T\ (-0.1158\ IRI_P - 0.0686) \qquad (12)$$

AC/PC Pavements:

Upper Limit: $$IRI_E = IRI_P + \Delta T\ (0.3244\ IRI_P - 0.1538) \qquad (13)$$

Lower Limit: $$IRI_E = IRI_P + \Delta T\ (-0.1158\ IRI_P - 0.0006) \qquad (14)$$

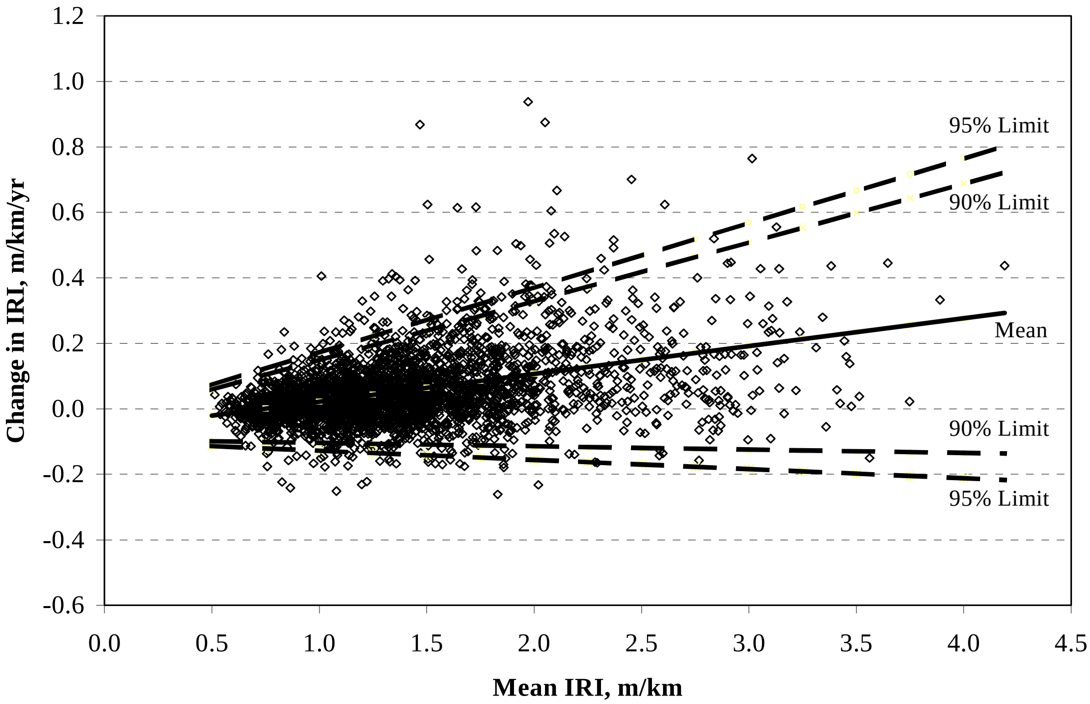

Figure 30. Confidence limits for AC IRI change.

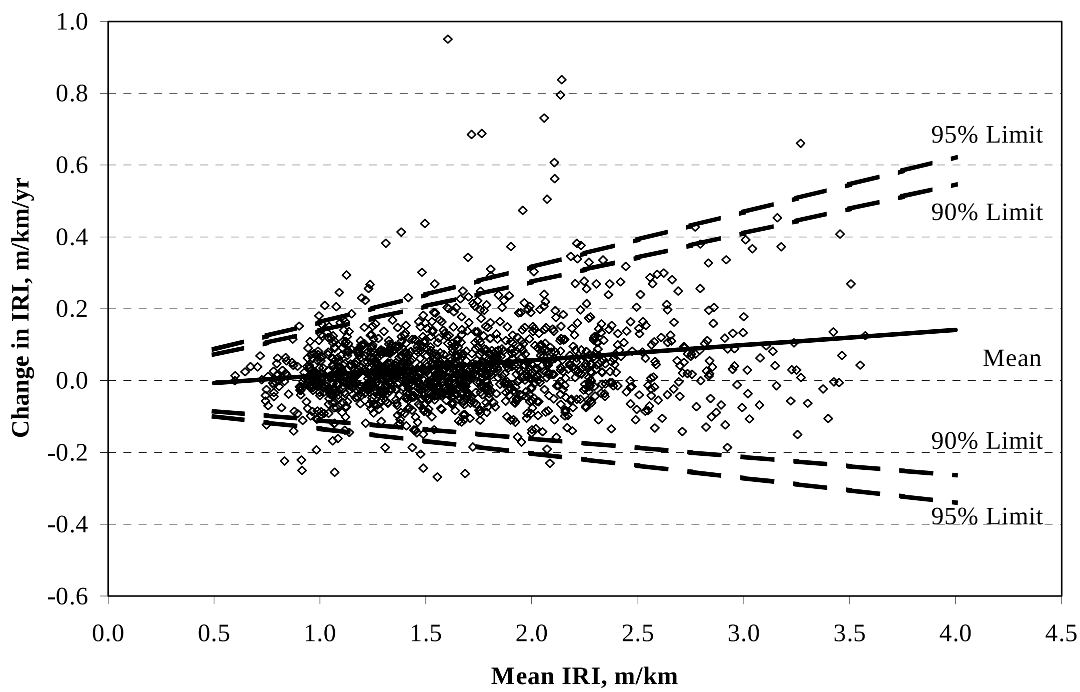

Figure 31. Confidence limits for PC IRI change.

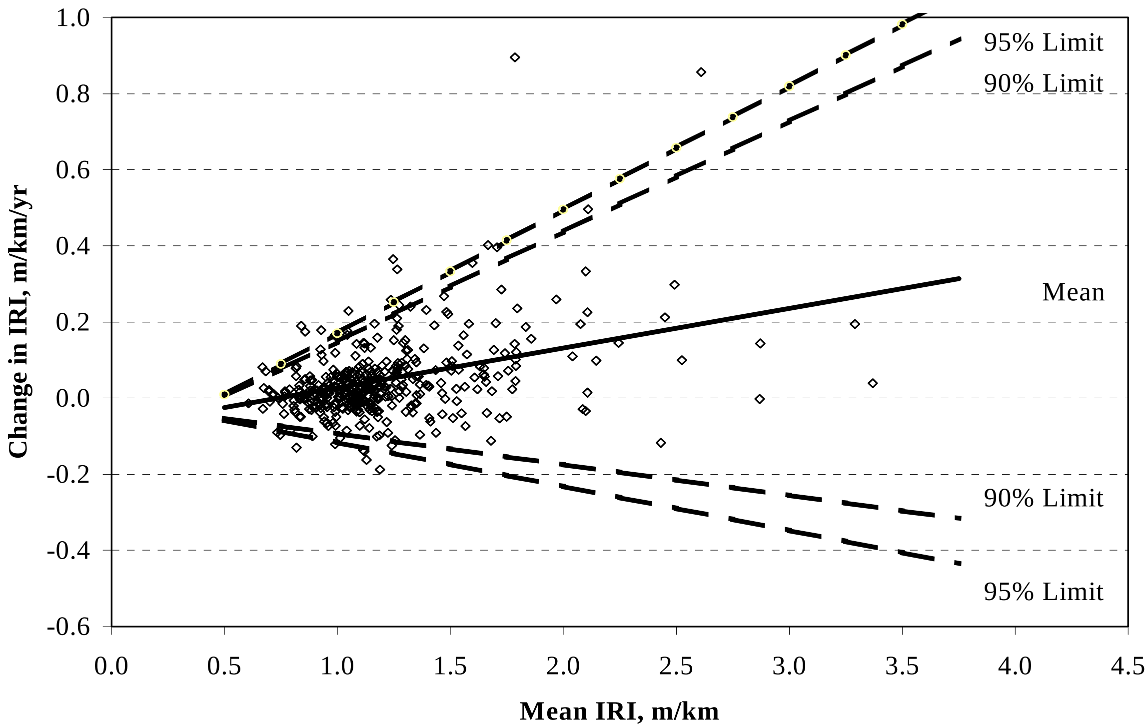

Figure 32. Confidence limits for APC IRI change.

Where:

IRI_E = Expected IRI, m/km
IRI_P = Previous IRI, m/km
ΔT = Time since previous visit, yrs

In contrast to the ±10 percent limit currently used to check for expected IRI values, these confidence limits adjust for the different variability and IRI changes associated with different roughness levels. Between IRI levels of 0.75 and 3.5 m/km, the AC confidence limits correspond to average allowable yearly reductions of 8.6 percent and allowable increases of 18.2 percent. For PC sections, the average allowable reduction and increase are 10.7 and 15.9 percent, respectively. Finally, the allowable yearly reduction for APC sections is 11.6 percent, with an allowable increase of 23.5 percent.

These limits are intended to provide guidelines for future profile data collection. IRI changes outside the upper limits are not unreasonable; however, changes below the lower limits may indicate problems in data collection or unreported maintenance or rehabilitation. These confidence levels should be used as a quality control guide. If limits are exceeded, it is recommended that the newly collected profiles be reviewed and compared with profiles from previous visits. Also, the pavement section should be visually surveyed to identify changes in its condition.

Summary of Between-Visit Variability

Through this analysis, researchers have drawn several conclusions that can be applied to the future collection of profile data. Several of the previously discussed key findings are provided below:

- Linear trends in the LTPP IRI data currently prohibit the identification of inflection points for development of incremented collection frequency guidelines.

- IRI standard deviations associated with seasonal effects are about 0.089 m/km. This is about six times the variability of the single-visit standard deviations for the same data.

- Daily cycling of IRI roughness on PC sections results in an average standard deviation of 0.047 m/km for the PC GPS seasonal sections in the LTPP database. The individual standard deviation for these sections at each time of day is 0.019 m/km. This indicates that the increased standard deviation typically associated with daily cycling of PC pavement sections is up to 0.028 m/km.

- Confidence limits for AC, PC, and APC pavements have been developed using the data from the LTPP database. These limits can be used as quality control checks for future profile data collection.

CHAPTER 6. ADDITIONAL ANALYSIS RESULTS

In addition to the visual review and statistical analysis, data processing analysis and field testing have been conducted. Since unreported saturation spikes have been identified on 1,810 test site profile runs, the effect of unedited saturation spikes on IRI using spikes of various amplitude was analyzed.

The shifting of profiles more than 5 m from the true 152.4-m location was also noted on 1,728 test site profile runs. Using PC and AC pavement sections ranging in IRI from 0.85 to 2.34 m/km, the effect on IRI of profile location shifts up to 15 m was also evaluated.

Variation of wheelpath location was also reviewed. Since no information is available regarding the effect of transverse vehicle location on IRI, field testing was completed on three sections with an IRI ranging from 1.18 to 2.87 m/km. The location of the profile sensors was shifted 0.3 m to the left and right of the wheelpath location, and IRI variability was summarized. The results of these and other analyses are described in this chapter.

Effect of Saturation Spikes

The effect of the unreported saturation spikes (noted in profiles from about 5 percent of the section profile runs) on IRI and other smoothness indices is unknown. To document this effect, spikes of various amplitudes were inserted at the start of the profile for Illinois section 5217 collected on June 15, 1991. The IRI average for both wheelpaths when no spikes were present was 2.4 m/km. Figure 33 shows the effect of spikes with amplitudes of 5 to 75 mm.

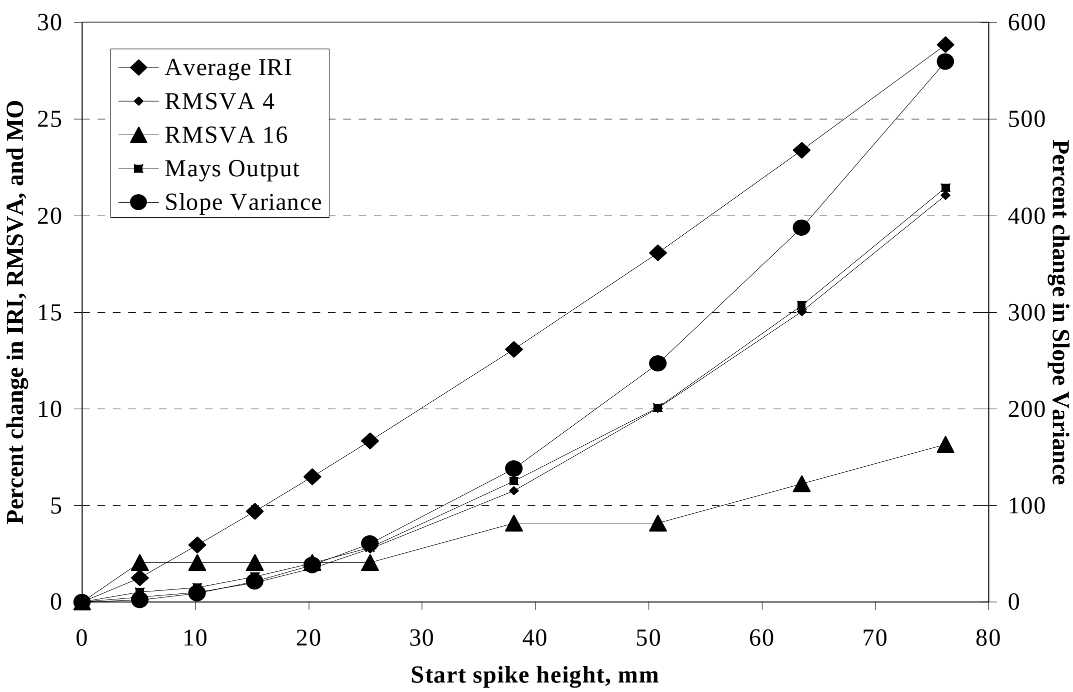

Figure 33. Effect of spike height on smoothness statistics.

The relationship between spike amplitude and IRI is nearly linear, with a 1.8-percent increase in average IRI for every 5-mm increase in spike amplitude. Average effects on slope variance values are much more dramatic, with a 24-percent increase for every 5-mm spike height increase. Other smoothness statistics are less sensitive to the presence and amplitude of spikes. For each 5-mm increase in spike height, the average increases in Root Mean Squared Vertical Acceleration (RMSVA) with a 1.2-m (4-ft) baselength (RMSVA 4), RMSVA 16 (4.9-m baselength), and Mays Output were 1.0, 0.5, and 1.0 percent, respectively.

This evaluation shows that the effects of spikes in the typical 12- to 75-mm range on IRI and other smoothness statistics can be dramatic, and it reinforces the importance of not including saturation spikes greater than 5 mm in profile smoothness statistics computation from profiles in the LTPP database.

Effect of Shifted Profiles

The problem of shifted profile start locations is particularly important given that about 3.6 percent of the LTPP section profile runs are shifted more than 5 m. IRI values ranging from 0.5 to 4.5 m/km were computed for 25 AC and PC SPS sections. The start and end locations of each profile were shifted backward 15, 12, 9, 6, and 3 m, and the IRI values were recomputed on the shifted profiles. Comparing the IRI values for the shifted profiles with those of the original profile, it was noted that the difference from the true IRI value ranged from 0 to 28 percent. Figure 34 shows the results of this analysis. The importance of testing a section at the same location is evident. For profiles shifted 12 m, normalized statistics indicate that about 70 percent of the shifted IRI values were within 5 percent of the true IRI.

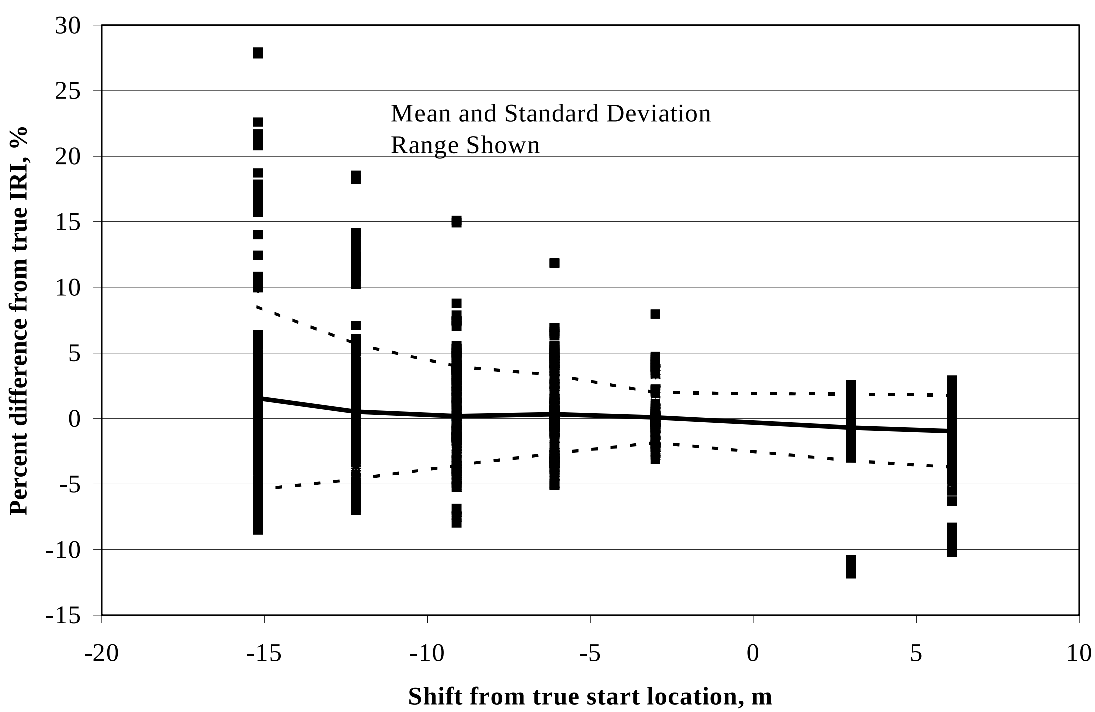

Figure 34. Effect of shifted profile start locations.

For profiles shifted 15, 9, 6, and 3 m from the original location, about 70 percent were within 7.0, 3.8, 3.0, and 1.9 percent, respectively.

However, the average effect on IRI from shifted profiles is negligible because the profile sections added or deleted from the beginning and end of the true profile location can be smoother or rougher than the true section. A random selection results in no average IRI change.

For quality control, the data indicate that profiles shifted up to 3 m can be expected to be within 3.7 percent of the true IRI values in 95 percent of the data. This is well within the effect of seasons on IRI variability. However, profiles shifted more than 3 m can be expected to greatly affect the IRI values and should be avoided.

Effect of Wheelpath Location

No definitive evaluation of the effect of the transverse location (i.e., wheelpath location) of testing longitudinal profiles has been completed by FHWA. It has been FHWA policy to allow the LTPP Profilometer operators to visually define the wheelpath location to be tested at each visit. This has raised questions about the effect on IRI if different operators in different years measure the profiles in a slightly different wheelpath location.

To help study this effect, in February 1998, the Texas Department of Transportation assisted in the location and marking of three AC test sites of different roughness levels. Sites 1 and 2 are located on westbound SH 71, approximately 31 km east of Interstate 35 in Austin, Texas. The third site is on Pope Bend South Road, a service road adjacent to sites 1 and 2 in the westbound direction. Air temperatures were between 22 and 26°C, and the skies were clear to partly cloudy. Five repeat runs were made at each site for the center of the wheelpaths and 300 mm left and right of the center using the Southern Region's K.J. Law T-6600 Profilometer.

Figure 35 shows the average of five runs for each site and wheelpath location. Shifting transverse location left or right 300 mm for smooth, medium, and rough AC pavement sites resulted in average left and right wheelpath IRI changes of 7.1, 15.3, and 4.0 percent, respectively. Tables 12, 13, and 14 list the results of ANOVA and Tukey multiple comparison of average values analysis. The ANOVA indicated that, for each site and wheelpath, there is a significant difference between one or more of the shifted profile IRI values. P-values listed on these tables all indicate good statistical results. Mean values for each location are shown in the tables, along with the Tukey significance-level groupings defining data sets that are significantly different. Based on the mean and variability of the five runs left, right, and center of the true wheelpath, these significance-level groupings identify locations where the IRI values are statistically the same. For example, in the left wheelpath of site 1, there is no significant difference at the 95-percent confidence level between runs taken at the center of the wheelpath and 300 mm to the right of center. However, the IRI values measured 300 mm left of center are significantly greater.