Road Profiler Performance Evaluation and Accuracy Criteria Analysis

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Thesis Submitted to the Faculty of

Virginia Polytechnic Institute and State University

In partial fulfillment of the requirements for the degree of:

Master of Science

In

Civil and Environmental Engineering

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July 24, 2006

Blacksburg, Virginia

Keywords: Profiler, Road Profile, IRI, Accuracy, Repeatability

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Abstract

Road smoothness is one of the most important road functional characteristics because it affects ride quality, operation cost, and vehicle dynamic load. There are many types of devices that measure the road profile, which is often used to compute different smoothness indices. The development of performance-based specifications and pavement warranties that use ride quality as a performance measure has increased the need for accurate measurement of pavement smoothness. For this reason, researchers have compared and evaluated the performance of available profilers and several profiler accuracy criteria have been proposed. However, there is not a definite answer on the ability of available profilers to accurately measure the actual road profile as well as the various smoothness indices.

A recent profiler round-up compared the performance of 68 profilers on five test sections at Virginia Smart Road. The equipment evaluated included high-speed, light-weight, and walking-speed profilers, in addition to the reference device (rod and level). The test sites included two sites with traditional hot-mix asphalt (HMA) surfaces, one with a coarse-textured HMA surface, one on a continuously reinforced concrete pavement (CRCP), and one on a jointed plain concrete pavement (JCP). This investigation used a sample of the data collected during the experiment to compare the profiles and International Roughness Index (IRI) measured by each type of equipment with each other and with the reference. These comparisons allowed determination of the accuracy and repeatability capabilities of the existing equipment, evaluation of the

appropriateness of various profiler accuracy criteria, and recommendations of usage criteria for different applications.

The main conclusion of this investigation is that there are profilers available that can produce the level of accuracy (repeatability and bias) required for construction quality control and assurance. However, the analysis also showed that the accuracy varies significantly even with the same type of device. None of the inertial profilers evaluated met the current IRI bias standard requirements on all five test sites. On average, the profilers evaluated produced more accurate results on the conventional smooth pavement than on the coarse textured pavements. The cross-correlation method appears to have some advantages over the conventional point-to-point statistics method for comparing the measured profiles. On the sites investigated, good cross-correlation among the measured and reference profiles assured acceptable IRI accuracy. Finally, analysis based on Power Spectral Density and gain method showed that the profiler gain errors are nonuniformly distributed and that errors at different wavelengths have variable effects on the IRI bias

Acknowledgements

The author expresses his most sincere gratitude to his advisor, Dr. Gerardo Flintsch, for his guidance and assistance in completing this research and writing thesis. Thanks are also extended to committee members Dr. Amara Loulizi and Dr. Linbing Wang for giving helpful comments and providing support.

The help of Steve M. Karamihas, from the University of Michigan Transportation Research Institute (UMTRI) is greatly appreciated. He designed the experiment, conducted the profiler round-up, and provided the data for this investigation.

The author extends his heartfelt appreciation to his wife and his family for their support and encouragement during his study at Virginia Polytechnic Institute and State University.

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CHAPTER 1 INTRODUCTION

1.1 Background

Road smoothness, or roughness, is one of the most important road functional characteristics because it greatly affects ride quality and vehicle dynamic load. It is also closely associated with vehicle operating costs, such as fuel consumption, tire wear, and vehicle durability. Therefore, establishment of methods for measurement and evaluation of road smoothness is a common concern of highway state agencies. Many techniques are available for measuring road smoothness, most of which measure the vertical deviations of the road surface along a longitudinal line of travel in a wheel path, known as the profile. The American Society of Testing and Materials (ASTM) standard E-867 defines roughness as the deviations of a pavement surface from a true planer surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads, and drainage.

Road profile measurements started with straight edge devices in the early 1900s, and they have evolved to vehicles that can measure the road profile while traveling at normal traffic speed. These equipments measure longitudinal profiles, which provide vertical elevation as a function of longitudinal distance along a prescribed path. The equipment used to measure roughness of pavements varies across highway agencies. Generally these equipments can be divided into the following five categories: (1) Response type road roughness measuring systems; (2) High-speed inertial profilers; (3) Profilographs; (4) Light-weight profilers; (5) Manual devices (Perera and Kohn, 2002).

Smoothness measurements are performed to monitor the condition of a road network in a pavement management system (PMS), or to evaluate the ride quality of newly constructed or rehabilitated pavements. Profile data can also be used to diagnose the condition of specific sites and determine appropriate remedies, and to study the condition of specific sites for research. Many smoothness indices are derived from profile data and/or correlated with road user's perception of ride quality to indicate the level of road roughness. These include Profile Index (PI), International Roughness Index (IRI), Ride Number (RN), Michigan Ride Quality Index (RQI) and Truck Ride Index (TRI) (Sayers and Karamihas, 1996). One common problem is the use of different pavement profile indices for initial and long-term evaluations, e.g., PI from profilograph for construction acceptance and IRI from inertial profiler for pavement monitoring. This makes it difficult to directly compare between initial smoothness and subsequent evaluations.

The International Roughness Index (IRI) is the index most widely used in the USA for measuring road roughness. Since 1990, FHWA has required state highway agencies to submit the roughness values of the Highway Performance Monitoring System sections in IRI. The American Society of Testing and Materials (ASTM) standard E-1926 defines the standard procedure for computing IRI from longitudinal profile measurements. The computation of IRI is based on a mathematical model called a quarter-car model. The quarter car is moved along the longitudinal profile at a simulation speed of 80 km/h (50 mph). The mathematical model calculates the suspension deflection of the quarter car using the measured profile displacement and standard car structure parameters. The simulated suspension motion is accumulated and then divided by distance traveled to give an index with unit of slope (m/km or in/mi), which is called IRI. Most States are using IRI derived from profiler measurements to evaluate pavement condition, and some States are using it for construction quality control for individual projects.

1.2 Problem Statement

Many types of profilers attempt to measure the road "true" profile, which is used to compute various smoothness indices using different algorithms. The accuracy of the computed indices depends greatly on the accuracy of the measuring equipment.

Therefore, different devices may produce different values of IRI for the same road section. The development of performance-based payment adjustments for paving contractors and pavement warranties including ride quality has increased the need for accurate measurement of pavement smoothness. Since the measured smoothness determines the payment amount of incentive or disincentive, the accuracy of the smoothness measurement is a critical issue for both paving contractors and highway agencies. Thus, there is a need to evaluate pavement profilers and establish the availability of equipment for implementing a profile-based smoothness specification (Fernando, 2000). For this application, it is necessary to recommend the equipment and method for measuring the surface profile based on its ability to offer the required accuracy and production rates.

Conventional methods for evaluating profiler accuracy usually place tolerances on the agreement between profile elevation values over a broad waveband. This approach is used in ASTM E-950 and AASHTO PP 49. A weakness of this approach is that it fails to emphasize the aspects of profile measurement that are more relevant to the intended application. The approach emphases the long wavelength contents that do not have a significant impact on the smoothness index, and it is very sensitive to phase shift between different profiles measurements (Karamihas, 2002 (a)). As a result, the most common method of objective profile comparison, ASTM E-950, does not assure that two certified profilers can measure the same value of IRI within an acceptable tolerance (Li and Delton, 2003). When the approach is used for profiler certification in construction quality control, two certified profilers might produce different IRI values that result in different levels of smoothness pay adjustment for the same site.

1.3 Objective

The profiler comparison and verification study (round–up) performed by UMTRI in 2004 tested 68 road profilers on five test sections at the Virginia Smart Road. The round-up experiment included high-speed, light-weight, walking-speed profilers, and one reference device. This investigation used the data collected at the Smart Road to investigate the following four objectives:

- Evaluate the accuracy (bias and repeatability) of each type of profiler in terms of both, IRI and longitudinal profile.
- Analyze the effect of pavement surface characteristics on profiler accuracy.
- Compare the existing profile accuracy criteria (ASTM E950 and cross-correlation)
- Evaluate the influence of profile gain error at different wavelength on total IRI bias using spectrum analysis

Comparative evaluations were conducted between different types of profilers, and between each profiler and the reference device. These comparisons allowed determination of the accuracy and repeatability capabilities of the existing equipment, evaluation of the appropriateness of various profiler accuracy criteria, and recommendations of usage criteria for different applications.

1.4 Significance of the Research

At least 48 states are using profilers to evaluate pavement quality and 10 are using profile measurement for construction quality control for individual projects. Additionally, 25 states are considering the use of profilers for construction quality control (McGhee, 2004). Thus, it is very important that profilers provide stable and consistent smoothness measurements. Verification of the accuracy of these devices has become a significant concern of state highway agencies.

The profiler round-up experiment compared different profilers' performance on a variety of pavement surface type. Thus, the results of this investigation allow providing guidelines for highway agencies and contractors on the availability of profilers that can measure the longitudinal profile and smoothness index accurately on various pavement surfaces. The investigation also provides useful benchmark data and procedures that agencies can use for profiler verification or certification. This thesis will help highway agencies selecting, evaluating and using profilers for construction quality assurance of pavement condition monitoring.

1.5 Organization of the Thesis

In this thesis, Chapter 2 presents a review of literature pertaining to profile measurement equipment, previous profiler comparisons and evaluation projects, and current profiler accuracy criteria. Chapter 3 describes the experimental program used for the 2004 profiler round-up. Chapter 4 covers the data analysis performed and the results obtained, including repeatability and bias of computed IRI, profile visual inspection, point-to-point statistics of profile elevations, and cross-correlation analysis. Chapter 5 presents the analysis of the profiler gain error based on Power Spectral Density (PSD) analysis and gain method. Chapter 6 reports the main findings and conclusions of the investigation and recommendations for future research.

CHAPTER 2 LITERATURE REVIEW

2.1 Equipments of Profile Measurements

Equipment used to measure roughness of pavements varies among highway agencies and intended purpose. Available devices can be divided into the following five categories (Perera and Kohn, 2002):

(1) Response type road roughness measuring systems;

(2) High-speed inertial profilers/profilometers;

(3) Profilographs;

(4) Light-weight profilers; and

(5) Manual devices.

Until the mid 1980s, highway agencies used mostly Response Type Road Roughness Measuring System (RTRRMS) to measure roughness, or smoothness, of their pavement networks. The response type devices measure the response of the vehicle to the road profile using transducers to accumulate the vertical movement of the axle of the automobile or trailer with respect to the vehicle frame. The measurement directly reflects the user's feeling of ride quality. A variety of RTRRMS have been developed over the years. Popular response type devices included the BPR Roughometer, PCA Roadmeter, and Maysmeter. These devices have the disadvantages that the measured results are influenced by the properties of vehicle mechanic system and measuring speed. With the advent of inertial profilers, the use of RTRRMS has declined.

High-speed road profiling is a technology that began in the 1960s at the General Motors Research Laboratory. The number of States that have adopted high-speed profilers to collect roughness data on their highway networks has shown a dramatic increase in the past decade (McGhee, 2004). Inertial profilers collect pavement profile data at highway speeds, and generate the true profile of a roadway. The principal components of an inertial profiler are height sensors, accelerometers, and distance measuring system. The height sensors record the height to the pavement surface from the vehicle. The accelerometers, located on top of the height sensors, record the vertical acceleration of the vehicle that can be integrated twice to obtain the vehicle vertical displacement. The difference between the measurements of the height sensors and accelerometers is the surface profile. The distance measuring system refers the measurements with respect to a reference starting point. The non-contact height sensors currently used in profilers are either laser, ultrasonic, optical or infrared. Ultrasonic sensors were the most common type of sensors used in the 1980s. However, because of the effect of environmental conditions on this type of sensors, their use has declined over the past several years (Perera, 1995). Currently, laser sensors are the height sensors most commonly used in profilers.

Profilographs are widely used to evaluate the as-constructed smoothness of new pavements and overlays. A profilograph consists of a rigid beam or frame with a system of support wheels at either end, and a center wheel. The center wheel is linked to a strip chart recorder or a computer that records the movement of the center wheel from the established datum of support wheels. Most States use the Profile Index (PI) that is obtained from the profile trace measured by the Profilograph for pavement quality assurance. Many incentive and disincentives specifications are also based on the PI value.

Light-weight profilers are increasingly used to evaluate new construction. The term light-weight profiler is used to refer to devices in which a profiling system has been installed on a light vehicle, such as a golf cart or an all-terrain vehicle. The profiling system in the light-weight profilers is similar to ones used in high-speed profilers. The profile data is commonly used to simulate a profilograpgh over the pavement section, generate a PI, and identify bump locations. The profile data can also be used to compute other roughness indices, such as the IRI or RN.

Manual devices such as the Dipstick, ARRB walking profiler, and Rod and Level are generally used to collect profile data at a section in order to verify or validate the data collected by road profilers. The rod and level is perhaps the most accurate method of obtaining the true elevations along a pavement surface and its standard reference procedure is described in the ASTM E-1364. The Dipstick and walking profilers usually use an inclinometer between two support feet or multi wheels to compute the surface profile. The general procedure to verify the output from road profilers is to collect profile data at test sections using a manual reference device, then compute roughness index such as IRI from that data and compare the result with the output from the road profiler.

2.2 Previous Profiler Performance Evaluations

Many profiler comparison or evaluation experiments have been conducted in the past 20 years. The first International Road Roughness Experiment (IRRE) by The World Bank was conducted in Brazil in 1982, using a variety of RTRRMS and Profilometers, and resulted in the development of the IRI. The IRI has been accepted worldwide as one of the most reliable roughness indices (Sayers and et al., 1986).

The World Road Association (PIARC) also conducted an international experiment to harmonize longitudinal and transverse profile measurement and reporting procedures (EVEN project) in 1998 at three different locations: Arizona, USA, Hokkaido, Japan and Holland/Germany, Europe (Schmidt, 2001; Descornet and et al., 2001). Other profilers' performance evaluations conducted in USA are summarized in the following sections.

2.2.1. LTPP Profiler Comparisons

Profile data for the Long Term Pavement Performance (LTPP) have been collected using K.J. Law (DNC 690 and T 6600) and ICC inertial profilers. Comparisons between the profilers used by the LTPP regional support contractors have been conducted annually to ensure accurate data collection. In these comparisons, several test sections are profiled and the profiles are analyzed to: (i) evaluate the accuracy and consistency of the distance measurement system, (ii) compare IRI and profiles obtained by the various profilers, and (iii) compare IRI values obtained from profilers to that IRI obtained using the Dipstick. The bias and precision criteria used in 2003 comparison test for the measured IRI values are ± 0.16 m/km (10 in. /mile) and 0.04 m/km (2.5 in. /mile) respectively (FHWA, 2004).

The comparisons have shown that the difference between the profilers and the Dipstick IRI was greater than the 0.16m/km criteria at some sections, and such cases occurred on sections that had pavement distresses along the wheel paths (FHWA, 1998). The most probable reason is that the Dipstick has a footpad diameter of 32 mm that can bridge over cracks, while the laser sensors in the profiler can measure the depth of a crack. In addition, there are differences in the sampling interval between the profiler and the Dipstick that can also contribute to differences in IRI.

2.2.2. ACPA and NCAT Profiler Verifications for New Pavements

The American Concrete Pavement Association (ACPA) and UMTRI conducted a profiler verification experiment in 2002. The experiment included six light-weight inertial profilers, three high-speed inertial profilers, two walking-speed profilers, one profilograph, and a rod and level survey. Tests were performed on three newly constructed concrete and one HMA pavement. The study results demonstrated that repeatability of high-speed and light-weight inertial profilers in terms of cross correlation was inadequate on the new concrete site with transverse or longitudinal tinning, especially on the sites with coarse texture (Karamihas and Gillespie, 2002 (b)).

The National Center for Asphalt Technology (NCAT) track was utilized to evaluate the possibility of using the automated walking Australian Road Research Board (ARRB) profiler, the McCracken (a California-style profilograph), and the South Dakota Profiler for analyzing pavement smoothness. Results indicate that there was a poor correlation between the ARRB unit and the McCracken profilograph, and a fair correlation between the ARRB and the South Dakota profiler. Because the ARRB unit uses an inclinometer for determining the profile, use of this profiler should be limited to sections without severe super elevations. (Wagner, 2002)

2.2.3. Texas DOT and Florida DOT Profiler Performance Evaluations

The Texas Department of Transportation (TxDOT) implemented a research project to evaluate pavement profilers for establishing the availability of equipment for profile-based smoothness specification in Texas. Two reference profilers and five inertial profiling methods were tested on a number of test sites that ranged from about 1.0 to 1.9 mm/m in terms of IRI value measured over a 161 m interval. The reference profile was determined using rod and level measurements with a digital level that provides a resolution of 0.03 mm, thereby satisfying the requirements for a class I static level survey as specified in ASTM E-1364. These comparisons showed that there are devices available for collecting profile data that are accurate and repeatable. The study also indicates the lead-in effect of inertial profiler has little influence on its repeatability and accuracy (Fernando and Leong, 1997).

The Florida Department of Transportation also initiated a field study to assess the accuracy and precision of high-speed profilers. Profile measurements were acquired by using five profilers concurrently on a large number of randomly selected HMA pavement sections. The profile data collected were first analyzed to determine the repeatability and reproducibility of the IRI and RN profile indices at each test site. In addition, the effect of the operating speed and pavement surface texture on roughness measurements was assessed. (Choubane et al., 2002)

2.2.4. Light-weight Profiler Performance Evaluations

As-constructed smoothness measurements by four light-weight, non-contact profilers (LWPs) and two high-speed profilers were collected on four new PCCP sections on I-70 in Kansas. The data were statistically analyzed using Analysis of Variance (ANOVA) and the Least Square Means. Significant differences were observed, in some cases, among the values obtained from high-speed profilers and LWPs. No reasonably consistent correlation between PI and IRI was established. (Akhter and et al., 2003)

Another project evaluated light-weight profilers to assess their repeatability and reproducibility, as well as their potential for their use in Indiana. A field test compared four ASTM Class I light-weight profilers on three asphalt and three concrete sites. The evaluation of the devices in accordance with ASTM standards revealed good repeatability but poor reproducibility. Smoothness specifications of other states were reviewed in light of their application to light-weight profilers, and a draft smoothness specification based on light-weight profilers was developed for INDOT. (Mondal and et al., 2000)

2.3 Existing Profiler Accuracy Criteria

2.3.1. ASTM E-950

The ASTM Standard E-950 is currently widely used for rating the repeatability and accuracy of profilers. The Standard includes a classification system for profiler that is based on the requirement of precision (standard deviation) among repeat elevation measurements and bias (absolute difference) in elevation compared to a reference measurement. The composite precision and bias values are based on a minimum of 10 profile measurements and over a distance of 320 meters (1056 feet) at 0.3-meter (1 foot) intervals. The precision and bias requirements of different equipment classifications are shown in Table 2-1.

Table 2-1 ASTM E-950 Precision and Bias Criteria

Classification	Precision	Bias
Class 1	0.38 mm (0.015 in.)	1.25 mm (0.05 in.)
Class 2	0.76 mm (0.030 in.)	2.5 mm (0.10 in.)
Class 3	2.5 mm (0.10 in.)	6.25 mm (0.25 in.)

The main weakness of this approach is the emphasis on long wavelength content in the comparison of elevation values. In most road profiles, the amplitude of elevation content is roughly proportional to wavelength. Thus, short wavelength features often appear as relatively small deviations in elevation. The treatment of each elevation value as a distinct measurement weakens the ability of detecting short wavelength measurement problems (Karamihas, 2002 (a) and 2005). This method is also sensitive to the high-pass filter used in the profile computation and the phase shift between different measurements.

2.3.2. AASHTO PP 49-03 and Tex-1001-S

The AASHTO PP 49-03 and Texas Specification TEX-1001-S use a method similar to ASTM E-950, but they have additional IRI accuracy (bias) and precision criteria, as shown in Table 2-2. The bias for profile can be calculated using the absolute values of the differences or the raw differences in elevation between the profile being evaluated and the reference profile.

Table 2-2 AASHTO PP 49-03 and TEX-1001-S Precision and Bias Criteria

Criteria		Profile	IRI
Precision		0.51 mm (0.02 in)	0.047 m/km (3 in/mi)
Bias	Difference	± 0.5 mm (0.02 in)	0.19 m/km (12 in/mi) for TEX and 0.095 m/km (6 in/mi) for AASHTO
	Absolute difference	1.5 mm (0.06 in)	

2.3.3. Gain Method

Prem (1998) developed a method for validating pavement profile measurements using the transfer function between a reference profile and profiles collected by a device under evaluation. In this method, the reference profile measurement is treated as the input, and each repeat profile measurement by the evaluated device is treated as output with a linear relationship to the reference profile. The input and output profiles are converted to Power Spectral Density (PSD) in the frequency domain through a Fourier Transform. A transfer function ($f(v)$) is calculated between input and output profile spectra, as shown in the Equation (2.1).

$$G_{measure}(\nu) = f(v) \cdot G_{reference}(\nu) \tag{2.1}$$

Where: $G_{measure}(\nu)$ - Spectra of Measured Profile;

$G_{reference}(\nu)$ - Spectra of Reference Profile (“True Profile”);

$f(v)$ - Gain Function (Transfer Function) for Measured Profile

The transfer function has gain values at different wavelength (or wave number) and average gain across the set of repeat measurements. The gain limits are defined as the gain values of the transfer function as derived from the expected error limits in IRI. Prem (1999) analyzed the IRI sensitivity to the change of profiler gain and determined gain limit specification over the wave number range 0.2 to 2.0 cycles/m for three target levels of IRI accuracy (1%, 5%, and 10%). Karamihas (2005) used the gain method to develop the following recommendation for the gain limit of reference profilers relative to benchmark test: (i) gain error no greater than 1.00% for wavelength from 0.15 to 0.35 m, (ii) no greater than 0.25% from 0.35 to 35.9 m, and (iii) no greater than 1.00% from 35.9 to 67 m.

2.3.4. Cross correlation

The cross-correlation method had been proposed for rating the repeatability, reproducibility, and accuracy of profiles (Karamihas, 2002 (a)). The method is based on the cross correlation function for measurement of time delays between signals, rating the general dependence of one signal on another, or recovery of a given signal within noise (Bendat and Piersol, 1971). The cross correlation function of repeat profile measurements is defined in Equation (2.2). Since the profile measurements are finite in length and sampled at discrete intervals, the integral is replaced with a summation. The correlation coefficient is defined as the correlation function normalized by the standard deviation of two profiles, as shown in the Equation (2.3)

$$R_{pq}(\delta) = \lim_{L\to\infty} \frac{1}{L} \int_0^L P(x)Q(x+\delta)dx \qquad (2.2)$$

$$R_{pq}(\delta) = \frac{1}{\sigma_p \sigma_q} \sum_{i=1}^{N} P_i Q_{i+\delta/\Delta} \qquad (2.3)$$

Where: $R_{pq}(\delta)$ - Cross-Correlation Coefficient;

$P(x)$, $Q(x)$ - Profile Measurements as a Function of Distance x;

P_i, Q_i - Profile Measurements at Discrete Sampling Number i;

δ - Offset Distance between Two Profile Measurements;

L - Measuring Length;

Δ - Sampling Interval;

σ_p, σ_q - Standard Deviation of Two Profile Measurement

The cross-correlation coefficients are used to detect longitudinal distance offset between profiles and rate the correlation agreement between them at different offsets. A high coefficient indicates that the overall roughness level of two profiles is equivalent and that both of them distribute roughness equally within a profile. For example, when the method is applied to the IRI, a high rating indicates that features that contribute to the IRI appear in the same locations with the same shape. This feature makes the method a good candidate for certifying profilers for construction quality control, where the ability of a profiler to locate and prioritize isolated rough spots is important. Karamihas (2005) suggested the cross-correlation requirements for profiler certification shown in Table 2-3.

Table 2-3 Cross-Correlation Criteria with Benchmark Test (Karamihas, 2005)

Criteria	Reference devices	Profiler certification
IRI filter output	0.98	0.94
Long waveband	0.98	0.94
Medium waveband	0.98	0.94
Short waveband	0.94	0.88

2.4 Summary

Different equipments are used to measure pavements smoothness. They can be divided into the following five categories: (1) Response type road roughness measuring systems; (2) High-speed inertial profilers/profilometers; (3) Profilographs; (4) Light-weight profilers; and (5) Manual devices. High-speed profilers are widely used to collect network-level roughness PMS data on highway networks and light-weight profilers are increasingly being used to evaluate new construction.

Many profiler comparisons or evaluation experiments have been conducted in the past 20 years since The World Bank experiment. Most of these experiments used the ASTM or AASHTO accuracy (bias) and precision criteria to evaluate the profilers' performance and found good correlations between the smoothness indices from different devices. However, some of the equipment verification efforts have shown that the conventional accuracy criteria based on profile elevation cannot guarantee accurate smoothness index calculation. Other profile accuracy criteria, such as cross-correlation and gain method, should be used to capture the interaction relationship between the accuracy of profile and smoothness index.

CHAPTER 3 PROFILER ROUND-UP EXPERIMENT

A large road profiler comparison and verification study (round-up) was held on April 4–8, 2004, at the Smart Road in Blacksburg and the Pennsylvania Department of Transportation's road profiler testing facility in Newville (UMTRI, 2004). Only the data collected at the Smart Road were used for this investigation.

3.1 Test Sites

The Smart Road consists of a 3.2-kilometer fully instrumented pavement test facility, which includes 12 flexible pavement sections (A through L) and two rigid pavement sections (M and N). In the profiler round-up, 68 road profilers were tested on the five test sections located at the Smart Road. These sections include two sites with traditional hot-mix asphalt (HMA) surfaces, one with a coarse-textured HMA surface, one on a continuously reinforced concrete pavement (CRCP), and one on a jointed plain concrete pavement (JCP) that has been partially grounded, as shown in Figure 3.1.

Superpave

OGFC

SMA

CRCP

JCP

Figure 3.1 Surface Textures of Five Test Sits at Virginia Smart Road

Table 3-1 shows the range of surface macrotexture and smoothness levels available. The CRCP and JCP both have a transverse tined surface, and the JCP has received localized longitudinal diamond grinding. It should be noted that some of the sections are on a 6% downward grade, and no rod-and-level reference measurements were performed on the JCP site. The third HMA pavement section, which includes open grade friction course (OGFC) and stone mastic asphalt (SMA) surfaces, had relatively high IRI values due to the presence of pavement distress, including cracking and raveling in the OGFC.

Table 3-1 Test Sites for Road Profiler Performance Evaluation

Site	Location*	Surface type	Length (m)	Average Macrotexture (mm)	IRI by Rod and Level (inch/mi)
1	Section A and B	Superpave 12.5 mm and 9.5 mm	200	1.0	79.3
2	Section C and D	Superpave 9.5 mm	200	1.2	66.8
3	Section K and L	OGFC and SMA 12.5 mm	200	2.5	116.4
4	Section M	CRCP	160	1.5	71.8
5	Section N	JCP	160	-	-

* Smart Road denominations.

** 1 inch/mi = 0.015786 m/km.

3.2 Equipments Evaluated

The profilers evaluated included: 38 high-speed, 18 light-weight, and 12 slow-speed or walking-speed profilers in addition to the rod-and-level reference device. These profilers come from states departments of transportation (26), commercial companies (26), the Federal Highway Administration (8), paving contractors (5), vehicle manufacturers (2), and a university (1). Table 3-2, summarizes the profilers that participated in the experiment. In general, profilers of different makes and models differ in the following features: height-sensor type/accelerometer type, sensor spacing and location, number of sensors, sensor footprint, data sampling/recording interval, and data filtering methods. Only a sample of the devices that participated in the round up was selected for this investigation. Figure 3.2 shows examples of the profilers evaluated.

Table 3-2 Summary of Profilers Participated in the Round-up

Profiler Make/Model	Type	Number
ROSAN	High-Speed	3
ICC		13
ARAN		6
MGPS		1
Custom		3
RSP five0five1		2
ROADMAS		1
Pathway		2
K.J. Law		2
MHM		1
Digilog VX		1
Starodub/DHM		1
SSI		1
Ames		1
Starodub/ULIP	Light-Weight	1
ICC		6
SSI		4
Dynatest/Law T64five0		1
K.J. Law		2
Custom		1
Transtology		1
Ames		2
SuPro 1000	Walking-Speed	3
R/D-Meter		2
ARRB WP		3
Rolling Rod and Level		1
YSI RoadPro		1
COMACO GSI		1
ROADMAS Z2five0		1

Figure 3.2 Examples of the Profilers that Partipated in the Round-up

The published LTPP guideline for longitudinal pavement profile measurement required the following: (1) the sampling interval must be 167 mm (6.54 in) or less and the recording interval must be 250 mm (9.84 in) or less; and (2) the height sensor and accelerometer signals must pass through anti-alias filters with a cutoff wavelength equal to twice the sample interval. All profilers had to satisfy these requirements.

3.3 Test Procedure

The round –up was completed in three days and followed the sequence of high-speed inertial profiler, light-weight profiler, walking profiler (slow-speed profiler) and reference measurement. Before conducting the profile measurement, all profilers had to pass the height sensor static test and the bounce test, as well as calibrate the distance measurement instrumentation (DMI) on a 95-m (500-foot) DMI calibration site. The high-speed and light-weight profilers were asked to conduct five repeat runs at each site, while walking-speed profilers were only asked to take one to three repeat runs depending on the available time. Only data from the right wheel path were collected for analysis.

3.4 Data Preparation

Before the data could be analyzed, the quality of the profile data needed to be checked and confirmed to avoid elevation spikes, incorrect start locations, wrong test sections, and missing data. Nine profiler devices were excluded from the analysis because of these problems.

In order to reduce the data analysis work and include a variety of profiler models, only one profiler of each model and type was selected for performance evaluation in this investigation. Table 3-3 shows the main characteristics of the profilers selected for evaluation. For some devices that had several profilers of the same make and model attending the test, their profiles and computed IRI values were compared and found to be very similar. Eleven high-speed, six light-weight and three walking-speed/slow-speed profilers were selected for the profiler performance evaluation.

Since the different profilers used different length of lead-in sections in the tests, the profile data for the 160-m (528-ft) test sections were extracted from the original raw data and written as new ERD files, which can be opened with ProVAL (Profile Viewing and Analysis) or RoadRuf (Road Profile Analysis) Software.

Table 3-3 Main Characteristics of the Profilers for Selected Evaluation

Profiler Type	Number of Devices	Measurement Method	Reporting Interval	Footprint	Operation Speed
High-speed	11	Height Sensor and Accelerometer	2.5 – 7.6 cm (0.98–3 inch)	Less than 2.54 cm (1 inch)	64 km/h (40 mph)
Light-weight	6				12.8 – 40 km/h (8 – 25 mph)
Walking-speed	3	Inclinometer	24.13 cm (9.5inch)	3-6 cm (1.2 – 2.5 inch) at diameter	8 – 40 km/h (5 – 25 mph)
Rod and Level	1	Level Measurement	12 cm (4.75 inch)	7 cm (2.76 inch)	Less than 8km/h (5 mph)

ProVAL is an engineering software application that allows users to view and analyze pavement profiles in many different ways and it was developed by the FHWA and the Transtec Group, Inc (Chang and et al., 2006). ProVAL was used to compute the IRI values and conduct the cross-correlation analysis.

RoadRuf (Road Profile Analysis Software) is an integrated set of computer tools for interpreting longitudinal road roughness profile data (Sayers and Karamihas, 1996). This software, developed by UMTRI, was used to do profile spectrum analysis using Power Spectral Density (PSD).

CHAPTER 4 DATA ANALYSIS AND RESULTS

Profilers should produce accurate measures of both smoothness indices and longitudinal profile on different pavement surface types. However, many different factors may contribute to the variability of a profile measurement. These include the operator, the profiler used, the calibration of the profiler, the environment (temperature, humidity, wind and etc.), and the time elapsed between measurements.

4.1 IRI Repeatability and Reproducibility

Generally, the term precision is used to indicate the closeness of agreement between independent test results obtained under stipulated conditions. Two types of precision, termed repeatability and reproducibility are commonly used for describing the variability of a measurement method (ISO 5725-1, 1994). The repeatability is determined based on independent test results obtained using the same profiler and operator within short interval of time. The reproducibility is measured by using test results obtained using the same method but with different operators and/or profilers.

The IRI is the most used standard smoothness index because it is strongly correlated to many kinds of vehicle response. It is used in pavement condition monitoring and construction specification. A 250 mm moving average filter is used before the IRI computation to simulate the envelope effect of the vehicle tires (Sayers and Karamihas, 1996). The effect of moving average filter is like a low pass filter with cut-off length equal to the base length in the average. After this filter, the profile is smoother and the influence of profile dip such as cracking on IRI is reduced but not removed.

4.1.1. IRI Repeatability

The IRI repeatability is evaluated based on the standard deviation of repeated IRI values from different profile measurements of the same profiler at the same site. A large standard deviation indicates less repeatability. The use of coefficient of variance (COV) is not recommended for profile measurement because the lower COV on rough pavements under the same variability may incorrectly suggest that the profilers are more repeatable on rough sections than on smooth sections (Karamihas and et al., 1999). Another reason for avoiding normalization is that most pay incentive and disincentive adjustment schemes use similar IRI ranges on both smooth and rough pavements.

Table 4-1 shows the repeatability of IRI values for different profilers on the five test sites. One walking profiler that only had only one measurement at each site is excluded. Poor repeatability was observed for some of the inertial profilers on the JCP (site 5) probably due to the effect of the joints. The walking-speed profilers are not influenced because their footprints can bridge over the joints. Relatively good repeatability was observed on the other four sites for inertial profilers, and the repeatability was better on the fine-textured HMA sites than the coarse-textured HMA site.

The comparison also shows that the repeatability is degraded on the coarse textured HMA pavement site. One possible reason is that laser height sensors usually work by projecting an image on the ground, detecting its position when viewed at an angle, and determining the distance by triangulation (Sayers and Karamihas, 1998). This technology has large variability in the height output if the image is small relative to the scale of the texture feature.

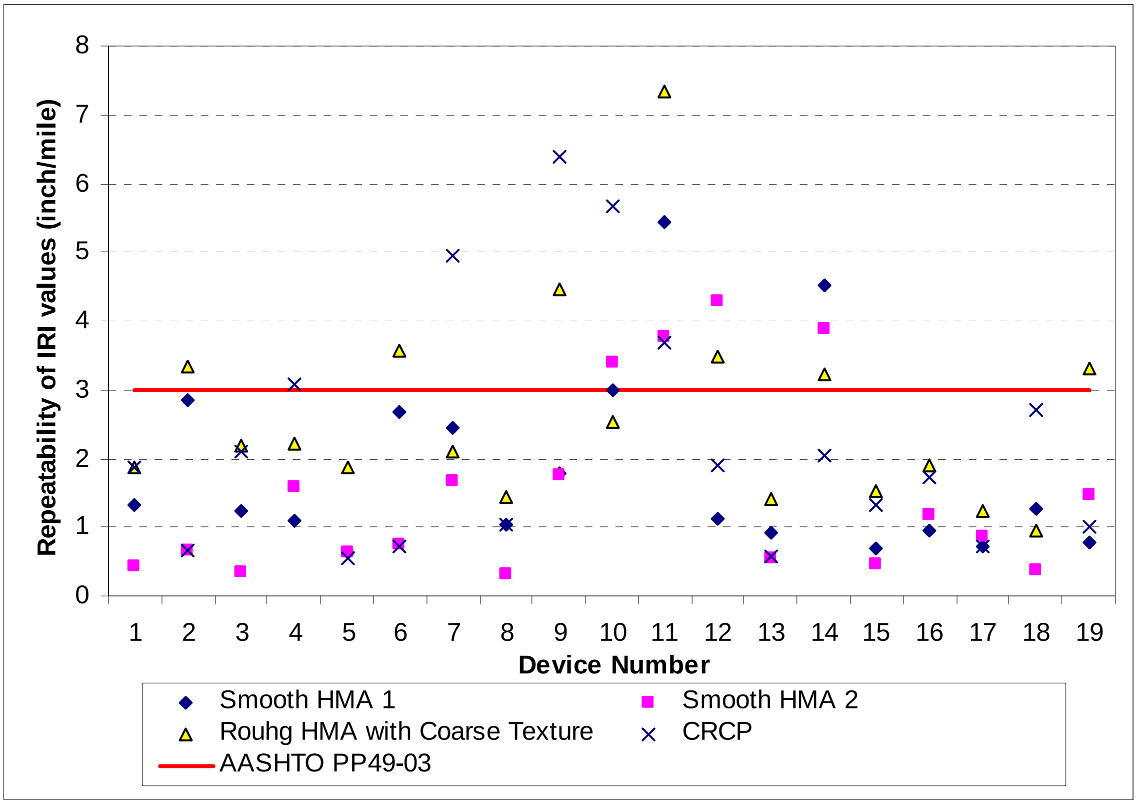
Table 4-1 Repeatability of IRI for Tested Profiler at Five Sites (inch/mi)

Device Number*	Type	Site 1 Smooth HMA	Site 2 Smooth HMA	Site 3 Rough HMA	Site 4 CRCP	Site 5 JCP
1	HS	1.32	0.43	1.86	1.88	4.26
2	HS	2.85	0.66	3.34	0.65	6.95
3	HS	1.25	0.34	2.19	2.11	6.87
4	HS	1.08	1.59	2.22	3.07	2.30
5	HS	0.62	0.63	1.87	0.55	9.36
6	HS	2.69	0.75	3.57	0.72	-
7	HS	2.45	1.66	2.09	4.94	20.87
8	HS	1.05	0.32	1.43	1.04	7.81
9	HS	1.79	1.75	4.46	6.40	9.41
10	HS	3.00	3.40	2.53	5.66	4.14
11	HS	5.45	3.77	7.33	3.67	17.75
Average	HS	2.14	1.39	2.99	2.79	8.41
12	LW	1.11	4.30	3.47	1.90	11.67
13	LW	0.91	0.56	1.41	0.58	4.07
14	LW	4.52	3.88	3.21	2.05	6.22
15	LW	0.70	0.45	1.52	1.31	4.33
16	LW	0.96	1.18	1.91	1.73	3.18
17	LW	0.72	0.85e	1.24	0.73	2.46
Average	LW	1.49	1.87	2.13	1.38	5.32
18	WS	1.28	0.38	0.95	2.71	0.45
19	WS	0.78	1.48	3.32	1.01	-
Average	WS	1.03	0.93	2.14	1.86	0.45

* These numbers do not agree with those in the original experiment to prevent the identification of the various specific devices.

** 1 inch/mi = 0.015786 m/km.

The AASHTO PP 49-03 (and the Tex-1001-S) standard requires a standard deviation in the IRI no greater than three inches/mile, which was fully met by 11 profilers (58% of 19 profilers) and 60 runs (79% of 76 runs) on HMA and CRCP sites. Figure 4.1 summarizes the results on the first four sites, excluding the JCP site. Only three devices (4, 17, and 18, one from each type) can satisfy the repeatability requirements on all five sites.



* High-speed: 1–11; Light-weight: 12–17; Walking: 18–19.

** 1 inch/mi = 0.015786 m/km.

Figure 4.1 Repeatability of IRI Values on Selected Sites

4.1.2. IRI Reproducibility

The IRI reproducibility is a measure of how well two different profiling devices are able to measure the same IRI value at the same site. Reproducibility is important because highway agencies or contractors often use different brands of the same type of profiler. Since different vendors use different component, software, and assembly procedures, profilers have not always demonstrated good reproducibility. The influence of profiler operator is neglected here because profilers that are operated by common users will more closely represent their field performance.

There are two methods used to compute the reproducibility of the same type of profilers (high-speed and light-weight). The simplest method is to compute the standard deviation of the average values from different profilers of the same type. However, this method does not consider the repeatability of each profiler in the reproducibility. A better method is presented in ISO 5725; this method decomposes the reproducibility as the sum of total repeatability and between-device variance, as shown in Equation (4.1), (4.2) and (4.3).

$$S_R = \sqrt{S_r^2 + S_b^2} \tag{4.1}$$

Where: S_R – Reproducibility;

S_r – Total repeatability;

S_b – Between-device deviation.

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$$S_r = \sqrt{\frac{\sum_{i=1}^{p}(n_i - 1)s_i^2}{\sum_{i=1}^{p}(n_i - 1)}} \tag{4.2}$$

Where: n_i – Number of test results for profiler i;

s_i^2 – Variance of tested results for profiler i;

p – Number of profilers of the same type.

$$S_b = \sqrt{\frac{s_d^2 - s_r^2}{n}} \tag{4.3}$$

Where: $s_d^2 = \frac{1}{p-1}\sum_{i=1}^{p} n_i(\bar{y}_i - \bar{\bar{y}})^2$, $n = \frac{1}{p-1}\left(\sum_{i=1}^{p} n_i - \frac{\sum_{i=1}^{p} n_i^2}{\sum_{i=1}^{p} n_i}\right)$;

$\bar{y}_i$ – Average of tested results for profiler i;

$\bar{\bar{y}}$ – Average of total tested results for all profilers in the same type.

The reproducibility of walking-speed profilers was not calculated because not enough repetitions were available. Table 4-2 presents the reproducibility calculated based on the ISO 5725 method. It is noted that high-speed profilers have better reproducibility than light-weight profilers on HMA pavement sites, and vise versa on concrete pavement sites. In general, the profilers have lower level of reproducibility than repeatability. However, the reproducibility follows a similar trend to the repeatability; the reproducibility is worse on coarse textured HMA pavement and JCP than on smooth HMA pavements and CRCP.

Table 4-2 Reproducibility of High-speed and Light-weight Profilers (inch/mi)

Statistics	Total Repeatability		Between-Device Dev.		Reproducibility	
	HS	LW	HS	LW	HS	LW
Site 1 Smooth HMA	2.51	2.02	2.01	3.27	3.22	3.84
Site 2 Smooth HMA	1.81	2.46	1.53	1.26	2.37	2.76
Site 3 Rough HMA	3.40	2.30	3.82	7.54	5.11	7.38
Site 4 CRCP	3.45	1.49	2.13	2.06	4.05	2.55
Site 5 JCP	10.60	6.14	8.02	11.68	13.29	13.20

* 1 inch/mi = 0.015786 m/km.

4.2 IRI Accuracy

Profiler accuracy is a function of how closely a profiling device measures the true profile and the resulting smoothness indices relative this true profile. Accuracy can only be judged when the reference profile is believed to produce the true profile. The profiler accuracy is computed as the bias between the average IRI of the tested profiler and the average IRI of the reference device from multiple runs on the same site. In accordance with ASTM E-1364, rod and level measurements with 4.75-inch recording intervals were used as the true profile for evaluating the accuracy of the IRI and profiles of the devices investigated. Though the static rod and level measurement is considered as the most accurate road profile, it is labor sensitive and has been questioned by previous research because it cannot properly measure some of the needed short wavelength content.

Table 4-3 shows the bias of IRI values for different profilers on four test sites. Generally small bias was found on three sites. The bias was very high for the rough HMA pavement site which includes OGFC and SMA surfaces, probably due to the influence of coarse texture. The high-speed and light-weight profilers have smaller footprints and sampling intervals than rod and level reference measurement, which can capture the short wavelength content of the macro-texture. Thus, the rod and level may simply miss rough features of very short duration, and at the same time the large sampling interval leads to aliasing errors (Karamihas, 2005). The first phenomenon leads to underestimations of the IRI by reference device, and the second phenomenon causes roughness to be overestimated. The final result is dependent on the properties of the road surface. The test data showed that most IRI values measured by inertial profilers are greater than those measured with the reference device, which indicates that the influence of missing short wavelength content is more significant than the aliasing effect for reference device.

Table 4-3 also shows the coefficient of determination (R^2) of linear regression equation between IRI values from tested profilers and those from reference devices at different sites. A very good linear relationship is found for all the tested profilers because all the coefficients of determination (R^2 values) are greater than 0.97. This indicates that a good correlation exists between the different profilers and the reference device for measuring IRI even with different IRI biases.

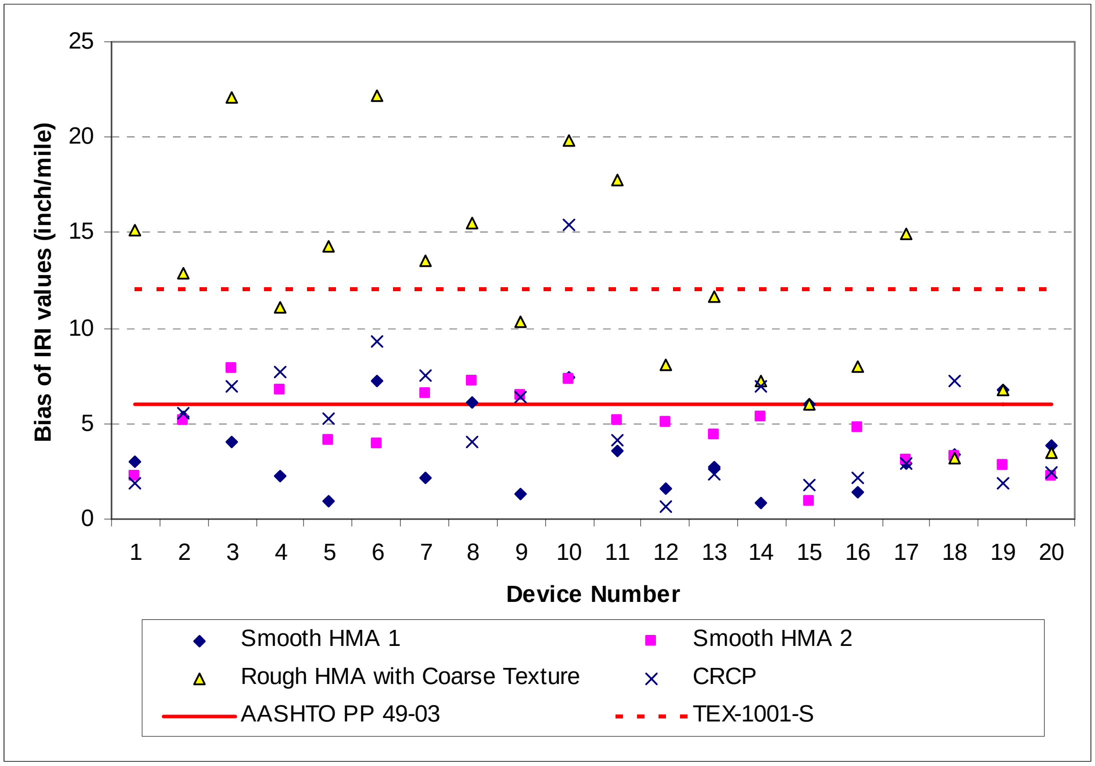
Table 4-3 Bias of IRI for Tested Profiler at Five Sites (inch/mi)

Device Number	Type	Site 1 Smooth HMA	Site 2 Smooth HMA	Site 3 Rough HMA	Site 4 CRCP	R^2
1	HS	2.98	2.30	15.12	1.90	0.9983
2	HS	5.38	5.20	12.84	5.52	0.9991
3	HS	4.02	7.90	22.06	6.92	0.9872
4	HS	2.28	6.78	11.12	7.66	0.9868
5	HS	0.92	4.16	14.30	5.26	0.989
6	HS	7.26	3.96	22.18	9.27	0.9957
7	HS	2.20	6.60	13.52	7.56	0.9859
8	HS	6.12	7.20	15.52	4.04	0.9951
9	HS	1.32	6.52	10.30	6.40	0.9859
10	HS	7.46	7.36	19.86	15.44	0.9782
11	HS	3.58	5.18	17.78	4.10	0.9944
Average*	HS	3.96	5.74	15.87	6.73	0.9905
12	LW	-1.60	5.08	8.08	0.64	0.9815
13	LW	2.75	4.46	11.68	2.38	0.9958
14	LW	0.80	5.32	-7.22	6.96	0.9887
15	LW	-6.00	0.92	6.02	1.82	0.9737
16	LW	1.38	4.78	7.98	2.16	0.9936
17	LW	2.96	3.10	14.90	2.90	0.9975
Average*	LW	2.58	3.94	9.31	2.81	0.9885
18	WS	3.40	3.27	-3.20	7.23	0.9889
19	WS	-6.75	-2.85	6.75	-1.87	0.9869
20	WS	3.90	2.30	3.50	2.40	0.9972
Average*	WS	5.33	2.58	5.13	2.14	0.9910

* The average of the absolute of bias.

** 1 inch/mi = 0.015786 m/km.

The AASHTO PP 49-03 and Tex-1001-S standards require an IRI bias no greater than 6 inches/miles and 12 inches/mile, respectively. Most of profilers can satisfy the Tex-1001-S standard. Eleven profilers (55% of 20 profilers) and 43 runs (72% of 60 runs) satisfied the AASHTO standard without considering the performance on the more textured HMA pavement. Only two devices (15 and 20) can satisfy the AASHTO standard on all four sites. Generally, the light-weight profilers in this experiment have smaller bias than the high-speed profilers. The absolute value of IRI bias is presented in Figure 4.2.



* High-speed: 1–11; Light-weight: 12–17; Walking: 18–20.

** 1 inch/mi = 0.015786 m/km.

Figure 4.2 Absolute Value of IRI Bias on Selected Sites

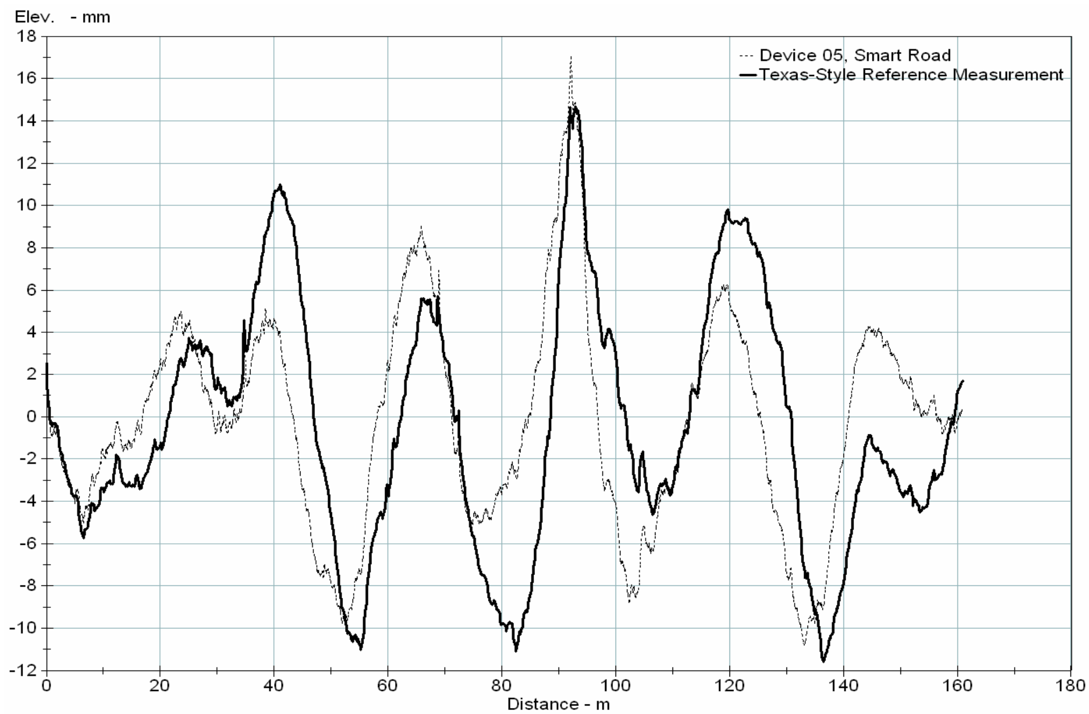
The IRI bias for different profilers varies from site to site. The variation is probably due to different sensors used in the measurement. For example, the difference between the laser and optical profilers is most likely the sensor footprint. The diameters of the footprint of laser sensors range from 1 to 5 mm and the optical profilers use a rectangular footprint that is 6 mm long and 150 mm wide. This large footprint means that the optical profilers are much less prone to variations caused by short features in the road, such as a narrow crack. The operating speed of profilers also has an effect on the performance of equipments. The lower speed will result in smaller acceleration sensed by accelerometer that is easily disturbed by the same scale of electronic noise.

The walking-speed profilers have relatively smaller bias even on rough HMA pavement with coarse texture because their footprint and sampling interval are similar to those of the rod and level measurements. Walking-speed profilers were developed to simulate the rod and level measurements but at a higher speed. These devices, as the rod and level, cannot sense cracks, or detect profile features that are small relative to the distance between its two supporting feet.

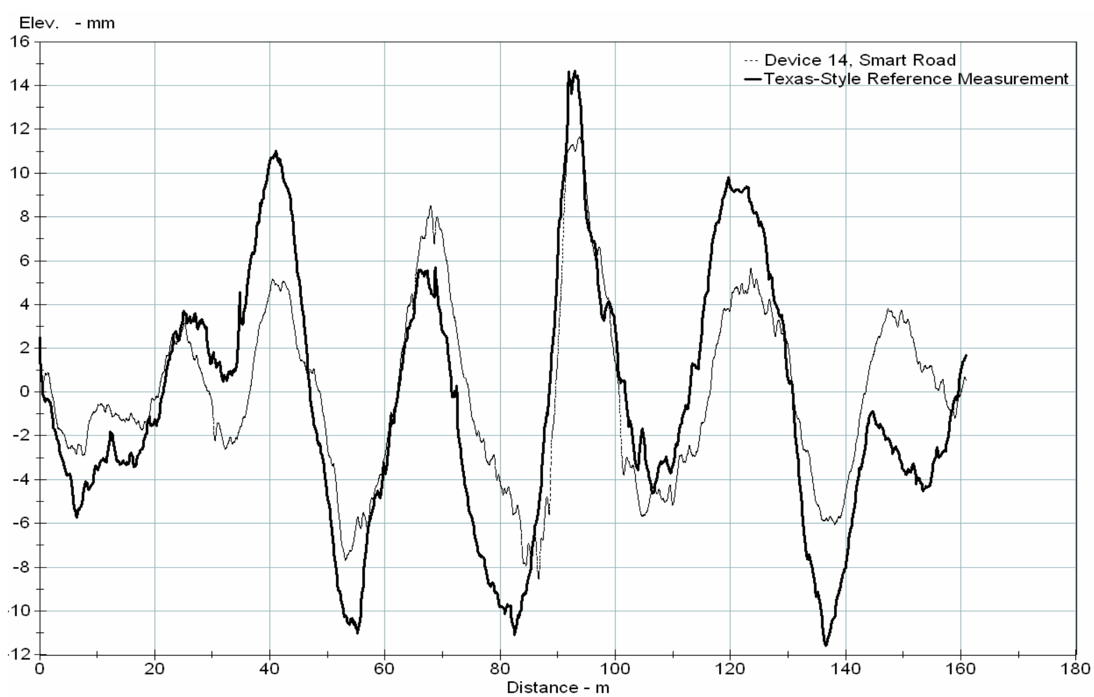
4.3 Visual Inspection of Profiles

A complete profiler evaluation should include the comparison of both summary indices (such as IRI) and the measured profiles. The comparison of IRI values provides little information about spatial distribution of the roughness along the wheel path and potential sources of profile measurement problems. Direct comparison of profiles can reveal some of the measurement problems using only a few repeat runs.

Visual inspection of profile plots is a useful diagnostic tool although it does not provide a quantitative measure of agreement between profiles. Good accuracy of computed IRI values cannot guarantee good agreement between profiles because IRI values may agree because of compensating errors. For example, the IRI values for Site 1 from devices 5 and 14 have less than 2 inch/mile bias. However, clear profile elevation differences are found between the profiles along the wheel path, as shown in Figure 4.3. Similar differences can be observed on the CRCP site 4, on which the profile measured with devices 1 and 12 have small IRI biases but high differences in the elevation profiles (Figure 4.4). It should be noted that the profiles measured by the walking-speed profilers and the rod and level reference were filtered using a 300 ft high-pass filter to eliminate the influence of long wavelength that can't be sampled by high-speed or light-weight profilers. The detailed algorithm of high-pass filter can be found on the manual of the RoadRuf software (Sayers and Karamihas, 1996).

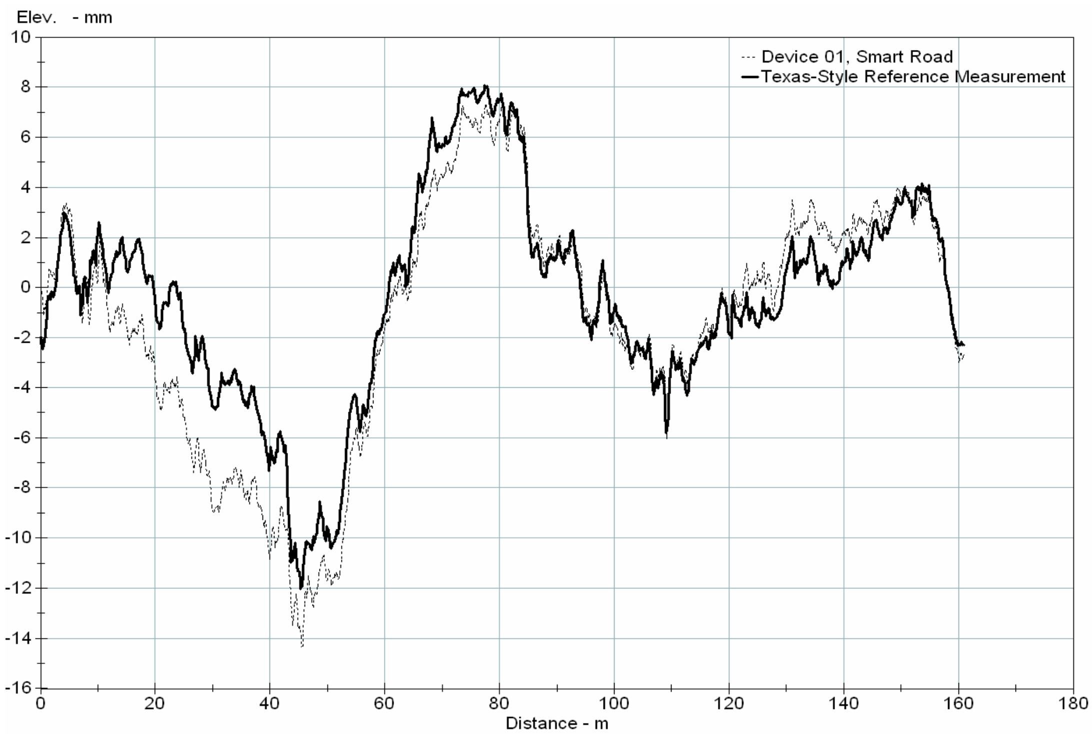


(a)



(b)

Figure 4.3 Site 1 Profile Measured with the Reference Device and (a) Device 5 and (b) Device 14.



(a)

(b)

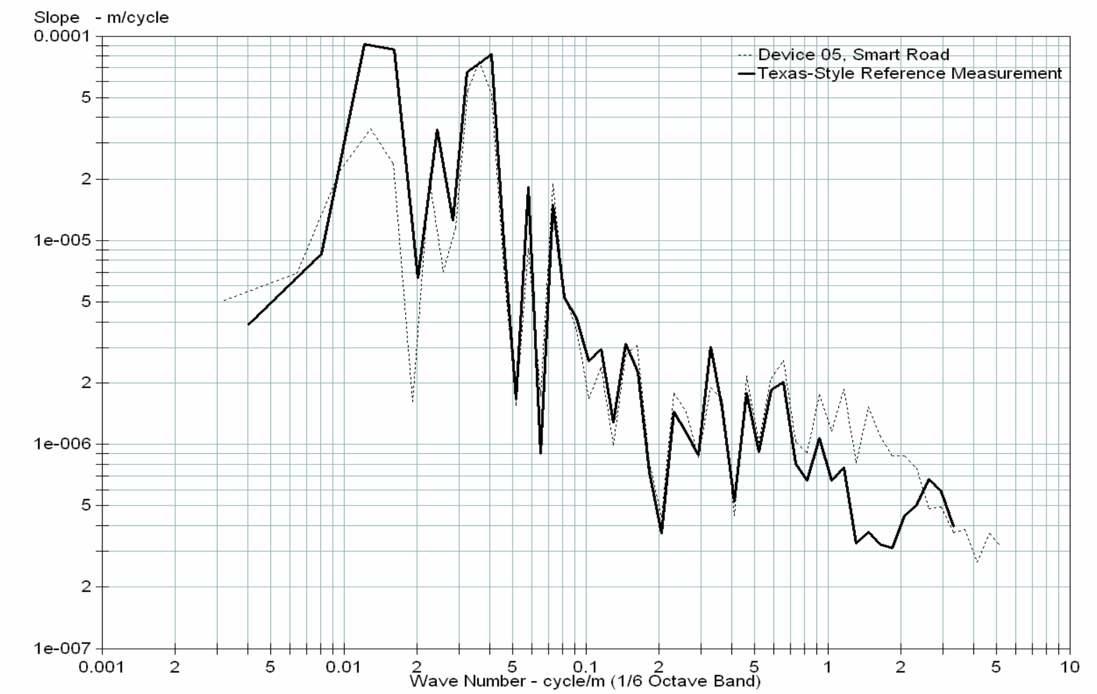
Figure 4.4 Site 4 Profile Measured with the Reference Device and

(a) Device 1 and (b) Device 12

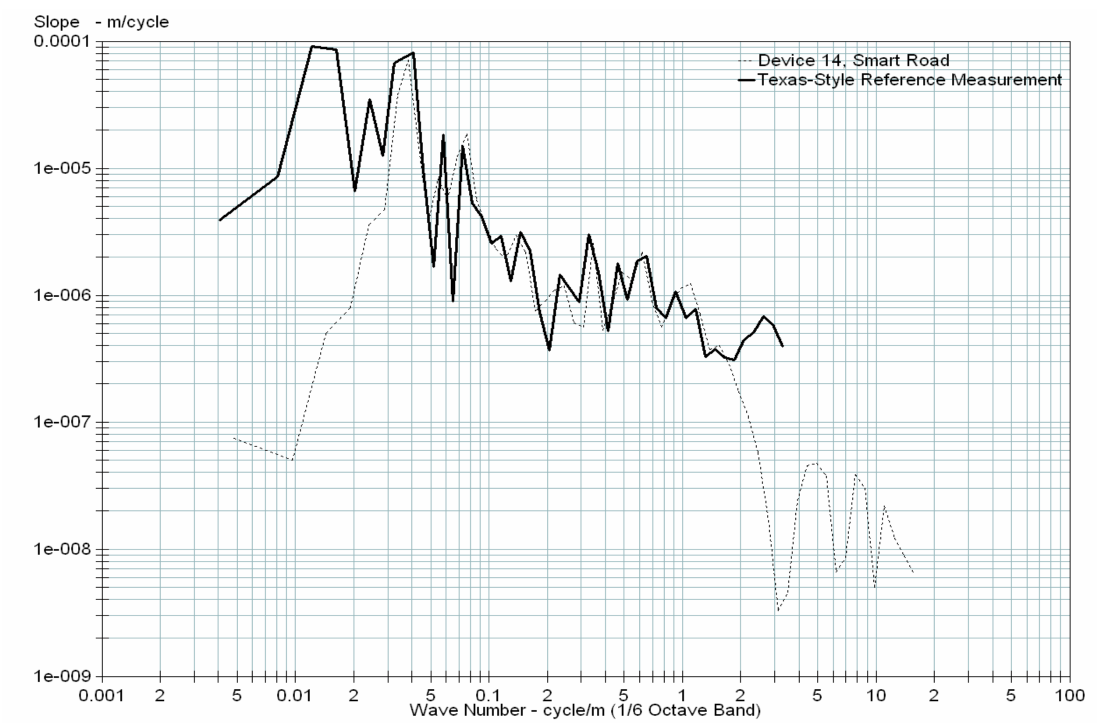
The poor agreement between the profiles measured by the various profilers evaluated and the reference profile could be due to three factors: (1) lateral profile variation because the operators could not follow exactly the same wheel path; (2) equipment differences, including the sensors, electronics, and the software used to compute profile from the transducer signals; and (3) the true profile of the pavement might have changed between runs because of temperature and other environmental effects. The experiment was not controlled sufficiently to quantify the sources of variation, which may explain some of the differences observed in the profiles.

In order to examine the contribution of different wavelength content to the profile, the Power Spectral Density (PSD) plots of these profile slopes and the reference profile slopes over different wave numbers for site 1 and 4 are shown in Figure 4.5 and Figure 4.6 respectively. The prominent wavelengths present in a profile produce marked spikes in the PSD plot. The figure shows good agreement between the profiles measured with the evaluated profilers and the reference profile in the range of wave number from 0.03 to 0.8 cycles/m. However, poor agreement is found outside of this range. The agreement in the central range allows the profiles to produce similar IRI values because the IRI is most sensitive to wavelength from 1.3 to 30 m (Sayers and Karamihas, 1996).

The poor agreement at low wave numbers, less than 0.03 cycles/m, is attributed to the long wavelengths that are captured by the reference static measurements but not by the inertial profilers and that are not fully filtered out in the 300 ft high pass filter. The poor agreement at high wave numbers, greater than 0.8 cycle/m, are probably due to could be due to the the short wavelength content that are not captured by the reference static measurement but are measured by the inertial profilers. The theory and application of PSD analysis will be discussed detailed later on this thesis.

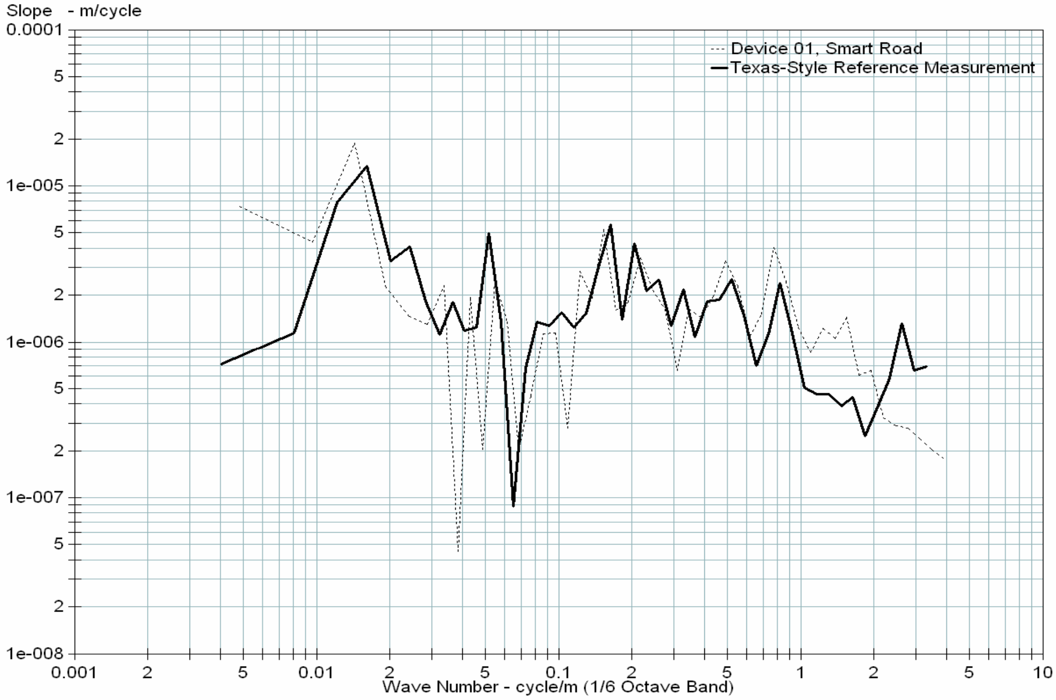


(a)

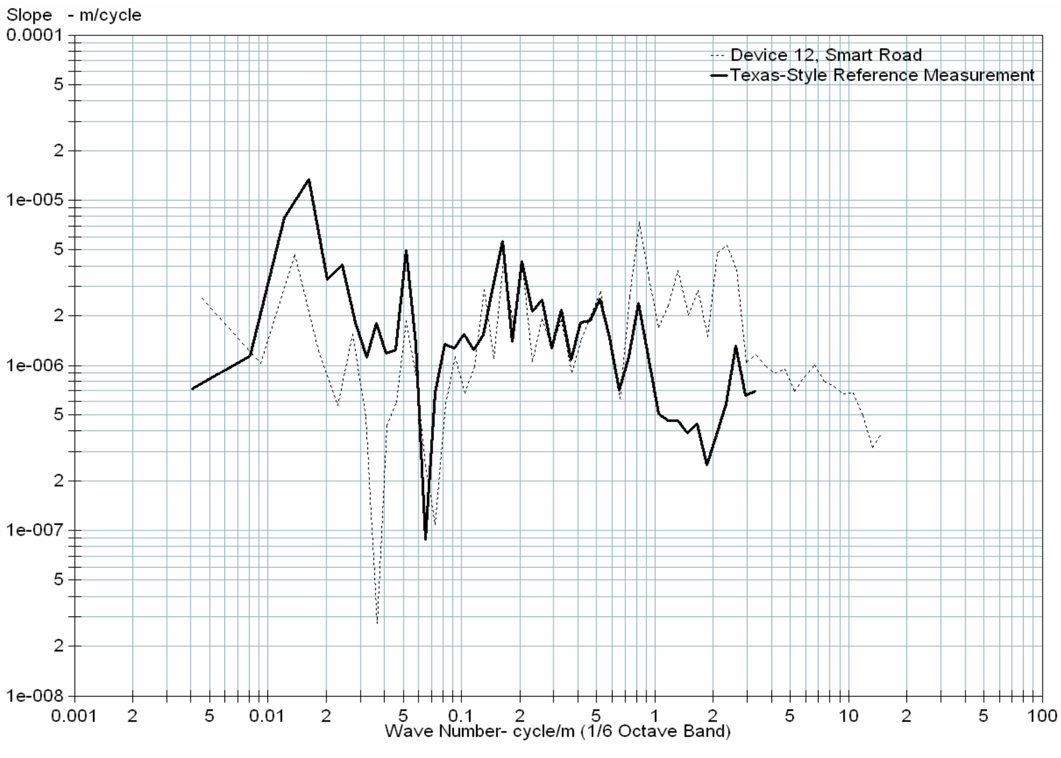


(b)

Figure 4.5 PSD of Profile Slopes Reference Device and (a) Device 5 and (b) Device 14 on Site 1



(a)

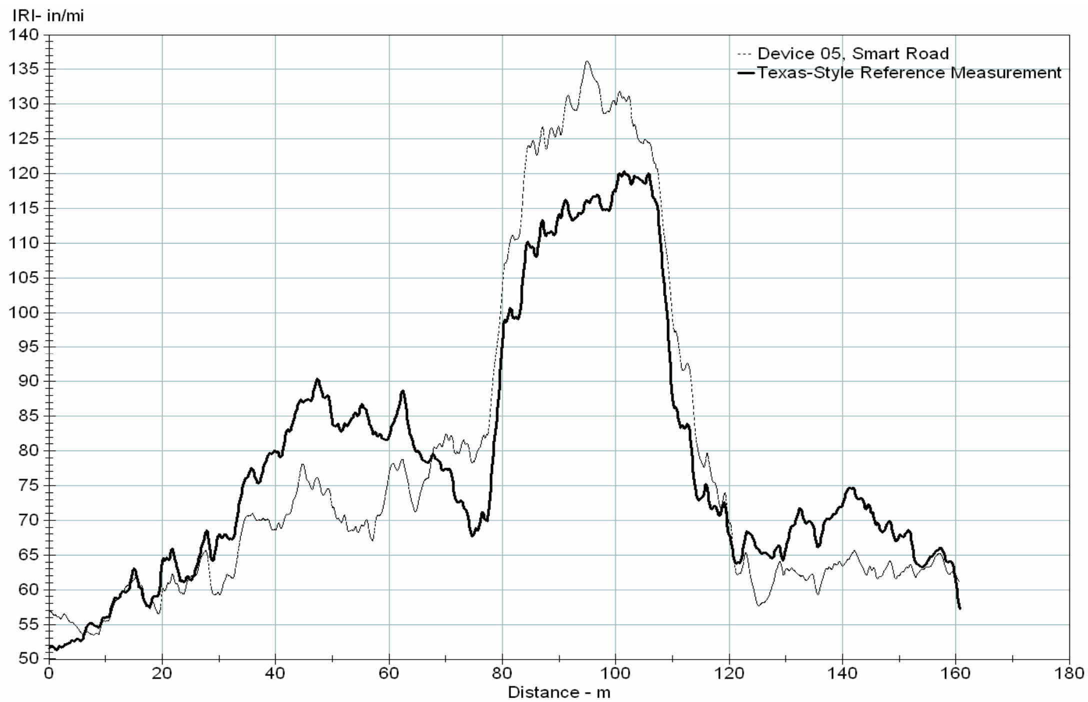


(b)

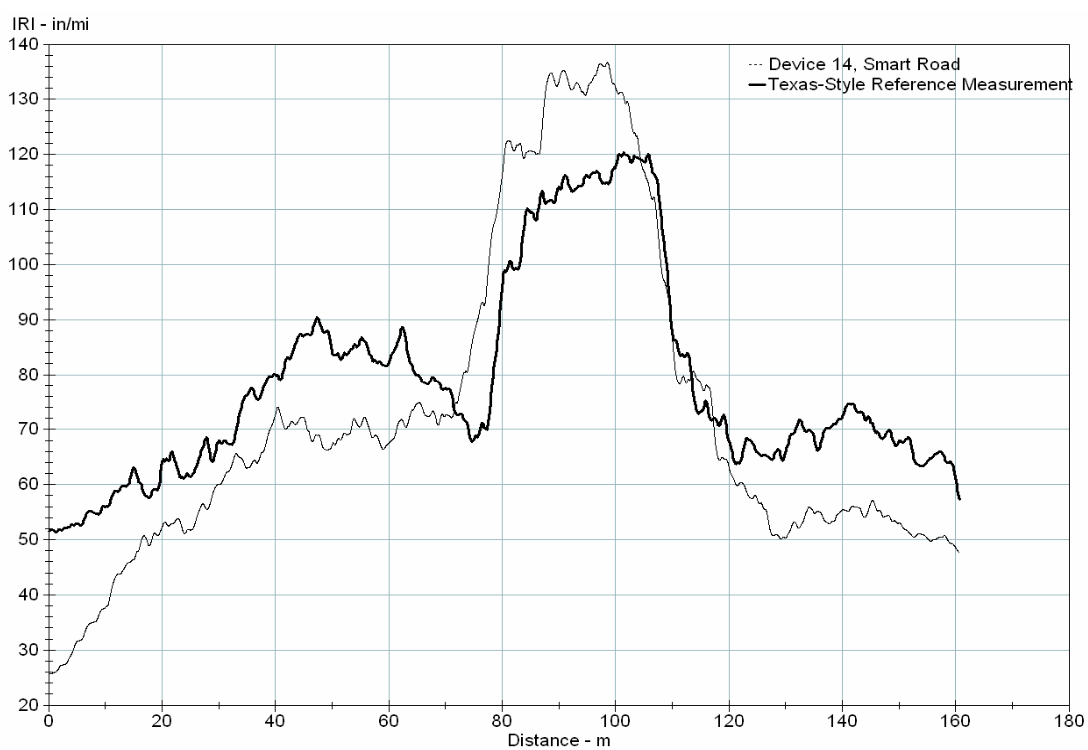
Figure 4.6 PSD of Profile Slopes Reference Device and (a) Device 1 and (b) Device 12 on Site 4

As illustrated in this example, it is important to recognize that a close agreement on the IRI from repeat runs or from two devices does not necessarily mean that the two devices are collecting similar profile data. The same conclusion can be obtained from the spatial distribution of IRI along the wheel path. The IRI computed at 30 feet interval from different profilers may differ at many points although the overall IRI for the sites are very similar, as shown in the Figure 4.7 and Figure 4.8.

Finally, it is important to note that it may not be appropriate to always specify accuracy requirements for both IRI and profiles for profiler certification. When the profiler measurements are used in quality control (QC) or quality assurance (QA), it is necessary to have accurate profile measurements, or roughness spatial distribution, so that contractors can find sections with localized high roughness and apply corrective actions. Some States have set their smoothness specification based on short segment such as 50 ft, which require detailed longitudinal road profiles. However, the profilers may need to meet less stringent certification requirements when they are used for network-level roughness measurement only because people's feelings about rideability are not very sensitive to the difference on profile elevations.

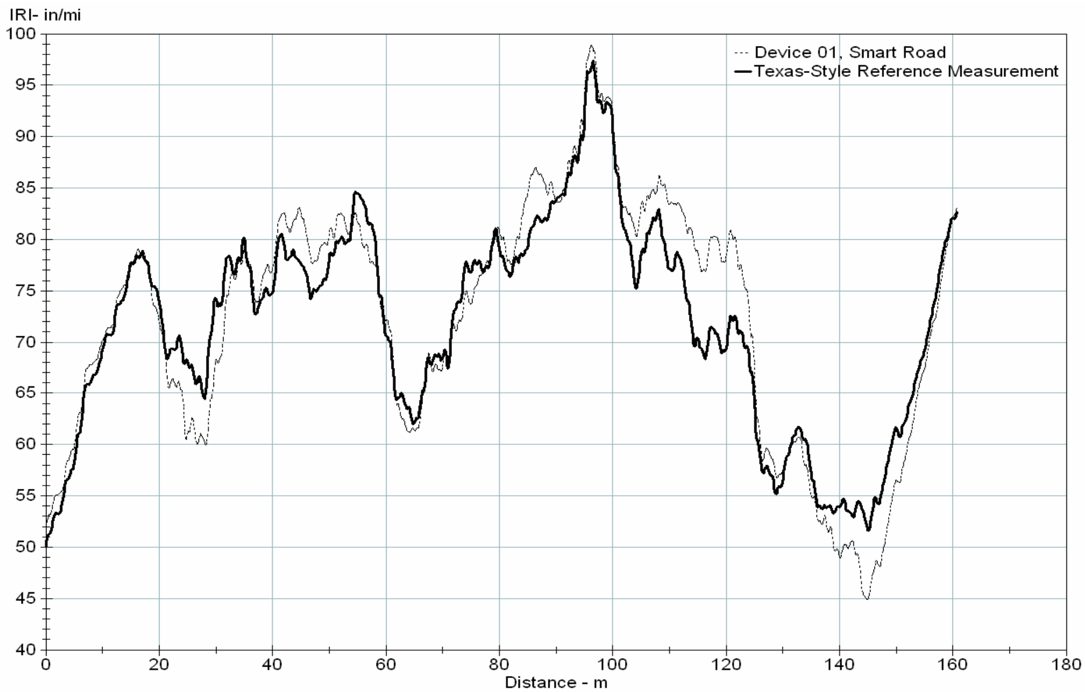


(a)

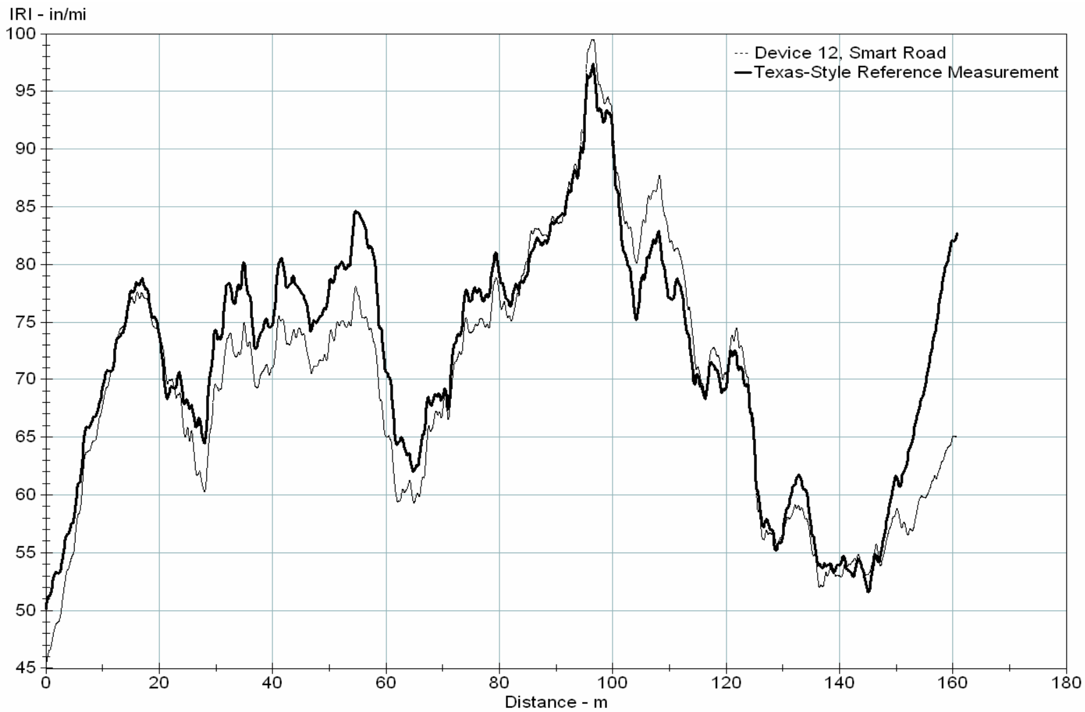


(b)

Figure 4.7 Roughness Spatial Distribution on Site 1 from the Reference Device and (a) Device 5 and (b) Device 14 (30 Feet Interval)



(a)



(b)

Figure 4.8 Roughness Spatial Distribution on Site 4 from the Reference Device and (a) Device 1 and (b) Device 12 (30 Feet Interval)

4.4 Accuracy of Profile Elevations

Conventional profiler accuracy criteria use point-to-point statistics (precision and bias) to evaluate the repeatability and accuracy of profile measurements. This approach is used in ASTM E-950, AASHTO PP 49-03 and TEX 1001 standards. In these methods, the standard deviation of repeat measurements at each reporting interval is computed for each wheelpath surveyed. The average of the standard deviations determines the repeatability.

Profile accuracy is evaluated by comparing the profile data with the corresponding reference measurement on the same site. Because the profilers evaluated and the reference measurement did not use the same sampled wavelength range and reporting intervals, it was necessary to filter and interpolate the profiles. The reference profiles were first filtered using the same filter type used by the profiler under evalaution. For this purpose, the owner or manufacturer of each profiler provided the cutoff length of their filter (usually 300 feet). After filtering, the test profiles were interpolated to get the same reporting interval as the reference profile.

The average profile on the different sites was computed by computing the point-to-point average of the repeat runs by the same profiler. The point-to-point differences between the average profile and the reference profile on a given site were then computed. The average of these differences or the absolute values of the differences is the bias of the profile from a given profiler with respect to the reference profile. The ASTM E-950 standard uses the absolute values of the differences to compute the total bias. The AASHTO PP 49-03 and Tex-1001-S methods use both the absolute and algebraic differences.

Highway agencies or contractors would expect that a profiler would provide good

IRI measurements if it is meets the accuracy criteria defined in these methods. This assumption is examined in the following analysis. Table 4-4 and Table 4-5 compare the profile elevations biases computed using the average of the point-to-point differences on profile elevations, and the average of the absolute values of the point-to-point differences determined for each site and device, respectively.

Table 4-4 Biases of Profile Elevations (mm)

(Average of Point-to-Point Differences on Profile Elevations)

Device Number	Type	Site 1 Smooth HMA	Site 2 Smooth HMA	Site 3 Rough HMA	Site 4 CRCP
1	HS	12.79	0.25	0.69	5.18
2	HS	-4.47	6.93	1.53	6.18
3	HS	1.65	-7.38	2.72	2.92
4	HS	0.64	9.45	3.70	-3.37
5	HS	-3.73	7.75	-1.86	5.14
6	HS	1.46	-7.21	6.85	5.29
7	HS	0.36	8.62	5.61	5.04
8	HS	4.85	8.05	0.54	5.29
9	HS	4.92	7.16	1.55	-5.28
10	HS	15.18	1.45	1.89	13.02
11	HS	-2.60	7.29	0.97	5.78
Average	HS	4.79	6.50	2.54	5.68
12	LW	7.38	-7.41	1.74	3.61
13	LW	4.62	7.24	0.69	5.76
14	LW	3.36	7.46	1.66	5.83
15	LW	6.77	–	–	2.93
16	LW	-8.84	6.27	2.07	5.65
17	LW	2.09	6.83	0.76	-5.87
Average	LW	5.51	7.04	1.38	4.94
18	WS	4.09	4.09	3.49	3.61
19	WS	0.71	4.58	-3.63	2.58
20	WS	-2.02	-4.14	2.49	3.13
Average	WS	2.27	4.27	3.20	3.11

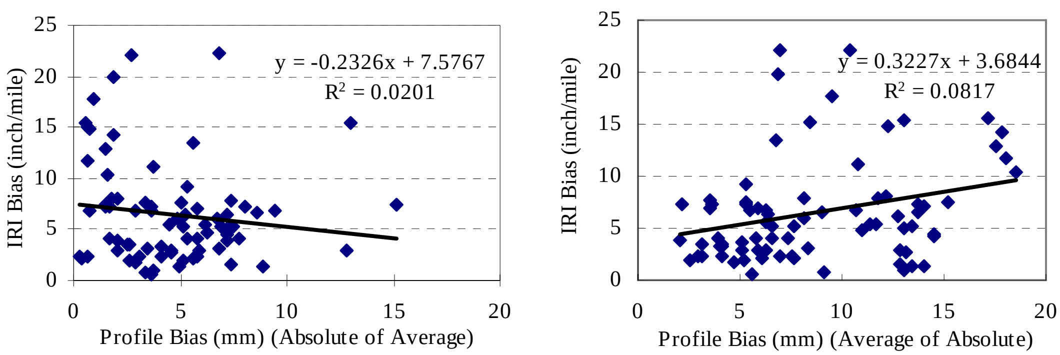
Table 4-5 Biases of Profile Elevations (mm)

(Average of the Absolute Values of the Point-to-Point Differences on Profile Elevations)

Device Number	Type	Site 1 Smooth HMA	Site 2 Smooth HMA	Site 3 Rough HMA	Site 4 CRCP
1	HS	12.81	2.96	8.43	5.18
2	HS	11.68	13.43	17.50	6.28
3	HS	3.92	8.13	6.94	3.54
4	HS	7.50	10.64	10.82	3.56
5	HS	13.04	14.48	17.84	6.57
6	HS	5.28	7.40	10.37	5.31
7	HS	6.08	9.02	6.77	5.27
8	HS	12.73	14.05	17.19	6.56
9	HS	14.06	13.71	18.52	6.36
10	HS	15.19	2.17	6.85	13.02
11	HS	5.05	7.63	9.49	5.78
Average	HS	9.76	9.42	11.88	6.13
12	LW	12.83	13.02	12.20	5.62
13	LW	13.17	14.49	18.04	6.99
14	LW	9.13	11.38	13.76	5.85
1f5	LW	8.14	–	36.05	4.69
16	LW	13.44	11.00	11.79	7.64
17	LW	6.26	8.37	12.27	5.87
Average	LW	10.50	11.65	17.35	6.11
18	WS	4.09	4.11	4.02	3.60
19	WS	5.48	5.06	6.28	2.59
20	WS	2.02	4.14	3.13	3.13
Average	WS	3.86	4.44	4.48	3.11

It must be noted that this investigation did not fully followed the ASTM E 950 method, which requires a minimum of 10 profile measurements over a distance of 320 m (1056 feet) at 0.3-m (1 foot) intervals. The profiler round-up used only five repeat measurements over a distance of 160 m (0.1 mile).

The calculation of the algebraic average of point-to-point differences on profile elevations often compensates individual errors, which results in a low total bias. For this reason, the average of the absolute values of the point-to-point differences on profile elevations was adopted for use in this investigation. However, there was no correlation between either of the two profile elevation biases and the IRI bias because the two coefficients of determination (R^2) are both less than 0.1, as shown in Figure 4.9. This means that a profile measurement that is close to the reference profile by the criteria defined in point-to-point statistics does not necessarily provide an IRI that is equivalently close to the IRI of the reference profile. For example, devices 1, 8, 11, 13 and 17 has profile elevation biases from 0.02 inch (0.54 mm) to 0.03 inch (0.76 mm) on site 3, which are close to the 0.02 inch (0.5 mm) criteria in AASHTO PP 49. However, the corresponding IRI biases are 12 to 18 inches/mile that are much greater than 6inches/mile criteria. A possible reason for the poor accuracy in the profiler elevation measurements is that their starting point may be slightly shifted and that no synchronization (phase shift) was performed before the point-to-point statistics computation.



(a) **(b)**

Figure 4.9 Correlations between the IRI Bias and the Absolute Value of the Averages of (a) Point-to-Point; and (b) Absolute Values of Differences

The lack of agreement between profile elevation bias and IRI bias may be explained by the many combinations of relative locations between the evaluated profiles and reference profile that provide the same value of profile bias. The evaluated profiles may have different shapes, offsets and elevation measurements but still have similar bias relative to the reference profile. Since the main application of profilers for many years has been the collection of IRI values for network-level pavement evaluation, many of the profilers may be optimized to produce the correct IRI but not necessarily the true profile. From the point of view of frequency response, a profile can be decomposed of many components with different wavelengths and the amplitude of each component is approximately proportional to the corresponding wavelength. Thus, short wavelength features often appear as relatively small deviations in elevation. The treatment of each elevation value as a distinct measurement weakens the ability of detecting short wavelength measurement problems (Karamihas, 2002 (a) and 2005).

4.5 Cross Correlation of Profiles

The Cross-Correlation method has been proposed as an alternative for rating the repeatability, reproducibility, and accuracy of profiles (Karamihas, 2002 (a)). In this method, the profiles are filtered to include only the wavelength of interest and synchronized, and the coefficient of cross correlation is computed using the discrete form of a convolution integral, as shown in the Equation (4.3). It yields a -100 to 100 rating of agreement between two profiles. A high rating using this method is obtained only if the two profiles have the same overall roughness level and the roughness occurs in the same locations within the profiles. This method can be used to evaluate the repeatability and reproducibility of profiles. If one of the measurements is considered as the true profile, the agreement level could be interpreted as profile accuracy.

The cross-correlation method can be used to compare the IRI for two profiles. Both profiles are first filtered with the IRI filter contained in the IRI algorithm. The cross-correlation method is then applied to these filtered profiles to obtain a cross-correlation rating. The profile elevation and slope gains after IRI filter are shown in Figure 4.10 (Karamihas, 2005).

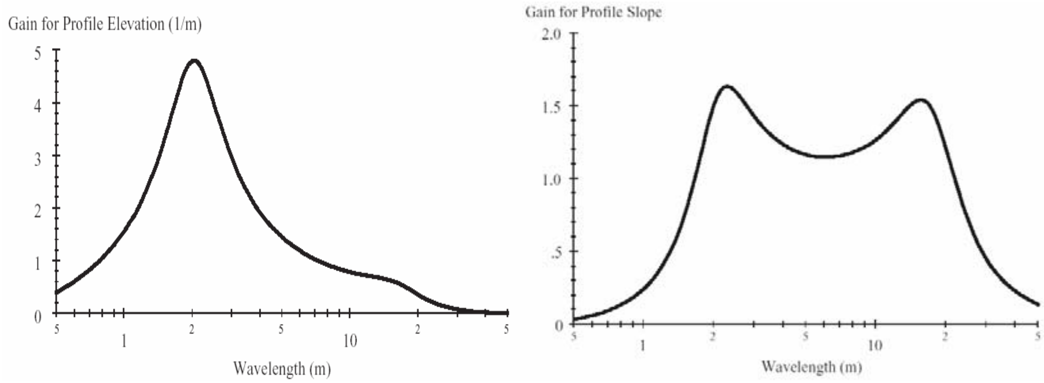


Figure 4.10 Profile Elevations and Slope Gain after IRI Filter

4.5.1. Profile Repeatability using Cross-Correlation

Table 4-6 shows the cross-correlation coefficients of repeated profiles for different profilers at the five test sites for 19 devices. These cross-correlation coefficients are the average of repeated runs for the same profiler. The table shows higher cross-correlation coefficients on smooth HMA sites than on the rough HMA with coarse texture, CRCP and JCP sites. This indicates that profilers have better profile repeatability on smooth HMA with conventional texture.

The relationship between profile repeatability through cross-correlation coefficients (independent variable) and the IRI repeatability variable for high-speed and light-weight profilers on different sites was analyzed using regression analysis. The coefficient of determination (R^2) and significance level (p-value) are presented in Table 4-7. All the t-statistics are less than 0.01, which indicates the cross-correlation coefficients have significant influence on the IRI repeatability. The coefficients of determination are between 0.586 and 0.881, indicating that the profile repeatability can reflect the IRI repeatability quite well and that higher cross-correlation coefficients will provide better IRI repeatability.

Table 4-6 Cross-Correlation Coefficients of Repeated Profiles

Device Number	Type	Site 1 Smooth HMA	Site 2 Smooth HMA	Site 3 Rough HMA	Site 4 CRCP	Site 5 JCP
1	HS	93.5	93.7	87.7	91.4	92.9
2	HS	89.2	96.4	89.8	94.9	83.9
3	HS	92.5	95.0	89.7	90.9	86.8
4	HS	95.8	79.7	84.1	79.8	86.9
5	HS	95.8	96.4	95.3	96.6	87.0
6	HS	85.4	90.9	83.9	95.3	93.5
7	HS	88.8	88.9	85.4	69.7	65.4
8	HS	96.9	97.3	92.4	73.9	72.5
9	HS	94.1	85.0	88.9	58.8	82.6
10	HS	85.2	87.6	77.8	66.3	83.3
11	HS	63.6	64.7	65.7	70.3	68.0
Average	HS	89.16	88.70	85.52	80.71	82.07
12	LW	92.1	86.4	81.2	89.5	83.1
13	LW	97.1	97.7	94.7	97.8	93.6
14	LW	82.1	77.8	73.0	67.0	69.3
15	LW	96.8	96.4	94.1	92.2	90.4
16	LW	94.9	96.6	93.8	88.2	93.3
17	LW	97.7	95.4	94.3	95.9	88.0
Average	LW	93.45	91.72	88.52	88.43	86.29
18	WS	93.5	93.7	87.7	91.4	92.9
19	WS	89.2	96.4	89.8	94.9	83.9
Average	WS	91.35	95.05	88.75	93.15	88.40

Table 4-7 Regression Analysis between Cross-correlation Coefficients and IRI Repeatability

Regression Parameter	Site 1 Smooth HMA	Site 2 Smooth HMA	Site 3 Rough HMA	Site 4 CRCP	Site 5 JCP
Coefficient of determination (R^2)	0.881	0.591	0.587	0.709	0.586
p-value for the coefficient of independent variable	2.5E-8	3.13E-4	3.33E-4	2.26E-5	3.43E-4

4.5.2. Profile Accuracy using Cross-Correlation

Table 4-8 shows the cross-correlation coefficients of repeated profile measurements for different profilers at the four test sites, excluding the profilers having one measurement at each site. This analysis found that the profilers are more accurate on smooth HMA sites than on the rough HMA site, similar to the finding from the IRI analysis. The light-weight profilers perform similarly on the CRCP and smooth HMA sites, while the high-speed profilers have lower accuracy on the CRCP site than on smooth HMA sites.

Only five measurements (6.25% of the total combinations of profilers and sites) have their coefficients of cross-correlation greater than 94, which is the profiler certification requirement recommended by Karamihas (2005). None of the profilers met this criteria on the four sites. Thus, this criterion appears to be too stringent for the tested profilers.

Cross correlation of profiles filtered with the IRI filter is meant to represent the agreement in the relevance of two profile shapes. However, it does not provide a direct indication on the agreement between the overall IRI values on a pavement segment. Poor correlation between cross-correlation values and IRI bias was found when considering all the tested data though the IRI bias decreased with increasing cross-correlation level (Figure 4.11). Two profiles with bad cross-correlation can have similar IRI values because the errors on profile shapes could compensate each other when calculating the IRI.

On the other hand, there exists correlation between cross-correlation degree and IRI bias for the tested data having coefficients of cross-correlation greater than 90, as shown in Figure 4.12. This validates the assumption that good cross-correlation between two profiles indicates both similar profile shapes and IRI bias. It would be very useful to find the threshold values of cross-correlation which can provide a reasonable expectation of the IRI value within some desired tolerance.

Table 4-8 Cross-Correlation of Tested and Reference Profiles on Five Sites

Device Number	Type	Site 1 Smooth HMA	Site 2 Smooth HMA	Site 3 Rough HMA	Site 4 CRCP
1	HS	91.98	94.12	78.77	86.10
2	HS	75.34	82.02	70.33	72.60
3	HS	87.16	85.80	87.03	74.90
4	HS	65.48	78.70	77.10	70.17
5	HS	87.46	90.32	79.93	88.30
6	HS	69.98	73.96	56.63	76.97
7	HS	83.46	85.30	76.50	75.33
8	HS	81.94	84.18	77.60	70.03
9	HS	74.60	63.78	70.40	66.73
10	HS	62.32	67.62	80.07	65.60
11	HS	90.30	89.33	84.80	71.87
Average	HS	79.09	81.38	76.29	74.42
12	LW	80.20	86.74	73.70	88.87
13	LW	87.06	90.20	80.73	94.10
14	LW	-	53.40	50.93	37.53
15	LW	72.82	87.70	83.77	85.80
16	LW	69.14	79.62	88.30	84.83
17	LW	90.82	93.98	85.20	91.60
Average	LW	80.01	81.94	77.11	80.46
18	WS	88.40	79.53	65.07	84.80
19	WS	85.20	80.20	76.20	82.80
20	WS	89.60	96.00	63.30	97.80
Average	WS	87.40	88.10	69.75	90.30

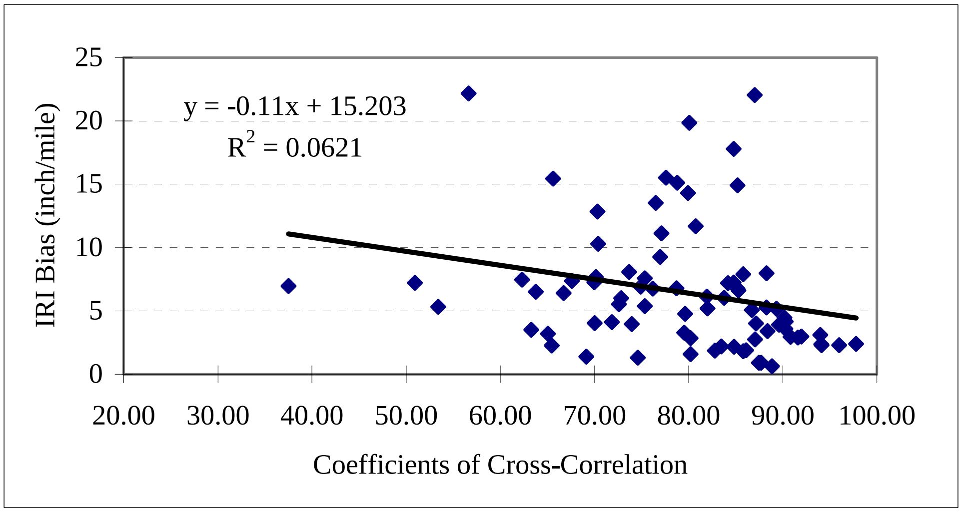


Figure 4.11 Correlations between Cross-Correlation Degree and IRI Bias Considering All the Data

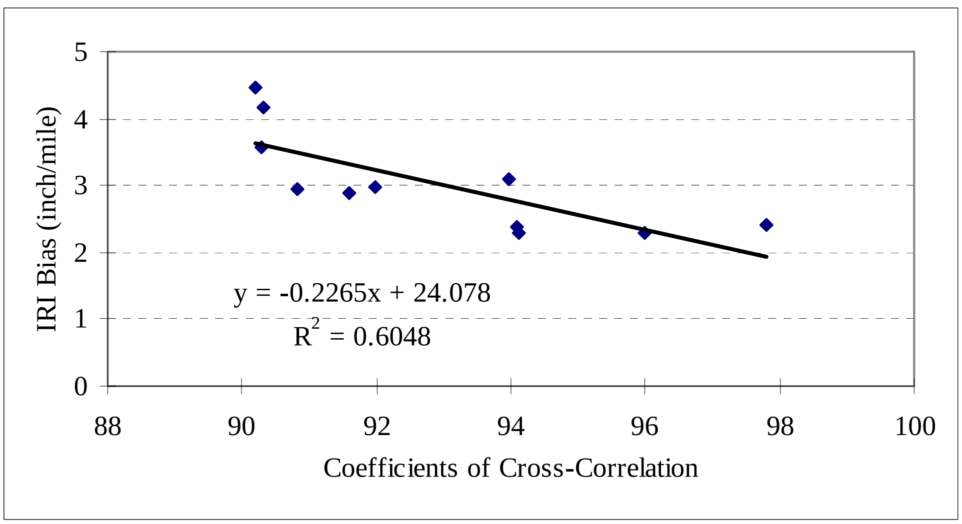


Figure 4.12 Correlations between Cross-Correlation Degree and IRI Bias Considering only data having coefficients of cross-correlation greater than 90

4.6 Summary

Profilers have different features, such as sensor type, footprint, and sampling/recording interval, which affect their ability to measure longitudinal road profile and smoothness index accurately. In general, the light-weight profilers in this experiment have smaller bias than high-speed profilers. As expect, the walking-speed profilers have good IRI repeatability and bias on all test sites because they have similar footprints and sampling interval with the rod and level measurement.

The profiler accuracy appears to be affected by pavement surface characteristics. The high-speed and light-weight profilers have good IRI repeatability, reproducibility and bias on smooth HMA pavement and CRCP. The repeatability and reproducibility is low on JCP due to the influence of joints and has a slight decrease on rough HMA pavement. The coarse texture on HMA pavement also induces an increase of IRI bias probably due to the influence short wavelengths that are missed by rod and level measurements.

Generally there is no correlation between profile elevation bias and IRI bias, possibly because there are many combinations of profile shapes that produce the same value of profile bias. This means that a profiler certified by the criteria defined in point-to-point statistics will not necessarily measure an IRI close to the IRI from reference device. Cross-correlation appears to be a more effective method to evaluate profile repeatability and accuracy. High cross-correlation coefficients produce good IRI repeatability and there exists correlation between cross-correlation degree and IRI bias when the coefficients of cross-correlation are greater than 90.

It is important to recognize that the agreement on IRI values does not necessarily mean that the profilers are collecting similar profile data. The lack of agreement may be due to many reasons, such as equipments performance or lateral variation.

CHAPTER 5 EFFECT OF PROFILER GAIN ERROR ON IRI BIAS

5.1 Power Spectral Density (PSD) of Road Profile

Road profile encompasses a spectrum of many sinusoidal wavelengths. The Power Spectral Density (PSD) is a statistical representation of the importance of the various wavelengths contained in the profile. Fourier Transform can be used to covert the profile to a frequency domain from the time (distance) domain. When the amplitude is scaled in a manner that indicates the distribution of the power (variance) of profile over frequency, this conversion is called PSD.

Mathematically, the derivation of PSD for a continuous time series signal is introduced using Equations 5.1 to 5.4.

Fourier Transform: $$X(w) = \int_{+\infty}^{-\infty} X(t)e^{-jwt}dt \qquad (5.1)$$

Signal Energy: $$\int_{-\infty}^{+\infty} |x(t)|^2 dt = \frac{1}{2\pi}\int_{-\infty}^{+\infty} |x(w)|^2 dw = \int_{-\infty}^{+\infty} |x(f)|^2 df \qquad (5.2)$$

Power: $$P_{av} = \lim_{T-\infty} \frac{1}{2T}\int_{-\infty}^{+\infty} |x_T(t)|^2 dt = \lim_{T-\infty} \frac{1}{2T}\int_{-\infty}^{+\infty} |x_T(f)|^2 df = \int_{-\infty}^{+\infty}\left[\lim_{T-\infty} \frac{|x_T(f)|^2}{2T}\right]df \qquad (5.3)$$

(When the mean of signal is zero, the power is equivalent to the variance of the signal)

PSD: $$S_x(f) = \lim_{T-\infty} \frac{|x_T(f)|^2}{2T} \qquad (5.4)$$

An alternative definition of PSD is the Fourier Transform of the autocorrelation sequence of the time series ($R_{tt}(t)$), as shown in Equation 5.5.

PSD: $S_x(f) = \int_{-\infty}^{\infty} R_{tt}(t) e^{-j2\pi ft} dt$ (5.5)

In practice, the profile is considered a stationary stochastic process and the distance replace the time domain. Different algorithms can be used for estimating the PSD, such as using Fast Fourier Transform (FFT) or autoregressive modeling (Newland, 1984). When the PSD is calculated with a constant bandwidth method, the plots in a log-log diagram will give an appearance, or visual impression, which over-emphasizes at high frequency the fluctuation of the PSD generated by the real power distribution and by the statistical noise, as shown in Figure 5.1. Thus the third octave-band is used as the frequency bandwidth in the PSD calculation. The mean PSD over each 1/3 octave band is computed as the PSD at the center wave number. The wave number (cycle/m) is the inverse of wavelength (m).

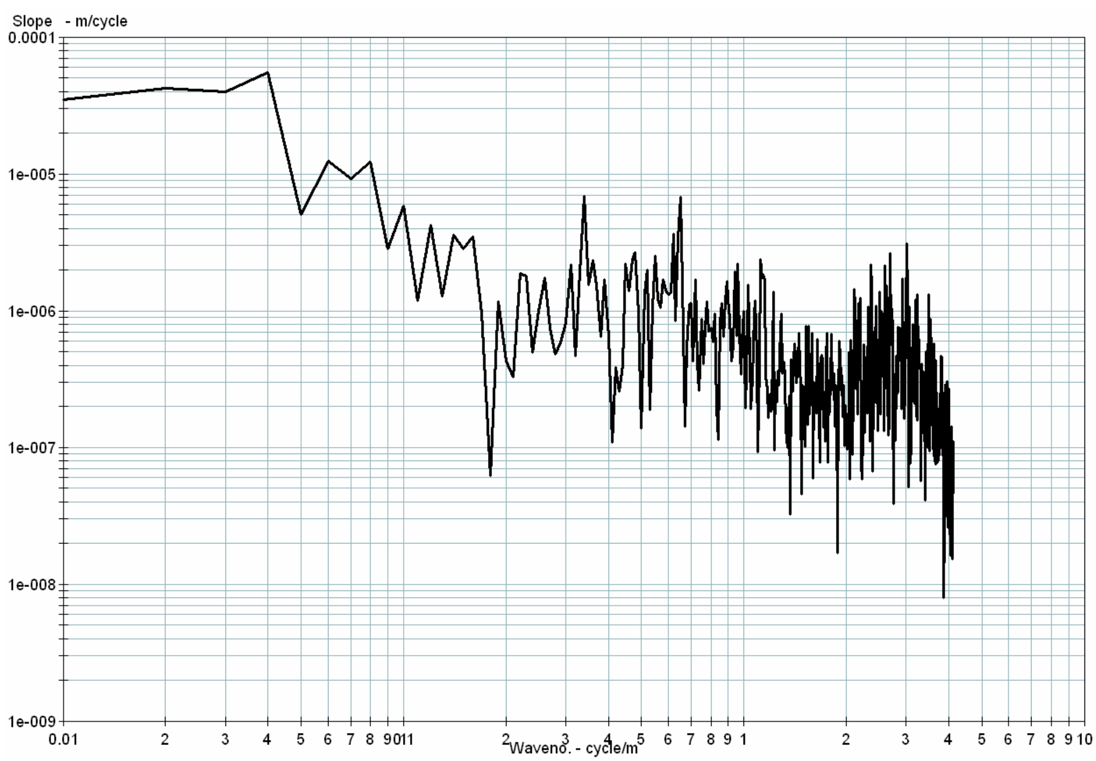


Figure 5.1 PSD Plot of Profile Slope on Site 1 (Constant Bandwidth)

Since it represents the power per unit of frequency, the dimensions of the PSD amplitude are power (mm^2) divided by cycle/m, which is mm^2 m/cycle. As plotted in Figure 5.2, the amplitudes for low wave numbers (long wavelengths) are much higher than for high wave numbers (short wavelengths), which indicates that long wavelengths are associated with high amplitudes of elevation variation. If prominent wavelengths are present in a profile, such wavelengths will show up as dominant spikes in the PSD plot.

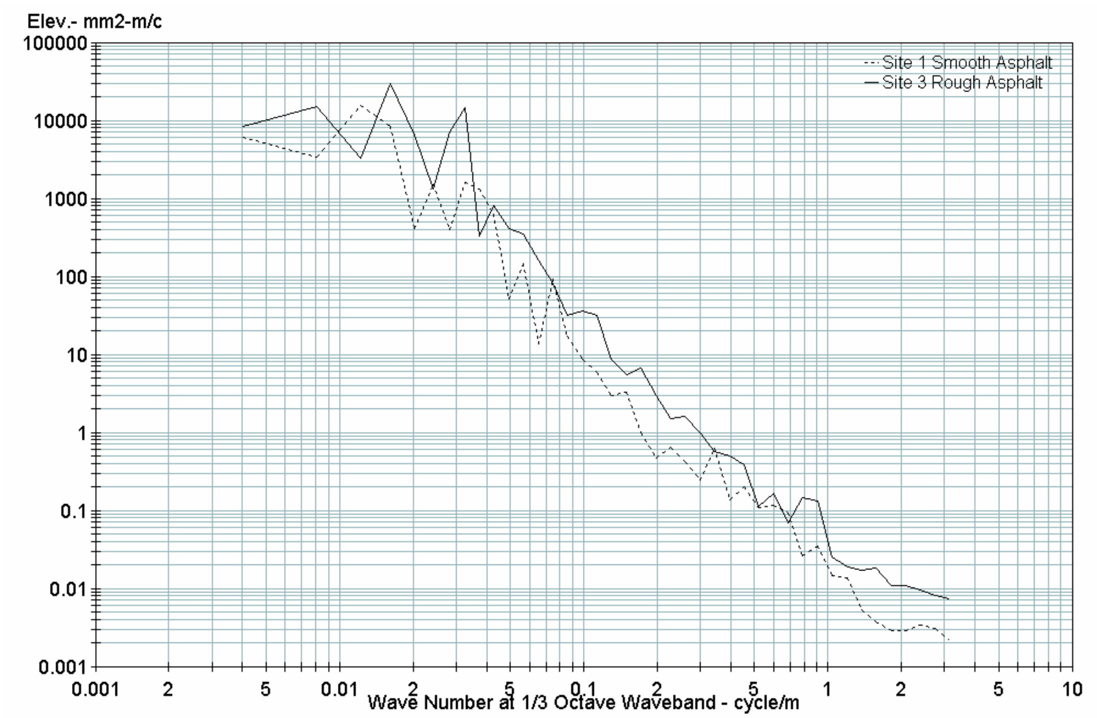


Figure 5.2 PSD of Profile Elevation at Site1 and 3 (1/3 Octave-band)

The PSD function of the profile slope is sometimes used instead of the PSD function of the profile elevation because the basic spectrum of profile slope over the wave numbers is more uniform and shows the differences in the roughness properties better than the spectrum for the profile elevations (Sayers and Karamihas, 1996). As shown in Figure 5.2, the range of PSD for profile elevations spans 7 orders of magnitude. The large difference in amplitude can complicate statistical analysis. In contrast, the PSD of profile slope only covers 3 orders of magnitude (Figure 5.3). In the PSD of profile slope, the dimension of PSD is just the inverse of frequency, which is m/cycle.

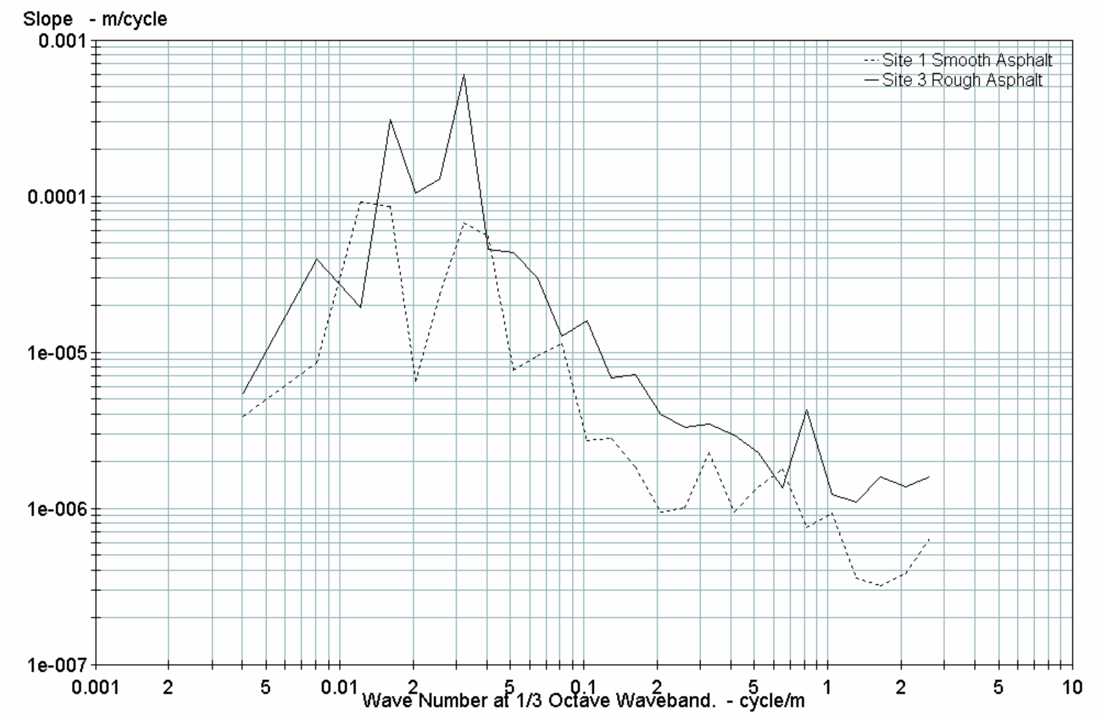


Figure 5.3 PSD of Profile Slope at Site 1 and 3 (Third Octave-band)

The PSD of profiles has been used to develop roughness index (such as RN and RQI) because the distribution of PSD amplitudes represents the roughness level of road surface. The International Standard Organization has also proposed a road classification based on different levels of PSD roughness (ISO 8608, 1995). For example, in Figure 5.2 and Figure 5.3, the solid PSD lines (site 3) have higher amplitudes than the dashed lines (site 1), which confirm that the site 3 has rougher surface than site 1. The PSD roughness is considered a direct statistics from road profile, which is different from IRI because the IRI is an indirect statistics of road profile, computed using a quarter-car simulation. The vehicle manufacturing industry for automobile design, has routinely adopted the PSD of vehicle acceleration, while the IRI is usually used by national and state highway agencies. Lu (2001) discovered that the IRI value can be estimated by the area surrounded by a certain kind of weighted PSD curve and frequency axis.

Furthermore, the PSD of profile is not a summary index and thus it could be used to detect surface type and diagnose periodic wavelength feature caused by pavement distress or measurement errors. For example, measurement errors in the height sensor tend to affect the PSD functions for high wave numbers and errors in the accelerometer or the software that processes the accelerometer tend to affect the PSD for low wave numbers.

5.2 Profiler Gain Error

According to the stochastic process theory, if the input of a linear time-invariable system is a stationary random process, then its output is also a stationary random process. In most cases, the profile measurement is considered as a zero-mean Gaussian ergodic random process (Newland, 1984). In the gain method proposed by Prem (1998), the reference profile measurement is treated as the input, and each repeat profile measurement by the candidate device is treated as output with a linear relationship to the reference profile.

If the profiler is to measure the true profile, the gain value of the profiler's transfer function must be exactly equal to unity over the range of spatial frequency of interest. In reality, however, this does not occur because of limitations associated with the profiler hardware, software, and measurement process (surface characteristics, lateral measurement variation, effect of temperature, etc.). When the gain is not equal to unity, the gain error is defined as the absolute value of the difference between the calculated gain and unity, as shown in Equation 5.6. The profiler gain error gives the distribution of amplifications or attenuations of the measurement over the relevant wave numbers of interest.

$$\text{Profiler Gain Error} = \left| \frac{G_{Measure}(v)}{G_{\mathrm{Re}\,ference}(v)} - 1 \right| \qquad (5.6)$$

Where: $G_{measure}(v)$ - Spectra of Measured Profile;

$G_{reference}(v)$ - Spectra of Reference Profile (True Profile).

The profiler gain errors in this investigation were calculated according to the following steps:

1. The average tested profiles on different sites were computed from the repeat runs by the same profiler;
2. Profile data were converted from space domain to spatial frequency domain using Power Spectra Density (PSD) analysis.
3. Profile spectra of the measuring profiler and reference device were compared and the gain errors were determined in the range of wave number from 0.02–1.03 cycles/m. This range included the profile contents that the IRI values are most sensitive to, which could be selected from the distribution of profiler slope gains after IRI filter (Figure 4.10).

Figure 5.4 – 5.7 show the profilers gain errors for the 20 tested profilers at site 1 through 4. The profiler gain errors appear nonuniformly distributed across the range of wavelength of interest on each site. The characteristics of the nonuniform distribution appear to be dependent on device and surface types. A general trend is that the highest error was found at the two boundaries of the wave number ranges of interest (0.02–0.08 cycles/m and 0. –1.0 cycles/m).

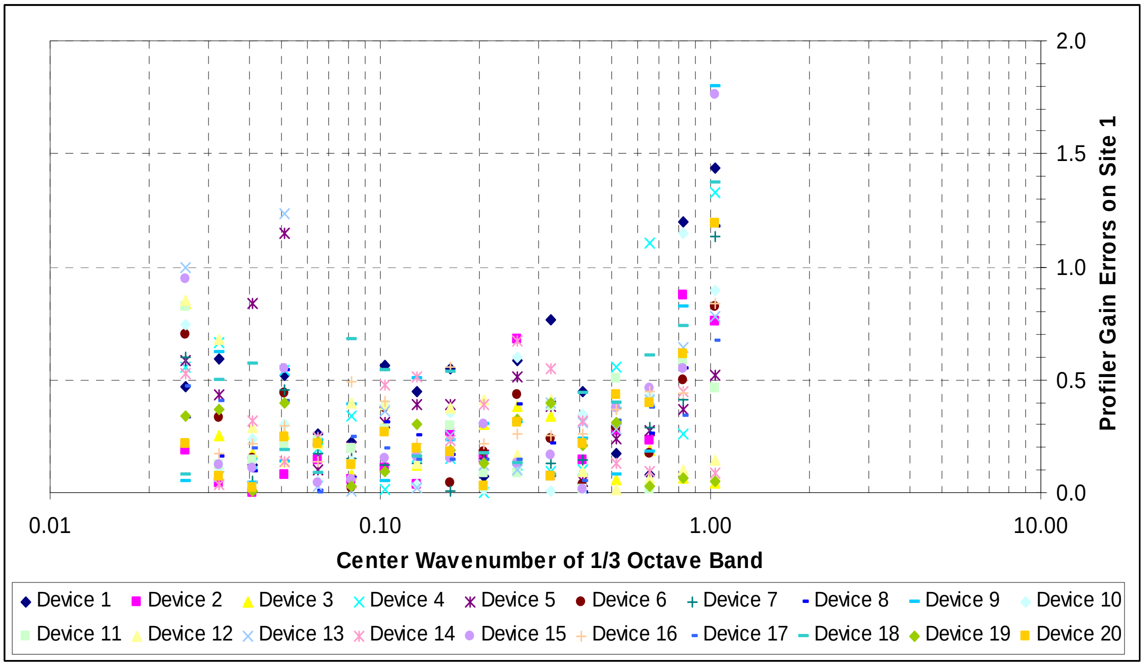


Figure 5.4 Profiler Gain Errors on Site 1

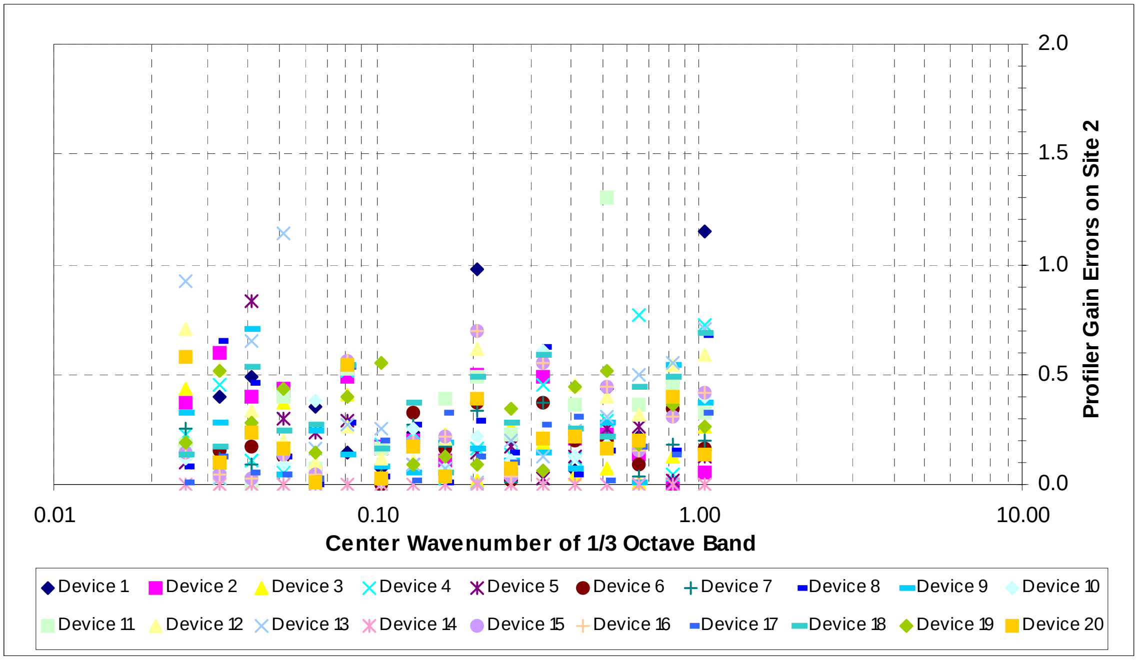


Figure 5.5 Profiler Gain Errors on Site 2

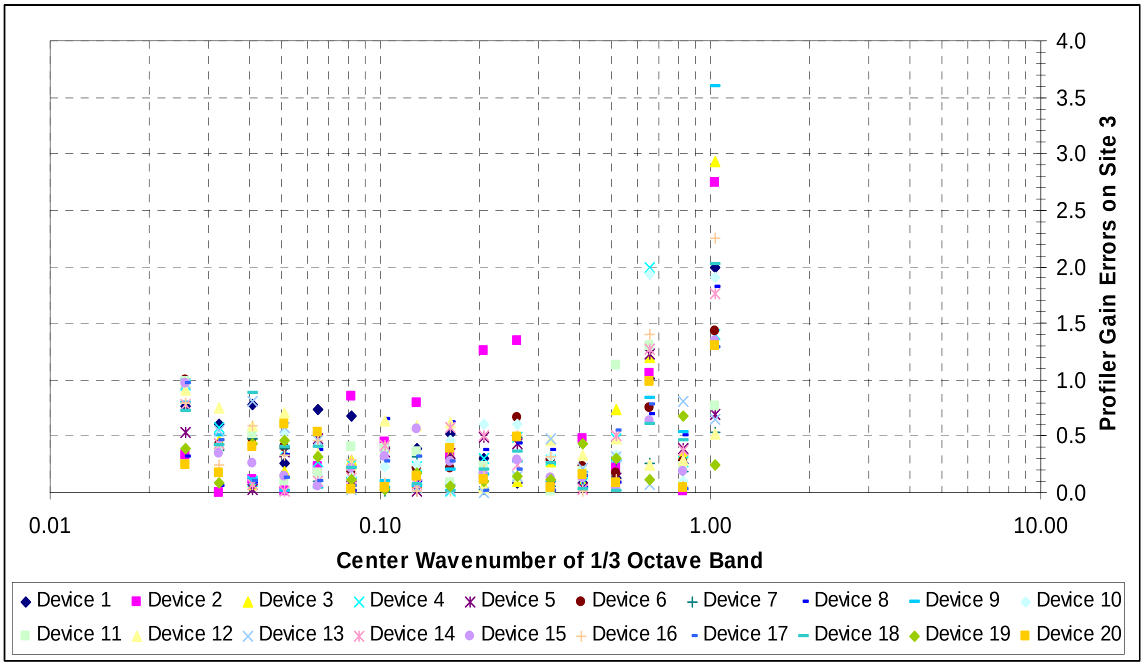


Figure 5.6 Profiler Gain Errors on Site 3

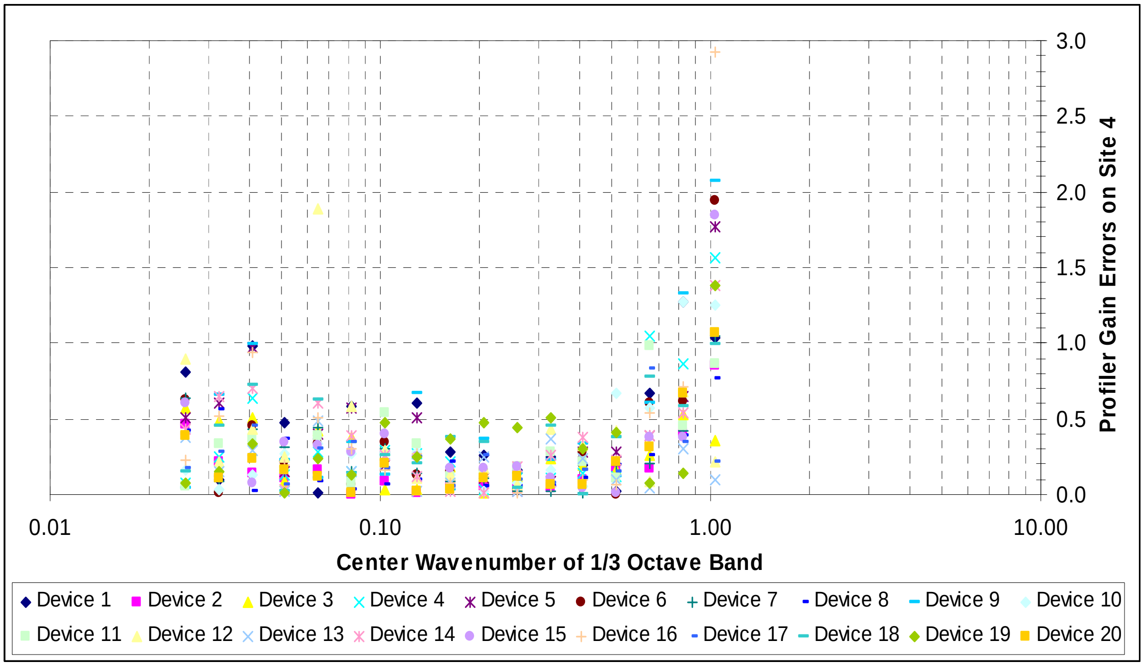


Figure 5.7 Profiler Gain Errors on Site 4

Another finding is that the profilers have higher gain errors over short wavelengths on site 3 than on the other sites. This finding can be better seen from the comparison of mean profiler gain errors on 4 Test Sites (Figure 5.8). This suggests that the coarse texture on site 3 affected the profiler accuracy at short wavelength features, which also explains why the profiles from inertial profilers have worse agreement with the reference profile on coarse-textured HMA surfaces than on HMA pavement with conventional texture.

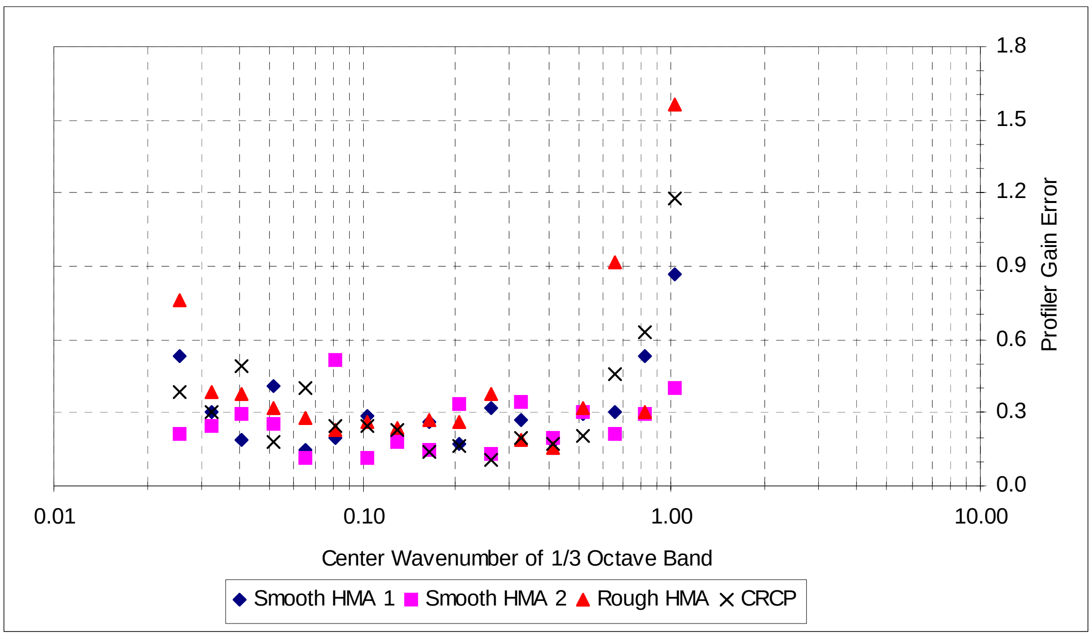


Figure 5.8 Mean Profiler Gain Errors on Selected Test Sites

The distribution of mean profiler gain error for different types of profilers is potted in Figure 5.9. The walking profilers have smaller gain error relative to the reference profile than the inertial profilers on the small wave numbers (long wavelength) because their similar sampling interval with rod and level measurements.

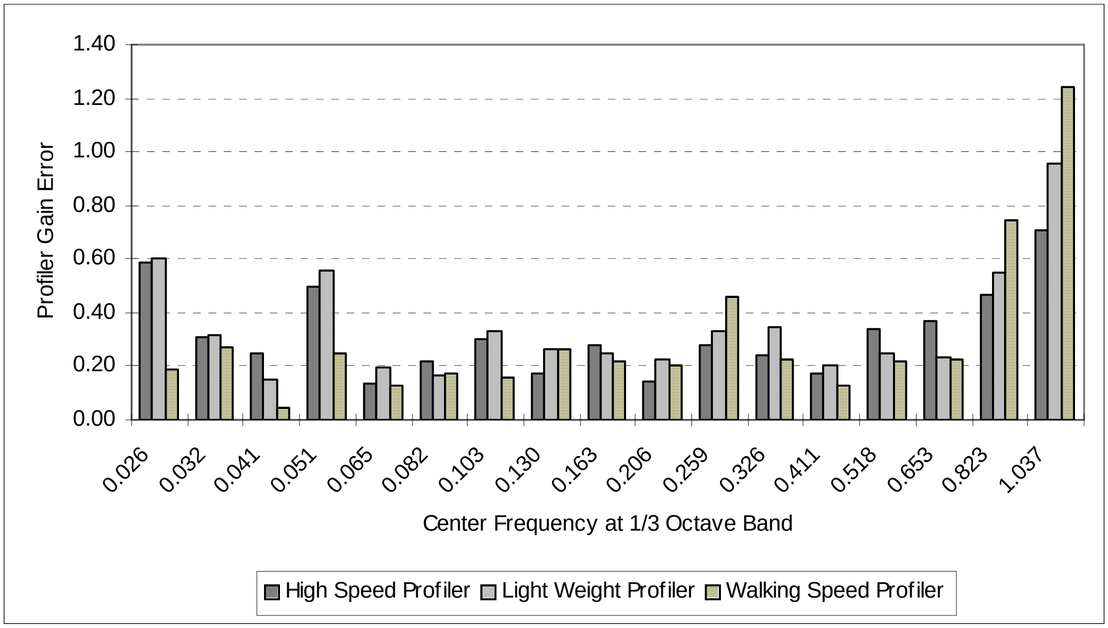


Figure 5.9 Mean Profiler Gain Errors for Three Types of Profilers

5.3 Effect of Profiler Gain Error on IRI Bias

The effect of non-uniform gain characteristics on the IRI bias is complicated and strongly depends on road spectral characteristics because the measured profiles have different frequency response in the calculation of IRI (Karamihas, 2005). As shown in Figure 5.8, some profile components are amplified, while others attenuated in the calculation process.

According to the linear system theory, the profiler gain errors will keep constant after the nonuniform frequency response in the quarter-car simulation because both the profiles from evaluated profilers and the reference profile have the same frequency response. However, the effect of profiler gain error at each wavelength on the total IRI value could be compensated or accumulated by each other. Prem (1999) analyzed the sensitivity of IRI change relative to the change of profiler gain at different wavelength and proposed the specification of profiler gain limits to achieve acceptable IRI errors.

An attempt to estimate the effect of profiler gains error on IRI bias is explored in this study. The 20 profile measurements on each site were divided into two categories: one with IRI bias percentages smaller than 5% and another with the percentages bigger than 5%. The mean profiler gain error within each category was calculated on each wavelength. The profiler gain error was normalized to the reference profile by using the IRI bias percentage—the IRI bias divided by reference IRI values at each site.

Figure 5.10 shows the comparison of mean profiler gain error for different IRI bias percentages. The solid line has the bigger profiler gain errors in the boundary range of the wave numbers of interest (0.02–0.08 cycles/m and 0.3–1.0 cycles/m), and the smaller errors in the middle range of the wave number (0.08–0.3 cycles/m) are shown by the dashed line. The profilers represented by the solid line have the highest IRI bias because the profiler gain errors are lager at the wave numbers that have the highest effect on IRI. The effect of profiler gain errors in the boundaries of the wave number of interest on IRI bias is more significant than the effect of the errors in the middle range. This is approximately in accord with the frequency response of the IRI quarter-car filter (Karamihas, 2005).

The correlation coefficients were calculated from the IRI bias and the profiler gain errors at different wavelengths on four sites in order to find which wavelength has the most significant influence on IRI bias, as shown in Figure 5.11.

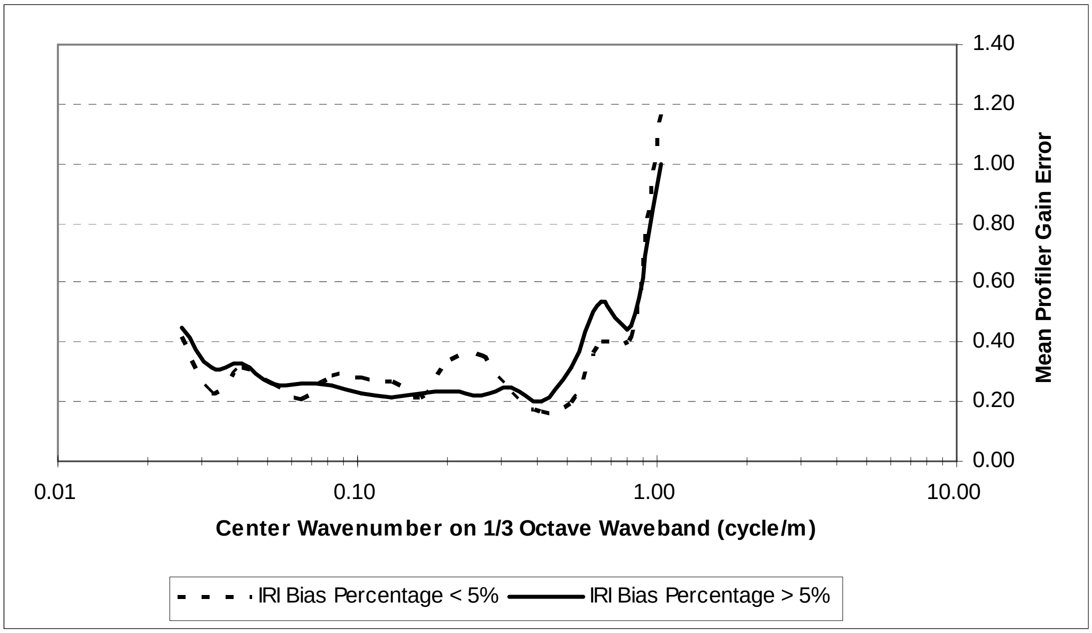


Figure 5.10 Comparison of Profiler Gain Errors for Different IRI Bias

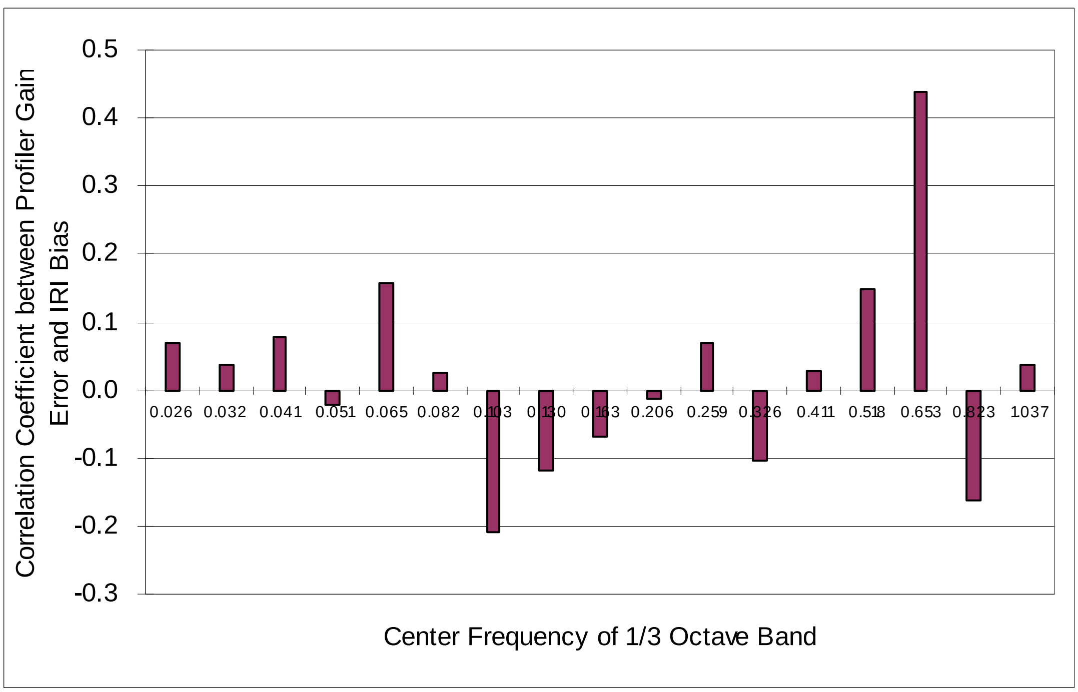


Figure 5.11 Correlation Coefficients between Profiler Gain Error and IRI Bias

Generally poor correlations were found between the IRI bias and the profiler gain error at each wavelength. The negative correlation between some profiler gain errors and IRI bias could be caused by the profiler gain errors on IRI compensating each other or by random measurement errors. The profiler gain error at the wave number of 0.653 cycles/m has the highest correlation with the IRI bias relative to other frequencies, which is similar to Prem's (1999) finding that the IRI is most sensitive to the change of profiler gain at 0.5 cycles/m.

With this information, the limits of profiler gain error can be customized for different wavelength ranges according to their influence level on IRI bias, so only the waveband having the higher effect on IRI bias is emphasized. Profiler designers and manufacturers should aim to achieve a profiler transfer function gain as close as unity as possible across the range of wavelengths with higher influence on IRI bias.

5.4 Summary

The profiler gain errors were calculated using Power Spectral Density (PSD) and gain method. The profiler gain errors appear nonuniformly distributed across the range of wavelength of interest on each site. The characteristics of the nonuniform distribution appear to be dependent on device and surface types. A general trend is that the highest error was found at the two boundaries of the wave number ranges of interest (0.02–0.08 cycles/m and 0. –1.0 cycles/m). The profiler errors over these ranges also have more significant influence on IRI errors.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATION

Profilers are routinely used for pavement condition monitoring and construction quality control and quality assurance. Thus, the accuracy of the profiler measurements has become a significant concern of highway agencies. Although many researchers have compared and evaluated the performance of available profilers and several alternative profiler accuracy criteria has been proposed, there are still unanswered questions regarding the ability of the various devices to accurately measure the road profile and smoothness indices. This investigation used the data collected at a profiler round-up conducted at the Smart Road to provide answer to some of these questions. This chapter summarizes the main findings, conclusions, and recommendations of the investigation.

6.1 Findings

The analysis produced the following findings relevant to the profiler performance evaluation and accuracy criteria:

- As expected, the walking-speed profilers have good IRI repeatability and bias on all test sites. In general, the light-weight profilers in this experiment have smaller bias than high-speed profilers. However, none of the inertial profilers evaluated met current IRI bias standard requirements on all five sites.
- Profiler accuracy is affected by pavement surface characteristics. The high-speed and light-weight profilers have good IRI repeatability, reproducibility and bias on smooth HMA pavement and CRCP. The repeatability and reproducibility of these devices are low on JCP probably due to the influence of joints. The coarse texture on the rough HMA pavement induced a small increase of IRI repeatability standard deviations and a high increase of IRI bias for the inertial profilers.

- Good agreement on IRI values does not necessarily mean that the profilers are collecting similar profile data. Differences may be due to many reasons, such as equipment performance or lateral variation.
- There is no good correlation between profile elevation bias and IRI bias. This means that a profiler certified by the criteria defined in point-to-point statistics will not necessarily measure an IRI close to the IRI from the reference device. On the other hand, higher cross-correlation coefficients produce better IRI repeatability, and there exists a good correlation between cross-correlation values and IRI bias for the data having coefficients of cross-correlation greater than 90.
- The profiler gain errors appear to be nonuniformly distributed across the wavelength range of interest, mainly depending on profiler performance and surface characteristics. The highest errors were found at the two boundaries of the wave number range of interest for IRI (0.02–0.08 cycles/m and 0.3–1.0 cycles/m). In addition, the profiler errors over this range also have more significant influence on IRI error based on the comparison of two IRI bias levels and correlation analysis.

6.2 Conclusions

The main conclusion of this investigation is that there are profilers available that can produce the level of accuracy (repeatability and bias) required for construction quality control and assurance. However, the analysis also showed that the accuracy varies significantly even among the same types of devices. None of the inertial profilers evaluated met all the current IRI bias standard requirements on all five test sites.

On average, the profilers evaluated produced more accurate results on the conventional smooth pavement that on the coarse-textured pavements. The cross-correlation method appears to have some advantages over the onventional point-to-point statistics method for comparing the actual measured profiles. On the sites investigated, good cross-correlation among the measured and reference profiles assured acceptable IRI accuracy. Finally, analysis based on PSD and gain method showed that the profiler gain errors are nonuniformly distributed and that errors at different wavelengths have variable effects on the IRI bias.

It is important to recognize that the agreement on IRI values does not necessarily mean that the profilers are collecting similar profile data. The disagreement may be due to many reasons, including equipment and operational factors (e.g., lateral placement). The requirements for equipment verification and validation should depend on its intended use. Profilers have to produce both accurate overall roughness values and accurate spatial distribution of roughness if used for construction quality assurance and control. However, the profilers should be subjected to less stringent requirements if used for network-level smoothness monitoring.

6.3 Recommendation

Although the experiment was successful in evaluating the performance of available profilers and current accuracy criteria, further studies are recommended to improve the profiler technology and accuracy criteria. The main recommendations are listed following:

- The results of profiler performance evaluation presented in this thesis may not cover all profiler technologies because the profile industry is very dynamic and design changes are continually being made. Periodic equipment comparison and evaluations will be needed to maintain the findings current.
- The investigation showed that profiler accuracy is influenced by pavement surface characteristics. More experiments including multilevel of roughness and texture should be implemented to fully evaluate the profilers’ performance.

- The existing profiler accuracy criteria appear to be too stringent when measurements are conducted on coarse-textured pavement. Further investigation should be undertaken to determine if it is necessary to change these criteria and if so, determine the most appropriate criteria.
- The Power Spectral Density (PSD) analysis is an efficient way to analyze profile contents and find measurement problems. However, the profiler spectra are influenced by profile length and wavelength resolution. Further reserach of this relationship is recommended.

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