# PERFORMANCE EVALUATION OF ROUGHNESS MEASURING DEVICES TO MEASURE RIDE NUMBER AND INTERNATIONAL ROUGHNESS INDEX


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16. Abstract

Pavement surface roughness is one of the most important pavement performance measures for pavement construction quality control and pavement management systems. Florida Department of Transportation (FDOT) uses International Roughness Index (IRI) and Ride Number (RN) to quantify pavement roughness conditions on Florida state highways. One of the devices that FDOT uses to measure IRI and RN is the High-Speed Profiler. FDOT uses the FACE Dipstick to calibrate the IRI measures of the High-Speed Profiler. However, the FACE Dipstick is not able to directly produce RN values. To evaluate whether the High-Speed Profiler could produce quality RN values at different operating speeds and sampling rates, FDOT requested the Department of Civil Engineering at the University of South Florida to conduct a research project. In the project, different roughness devices (including FDOT High-Speed Profiler, USF Walking Profiler, FACE Dipstick, and International Cybernetics Company Walking Profiler) were operated in FDOT calibration sites. The research focused on several performance measures. IRI results from all these devices were analyzed to evaluate the correlativity between these devices. Only the FDOT High-Speed Profiler and USF Walking Profiler were able to measure directly RN values from these test sites, and analysis was performed to evaluate the correlativity, repeatability, impact of sampling rate, and impact of operating speed. From field experiments and data analysis, several conclusions could be made: the FDOT High-Speed Profiler could be operated at different operating speeds with very little difference in RN values; the factor of sampling rate did show some impact on RN outputs of the FDOT High-Speed Profiler; both FDOT High-Speed Profiler and USF Walking Profiler showed satisfactory repeatability performances; and had good correlations at different sampling rates and operating speeds of the FDOT High-Speed Profiler; and correlation analysis showed that all the roughness measuring devices used in the project had good correlations between them in terms of IRI.

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## ABSTRACT

Pavement surface roughness is one of the most important pavement performance measures for pavement construction quality control and pavement management systems. Florida Department of Transportation (FDOT) uses International Roughness Index (IRI) and Ride Number (RN) to quantify pavement roughness conditions on Florida state highways. One of the devices that FDOT uses to measure IRI and RN is the High-Speed Profiler. To ensure the quality of the High-Speed Profile to measure roughness conditions, FDOT uses the FACE Dipstick to calibrate the IRI measures of the High-Speed Profiler. However, the FACE Dipstick is not able to directly produce RN values. Thus, the RN measures from the High-Speed Profiler cannot be directly calibrated, and the quality to measure RN by the High-Speed Profiler cannot be ensured.

To evaluate whether the High-Speed Profiler could produce quality RN values at different operating speeds and sampling rates, FDOT requested the Transportation Program in the Department of Transportation at the University of South Florida to conduct a research project. In the research project, different roughness devices (including FDOT High-Speed Profiler, USF Walking Profiler, FACE Dipstick, and International Cybenetics Company Walking Profiler) were operated in FDOT calibration sites (Sites 1, 4, 6, and 7). The research focused on several performance measures, such as correlativity, repeatability, impact of sampling rate, and impact of operating speed. IRI results from all these devices were analyzed to evaluate the correlativity between these devices. Since the FACE Dipstick and International Cybenetics Company Walking Profiler are not able to directly produce RN values, only the FDOT High-Speed Profiler and USF Walking Profiler were used to measure RN values from these test sites, and analysis was performed to evaluate the correlativity, repeatability, impact of sampling rate, and impact of operating speed. .

From field experiments and data analysis, several conclusions could be made: (1) the FDOT High-Speed Profiler could be operated at different operating speeds (30 mph – 60 mph) with very little difference in RN values for a given test section and sampling rate; (2) the factor of sampling rate did show some impact on RN outputs of the FDOT High-

Speed Profiler; (3) both FDOT High-Speed Profiler and USF Walking Profiler showed satisfactory repeatability performances; (4) the FDOT High-Speed Profiler and USF Walking Profiler had good correlations at different sampling rates and operating speeds of the FDOT High-Speed Profiler; and (5) correlation analysis showed that all the roughness measuring devices used in the project had good correlations between them in terms of IRI.

## ACKNOWDGEMENTS

This research project was sponsored by the Florida Department of Transportation. The authors of this report would like to take this opportunity to acknowledge the support from the State Materials Office of Florida Department of Transportation for their assistance in data collection and suggestions leading to the success completion of the project.

# CHAPTER 1. INTRODUCTION

## BACKGROUND

Pavement roughness is one of the most important performance measures for pavement surface performance conditions. Roughness condition has been used as the criteria for accepting new construction of pavement (including overlay) and also as the performance measure to quantify the surface performance of existing pavements in a pavement management system at both network level and project level. To measure pavement surface roughness conditions, automated or manual systems should be used. The commonly used roughness measures are the International Roughness Index (IRI) and the Ride Number (RN). Florida Department of Transportation (FDOT) uses both roughness measures for pavement roughness measurement.

Currently, FDOT uses the FACE Dipstick (Type-one system defined by ASTM E-950) and laser-based high-speed profilers (Type-one system defined by ASTM E-950) for roughness measurement on state highways. Basically, the FACE Dipstick is used as a reference for calibration of the laser-based high-speed profilers (called FDOT high-speed profiler) which is used for roughness measurement of existing pavement and, sometimes, for new construction acceptance. However, the FACE Dipstick does not have the capability to generate RN measurements. Thus, RN values obtained by FDOT laser-based high-speed profilers (called FDOT High-Speed Profiler) cannot be validated. This problem limits the capability of the FDOT High-Speed Profiler and FDOT is not able to confidently report the RN of Florida highways.

In Spring 2002, a research project sponsored by FDOT was initiated. The main purpose of the research project was to evaluate whether roughness performance indices (including IRI and RN) could be effectively measured by the FDOT High-Speed Profiler and other devices. To serve the purpose, field experiments would need to be performed to operate all available roughness measuring devices to measure IRI and RN values. Then, based on the field test results, data analysis could be done and conclusions regarding several measures could be made. This report summarizes the results obtained from the research project.

## RESEARCH OBJECTIVES

The main purpose of the proposed research was to validate RN and IRI values produced by FDOT High-Speed Profiler. The main objectives of the proposed research were:

1. To search and review existing practices for measuring and reporting RN;
2. To collect roughness data in the field with the use of the FDOT High-Speed Profiler, USF Walking Profiler, FACE Dipstick, and International Cybenetics Company Walking Profiler; and
3. To perform correlation analysis between these roughness measuring systems and perform other analysis.

## RESEARCH APPROACH

The Transportation Program in the Department of Civil and Environmental Engineering at the University of South Florida (USF) developed an automated (computerized) pavement profiling system, which can measure pavement roughness in terms of IRI at a walking speed. This system, called USF Walking Profiler, is a type-one system that basically measures the true longitudinal profile of pavement surfaces and converts the true profile into IRI. This system was implemented and tested in the field and programmed to generate both IRI and RN. In the research project, the system was also further evaluated through field experiments.

For field evaluation, test sections with a wide range of roughness conditions were selected. The FDOT State Materials Office in Gainesville had several test sections available. Based on the recommendation by FDOT State Materials Office, four test sites (Sections 1, 4, 6, and 7) in Gainesville area were selected for the research. These sites covered the roughness ranged from rough to smooth conditions. Field data collection was performed in April 2002. Several roughness measuring systems including FDOT High-

Speed Profiler, USF Walking Profiler, FACE Dipstick, and International Cybenetics Company Walking Profiler (called ICC Walking Profiler) were operated on these sections to collect roughness data. Several repeated runs from each device were performed on each section. All systems had the function to generate IRI values. However, only the FDOT High-Speed Profiler and USF Walking Profiler were able to generate both IRI and RN values.

The data analysis and system performance evaluation focused on repeatability and correlativity of the systems to be evaluated. Generally, a measuring system is said to be satisfactory if it has good repeatability and correlativity with reference system. In addition, the impact of operating speed on and the impact of sampling rate of the FDOT high-speed profiler on RN measurements were evaluated based on statistical analysis.

# CHAPTER 2. DESCRIPTION OF IRI AND RN

## INTRODUCTION

The International Roughness Index (IRI) has been widely used in many pavement roughness measuring systems. IRI was first introduced in the International Road Roughness Experiment (IRRE) that was held in Brazil [1]. In addition to evaluation of pavement roughness performance, IRI is often used as an accepted standard against which roughness measuring systems are calibrated. Sayers gives additional background on the IRI along with theoretical and practical issues with its measurement in Transportation Research Record 1501 [2].

Ride Number (RN) is the result of a NCHRP research in the 1980's. RN is an estimate of Mean Panel Rating. Ratings from people reflect their opinions and are subjective. Subjective rating scales for road usually range from 0 to 5. When a group of ratings are taken together, the average rating can be fairly consistent. After statistical processing, the results are processed to yield a single rating for the panel as a whole, typically called mean panel rating (MPR).

## CALCULATION OF IRI

IRI has become a well recognized standard for measurement of road roughness. The IRI has been reported to be (1) relevant as an indicator of pavement serviceability, (2) independent of the particular equipment used to measure it, (3) internationally and geographically transferable, and (4) time stable [3].

Although the "in/mile" measures from response-type systems has been popular since the 1940's, it was not possible to obtain the same values from different vehicles, or even from the same vehicle over time. In order to calibrate the response-type systems, an ideal system was defined for the computer. Mathematical models of the vehicle and road meter were developed and tested, and shown to provide the same type of “in/mi” index as mathematical function of the longitudinal profile.

Because response-type road roughness measuring systems were common, the profile index was tailored to correlate well with the output of these systems. The filter is based on a mathematical model called a quarter-car. The quarter-car filter calculates the suspension deflection of a simulated mechanical system with a response similar to a passenger car. The simulated suspension motion is accumulated and divided by the distance traveled to give an index with units of slope (m/km, in/mi, etc.). This index is called IRI.

IRI is computed from a single longitudinal wheel path profile. The smoothed profile is filtered using the quarter-car simulation with specific parameter values (golden car) at a simulated speed of 80 km/hr. The quarter-car model used in the IRI algorithm is just what its name implies: a model of one corner (a quarter) of a car. The model is shown schematically in Figure 2.1. The model includes one tire represented with a vertical spring, the mass of the axle supported by the tire, a suspension spring and a damper, and the mass of the body supported by the suspension for that tire.

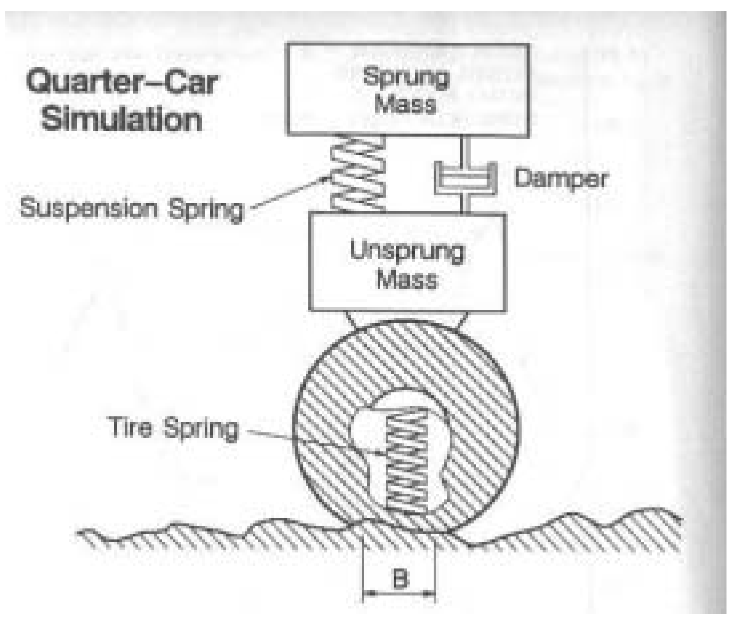


Figure 2.1. The Quarter-Car Model [4]

The quarter-car model was tuned to maximize correlation with response-type road roughness measuring systems. This quarter-car simulation is meant to be a theoretical representation of the response-type systems in use at the time the IRI was developed, with the vehicle properties of the “golden car” adjusted to obtain maximum correlation to the output of those systems. Considerations in its design are described in NCHRP Report 228 [5].

IRI is influenced by wavelengths ranged from 1.2 to 30 meters. The wave number response of the IRI quarter-car filter is shown in Figure 2.2. The amplitude of the output sinusoid is the amplitude of the input, multiplied by the gain shown in Figure 2.2. The gain shown in the figure is dimensionless.

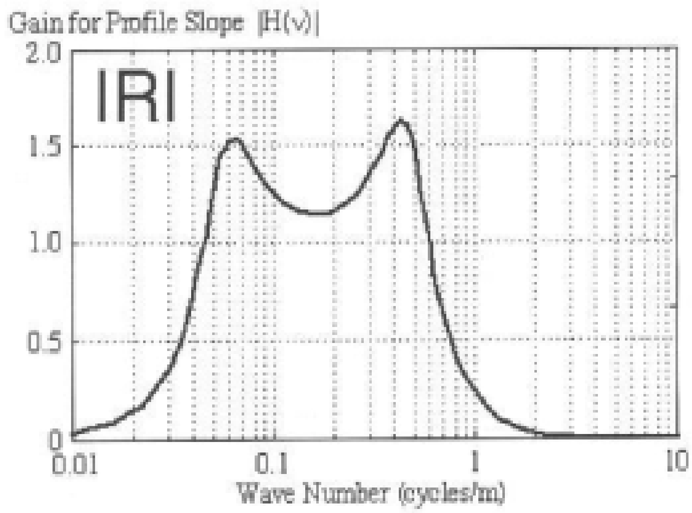


Figure 2.2. Sensitive Wave Number of IRI [4]

The IRI filter has maximum sensitivity to slope sinusoids with numbers near 0.065 cycle/m (a wavelength of about 15m) and 0.42 cycle/m (a wavelength of about 2.4m.). The response is down to 0.5 for 0.03 and 0.8 cycle/m wave numbers which correspond to wavelengths of 30m and about 1.25m, respectively. However there is still some response for wavelengths outside this range. An IRI of 0.0 means the profile is perfectly flat. There is no theoretical upper limit to roughness, although pavements with IRI values above 8 m/km are nearly impassable except at reduced speeds.

The IRI is rigorously defined as a specific mathematical transform of a true profile. The specific steps taken in the computer program to compute IRI are listed below.

The profile is filtered with a moving average with a 250-mm (9.85-in) base length. The moving average is a low-pass filter that smoothes the profile. The computer program does not apply the filter if the profile interval is longer than 167mm (6.6 in). The 250-mm moving average filter should be omitted for profiles obtained with some systems. This step should be omitted if: (1) the profile has already been filtered by a moving average or with an anti-aliasing filter that attenuates wavelengths shorter than 0.5m, and (2) the sample interval is less than 167mm (6.6 in). The profile is further filtered with a quarter-car simulation. The quarter-car parameters are specified as part of the IRI statistic, and the simulated travel speed is specified as 80km/hr (49.7mi/hr). The parameters for the quarter-car model are:

$$K_1 = K_t / M_s = 653,\ K_2 = K_s / M_s = 63.3,\ C = C_s / M_s = 6.0,\ M = M_u / M_s = 0.15$$

where $K_s$ is the spring rate, $M_s$ is the sprung mass, $K_t$ is the tire spring rate, C is the damper rate, and $M_u$ is the unsprung mass.

The output of the filter represents suspension motion of the simulated quarter car. The parameters of the quarter-car are shown in Figure 2.1. They include the sprung mass of the vehicle body; the suspension spring and damper (shock absorber) constants; the unsprung mass of the suspension, tire, and wheel; and the spring constant of the tire. Theoretical correctness would require a damper constant for the tire. However, practical application generally ignores this term. Mathematically, the behavior of a quarter-car can be described with two second-order equations:

$$M_S \ddot{Z}_S + C_S(\dot{Z}_S - \dot{Z}_U) + K_S(Z_S - Z_U) = 0 \qquad (2.1)$$

$$M_S \ddot{Z}_S + M_U \ddot{Z}_U + K_t(Z_U - Z) = 0 \qquad (2.2)$$

where

*Z* = road profile elevation points,

$Z_u$ = elevation of unsprung mass (axle),

$Z_s$ = elevation of sprung mass (body),

$K_t$ = tire spring constant,

$K_s$ = suspension spring constant,

$C_s$ = shock absorber constant,

$M_u$ = unsprung mass (axle), and

$M_s$ = sprung mass.

The double dot notation above the elevation terms represents acceleration while the single dot represents velocity.

Since response-type roughness measuring systems generally measure the movement between the vehicle axle and body, simulation requires calculation of the difference in elevation between the body and axle in response to the road profile and forward motion of the vehicle. This is accomplished by integrating the difference in the velocities between the sprung and unsprung mass, producing the quarter-car statistic, QCS:

$$QCS = \frac{1}{C}\int_{O}^{T}\left|\dot{Z}_{S} - \dot{Z}_{U}\right|dt \qquad (2.3)$$

The term C represents either the total time required to traverse the section of road being simulated, T, or the length of the section, L. if the time factor is used to normalize the quarter-car statistic, the calculation results in an average rectified velocity, while a distance base yields the average rectified slope.

The calculation of IRI is accomplished by computing four variables as functions of the measured profile. These four variables simulate the dynamic response of a reference vehicle traveling over the measured profile. The equations for the four variables are solved for each measured elevation point, except for the first point. The average slope over the first 11m (0.5 sec at 80km/h) is used for initializing the variables by assigning the following values:

$$Z_1' = Z_3' = (Y_a - Y_1)/11 \qquad (2.4)$$

$$Z_2' = Z_4' = 0 \qquad (2.5)$$

$$a=11/dx + 1 \quad (2.6)$$

where $Y_a$ is the “a-th” profile elevation point that is a distance of 11m from the start of the profile, $Y_1$ is the first point, and dx is the sample interval. The following four recursive equations are then solved for each elevation point, from 2 to n, where n is the number of elevation measurements:

$$Z_1 = s_{11}.Z_1' + s_{12}Z_2' + s_{13}Z_3' + s_{14}Z_4' + P_1Y' \quad (2.7)$$
$$Z_2 = s_{21}.Z_1' + s_{22}Z_2' + s_{23}Z_3' + s_{24}Z_4' + P_2Y' \quad (2.8)$$
$$Z_3 = s_{31}.Z_1' + s_{32}Z_2' + s_{33}Z_3' + s_{34}Z_4' + P_3Y' \quad (2.9)$$
$$Z_4 = s_{41}.Z_1' + s_{42}Z_2' + s_{43}Z_3' + s_{44}Z_4' + P_4Y' \quad (2.10)$$

where

$Y' = (Y_i - Y_{i-1})/dx$= slope input,

$Z_j' = Z_j$ from previous position, j=1, 2, 3, 4, (2.11)

and $S_{ij}$ and $P_{ij}$ are coefficients that are fixed for a given sample interval, dx. Thus, Eqs. 2.7 through 2.10 are solved for each position along the wheel track. After they are solved for one position, Eq.2.11 is used to reset the values of $Z_1'$ , $Z_2'$ ,$Z_3'$ and $Z_4'$ for the next position. Also for each position, the rectify slope (RS) of the filtered profile is computed as:

$$RS_i = |Z_3 - Z_1| \quad (2.12)$$

The IRI statistic is the average of the RS variable over the length of the site. Thus, after the above equations have been solved for all profile points, the IRI is calculated as:

$$IRI = [1/(n-1)]\, x \sum_{i=z}^{n} RS_i \quad (2.13)$$

The above procedure is valid for any sample interval between dx=0.25 and dx=0.61 m (2.0 ft). For shorter sample intervals, the additional step of smoothing the profile with a 0.25 m moving average is recommended to better represent the way in which the tire of a vehicle envelops the ground. Then the IRI is calculated by solving the equations for each averaged point using coefficients in the equations appropriate for the smaller interval.

The IRI summarizes the roughness qualities that impact vehicle response, and is most appropriate when a roughness measure is desired that relates to: overall vehicle operating cost, overall ride quality, dynamic wheel loads, and overall surface condition. Figure 2.3 shows IRI ranges represented by different of road.

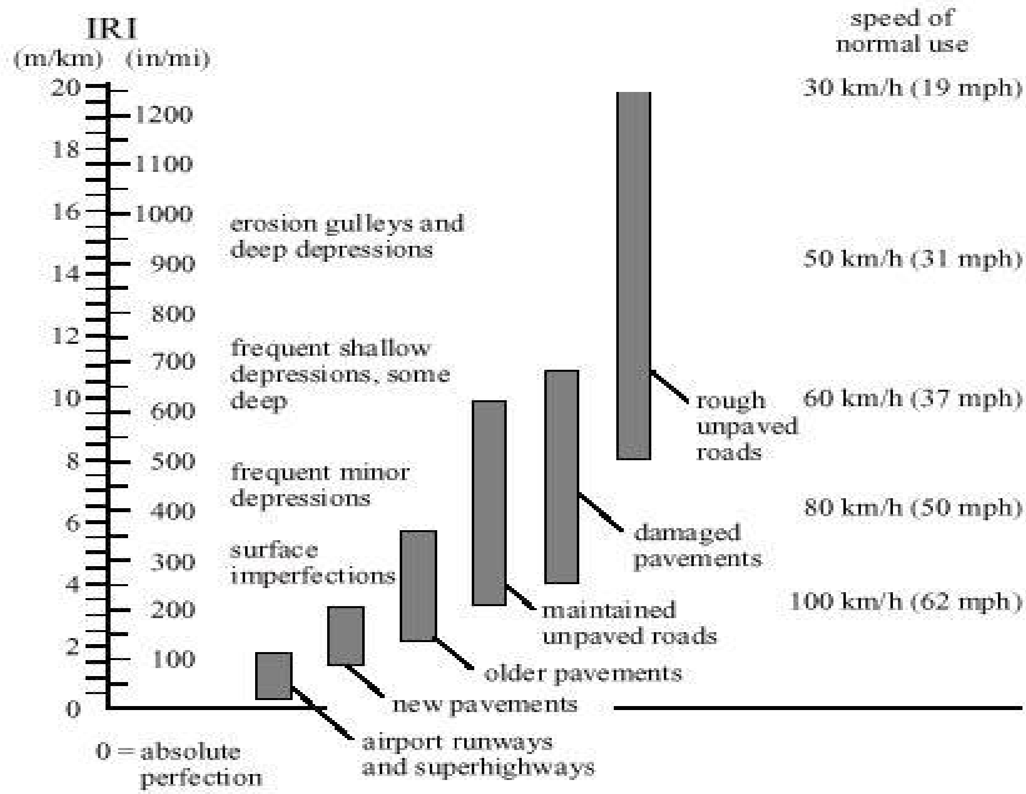


Figure 2.3. The IRI Roughness Scale [4]

## CALCULATION OF RN

RN is the result of two NCHRP researches performed in the 1980's by Janoff to investigate the effect of road surface roughness on ride comfort [6]. The objective of these researches was to determine how features in road profiles were linked to subjective opinion about the road from members of the public. During two studies, spaced at about a 5-year interval, mean panel ratings (MPR) were determined experimentally on a 0-to-5 scale for test sites in several states. The 0-to-5 scale as shown in Figure 2.4 was used for a large-scale road test conducted by AASHO in the 1950's, in which roads were subjected to mixed traffic and researchers tracked the condition of the pavement. Longitudinal profiles were obtained from left- and right-wheel tracks of the lanes that were rated. RN is an estimate of MPR. The mathematical procedure developed to calculate RN is described in NCHRP Report 275, but not in complete detail. In 1995, some of the data from the two NCHRP projects performed by Janoff and a panel study conducted in Minnesota were analyzed again in a pooled-fund study initiated by the Federal Highway Administration to develop and test a practical mathematical process for obtaining RN based on objective measurement, not subjective rating. The method was to be provided as portable software similar to that available for the IRI, but for predicting MPR rather than IRI.

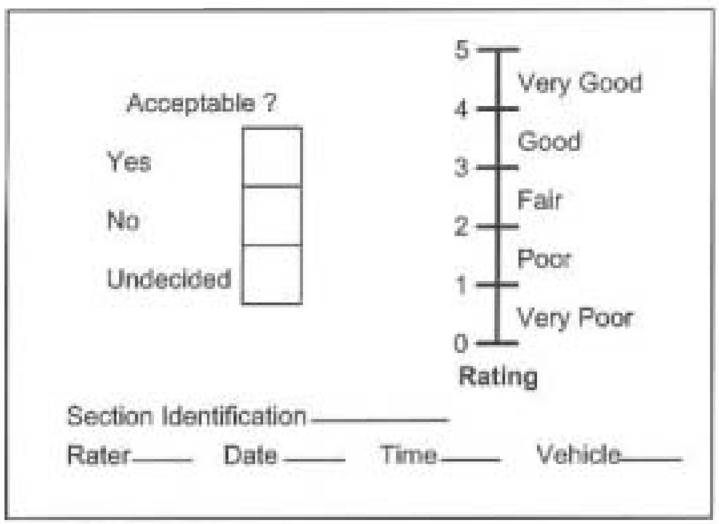


Figure 2.4. Subjective Rating Scales for Roads [4]

RN is a nonlinear transform of a statistic called profile index (PI). PI is calculated from one or two profiles. The profile is filtered with a moving average with a 250-mm (9.85-in) base length. The moving average is a low-pass filter that smoothes the profile. The computer program does not apply the filter unless the profile interval is shorter than 167mm (6.6 in). The profile is further filtered with band-pass filter. The filter uses the same equations as the quarter-car model in the IRI. However different coefficients are used to obtain the sensitivity to wave number shown in the last figure. The quarter-car parameters for the PI calculation are:

$$K_1 = K_t / M_s = 5120,\ K_2 = K_s / M_s = 390,\ C = C_s / M_s = 17,\ M = M_u / M_s = 0.036$$

The filtered profiles is reduced to yield PI, that should have units of dimensionless slope (ft/ft, m/m, etc). Then, PI is transformed to RN. RN is defined as an exponential transform of PI according to the equation:

$$RN=5e^{-160(PI)} \tag{2.14}$$

If a single profile is being processed, PI is calculated directly. If two profiles for both the left- and right-wheel tracks are processed, PI values from the two wheel tracks are averaged according to Eq. 2.15, then RN is calculated by Eq. 2.14.

$$PI = \sqrt{\frac{PI_L^2 + PI_R^2}{2}} \tag{2.15}$$

Figure 2.5 shows the sensitivity of RN to wave number. The maximum sensitivity of RN is for a wave number of 0.164 cycle/m (0.05 cycles/ft), which is a wavelength of about 6 meters (20 ft). Recall that the IRI has a great sensitivity to a wavelength of 16 meters (wave number of 0.065 cycle/m). The figure shows that RN has a low sensitivity to that wavelength and even lower sensitivity for longer wavelengths.

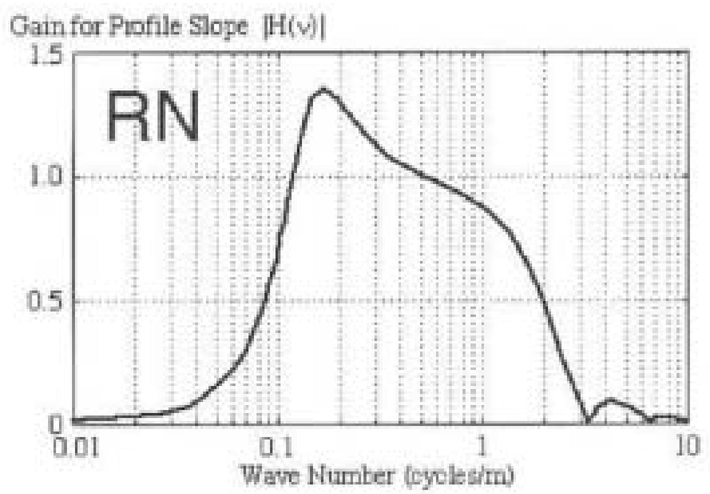


Figure 2.5. Sensitive of RN to Wave Number [4]

# CHAPTER 3. FIELD DATA COLLECTION

## ROUGHNESS MEASURING DEVICES USED

### USF Walking Profiler

USF Walking Profiler was developed couple years ago. Currently, this device has not been finalized, and the research team at USF is working on improving the technical performance of this device, such as the impact of longitudinal acceleration, which may have some impact on measurement repeatability. The picture of USF Walking Profiler is shown in Figure 3.1.

Figure 3.1. Picture of the USF Walking Profiler

USF Walking Profiler is a direct-type pavement profiler which directly measures longitudinal pavement surface profile. The data analysis function in the device can process profile data to obtain IRI and RN performance measures. The system function is described in Figure 3.2. The system has three basic functions: (1) data sampling, (2) data processing, and (3) system configuration (including calibration and parameter set-up). The computer programming language used in developing the software is Visual Basic. Since the power supply for sensors and interfaces is provided directly from the notebook computer's power source, there is no need to have any external power supply. Actually, the hardware part of the devise consumes little power source (20 ma at 5 volts). Thus, it will not affect the computer's normal work. Generally, a fully charged computer battery is able to continuously work for more than 2 hours.

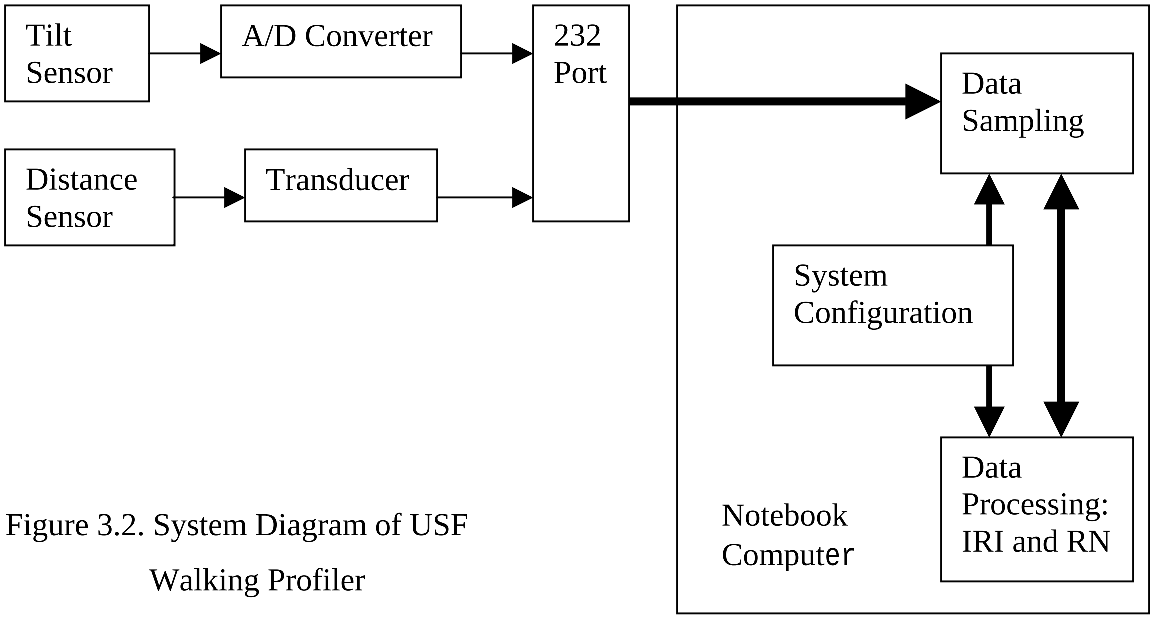


Figure 3.2. System Diagram of USF Walking Profiler

**FDOT High-Speed Profiler**

The main focus of the research project was to evaluate whether the FDOT High-Speed Profiler can adequately measure pavement roughness indices, IRI and RN, and whether the FDOT high-speed laser profiler, manufactured by the International Cybernetics Company (ICC) can be calibrated by USF Walking Profiler. The FDOT High-Speed Profiler uses a laser distance sensor to measure the spacing between pavement surface and vehicle bumper and uses an accelerometer to measure vehicle vertical acceleration. The acceleration signal is double-integrated to obtain vehicle vertical dynamic movement. The double-integrated signal is linearly combined with the signal from the laser sensor to obtain the estimated pavement longitudinal profile. The FDOT High-Speed Profiler is equipped with software that can process the profile data through the IRI model and the RN model to obtain IRI and RN of the pavement section. The picture of the FDOT High-Speed Profiler is shown in Figure 3.3.

Figure 3.3. Picture of FDOT High-Speed Profiler

**Other Devices**

Other pavement roughness measuring devices used in field data collection were the ICC Walking Profiler and the FACE Dipstick. Both devices can measure pavement longitudinal profiler and obtain IRI. However, both devices do not have the function to produce RN. In the research project, the ICC Walking Profiler and FACE Dipstick were used to provide additional roughness measurement references for the evaluation of the FDOT High-Speed Profiler. The pictures of the ICC Walking Profiler and FACE Dipstick are shown in Figures 3.4 and 3.5, respectively.

**FIELD DATA COLLECTION**

Field data collection was performed in Gainesville, Florida in April of 2002. Based on the suggestions from FDOT project manager, four FDOT pavement calibration sections (sections 1, 4, 6, and 7) were used for field roughness data collection. These sites had roughness ranged from rough to smooth conditions. Each section has a length between

500 to 600 feet. All these devices (including USF Walking Profiler, FDOT High-Speed Profiler, ICC Walking Profiler, and FACE Dipstick) were used for the data collection.

Figure 3.4. Picture of ICC Walking Profiler

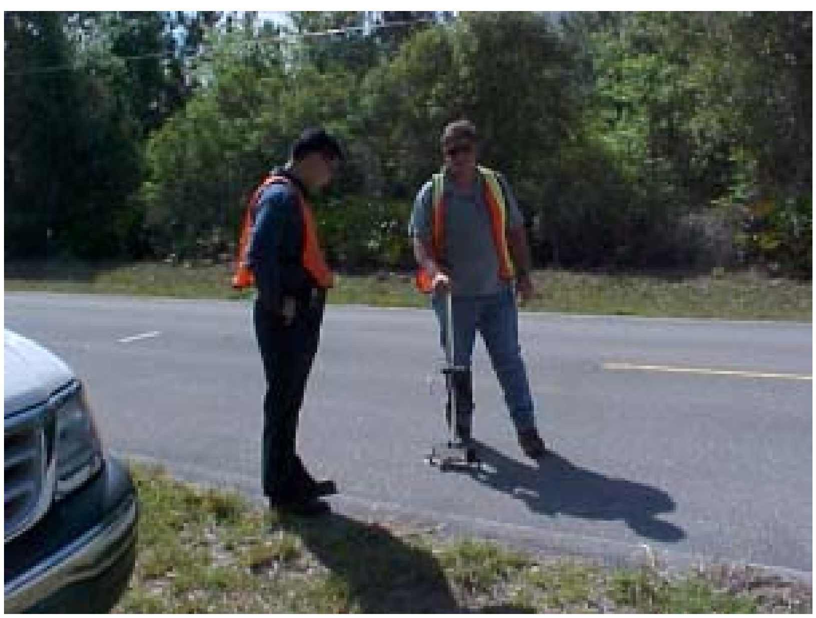

Figure 3.5. Picture of the Face Dipstick

Repeated runs of each device were performed on the same calibration section. Except the FACE Dipstick, all other devices had minimum three repeated runs on each FDOT calibration sections to minimize the operational biases. It is a very time-consuming process for the FACE Dipstick to collect pavement profile elevation data, only two repeated runs were used for the FACE Dipstick to be operated on each FDOT calibration section. In fact, it could take the FACE Dipstick about 2-3 hours to complete one run on each section.

The USF Walking Profiler and ICC Walking Profiler were operated at walking speed. The FACE Dipstick was operated even at muck lower speed. Since the FDOT High-Speed Profiler can be operated at high speed, different operating speeds were used to evaluate the impact of the speed on roughness outputs of the FDOT High-Speed Profiler. The operating speeds used were 30 mph, 45 mph, and 60 mph.

The FDOT High-Speed Profiler has four different sampling rates, i.e. sampling intervals of 0.273 ft. (rate 1), 0.545 ft. (rate 2), 0.818 ft. (rate 3), and 1.091ft. (rate 4). According to the definition of RN, it could be anticipated that the sampling rate may have certain impact on RN. Thus, in order to objectively evaluate the measurements of RN by the FDOT High-Speed Profiler, different sampling rates should be used to assess whether the sampling rate has impact on RN. In this research project, sampling rates 1 to 4 for the FDOT High-Speed Profiler were used in field data collection. The roughness data obtained from the FDOT High-Speed Profiler are summarized in Appendix A. Roughness data obtained by other devices are summarized in the following chapters.

# CHAPTER 4. EVALUATION ON RN

The evaluation on RN mainly focused on the FDOT High-Speed Profiler and USF Walking Profiler because only these two devices can measure RN values. To evaluate whether the FDOT High-Speed Profiler and USF Walking Profiler can obtain adequate RN values, several objective measures were used. These measures are repeatability, impact of operating speed, impact of sampling rate, and correlation with reference.

## REPEATABILITY

Repeatability refers to the capability of a measuring device to obtain statistically similar results from repeated runs with measuring conditions unchanged. Repeatability is one of the most important quality measures used to evaluate the performance of a measuring device. In this research, for a given calibration section, the USF Walking Profiler was operated for three repeated runs to obtain RN value on each run. For the FDOT High-Speed Profiler, since different operating speeds and sampling rates were used, thus, for each combination of operating speed and sampling rate, three repeated runs were used to obtain RN value on each calibration section. Table 4.1 shows the RN values obtained by the USF Walking Profiler from repeated runs on each calibration section. The difference of RN values between repeated runs was used to quantify the repeatability of USF Walking Profiler. From Table 4.1, it can be seen that the over-all average difference between repeated runs was 0.05. This number means that the USF Walking Profiler presented good repeatability.

**Table 4.1. RN Values of USF Walking Profiler in Each Section**

| Run | Section 1 | Section 4 | Section 6 | Section 7 |
|---|---|---|---|---|
| 1.00 | 3.30 | 3.00 | 2.83 | 3.02 |
| 2.00 | 3.31 | 2.95 | 2.82 | 2.98 |
| 3.00 | 3.37 | 2.97 | 2.86 | 3.01 |
| Difference | 0.07 | 0.05 | 0.04 | 0.04 |

Table 4.2 shows the average maximum differences of RN values between repeated runs of FDOT High-Speed Profiler. The original RN values are presented in Appendix A. From Table 4.2, it can be seen that the over-all average difference between repeated runs was 0.05. Thus, the FDOT High-Speed Profiler also had good repeatability.

**Table 4.2. Average Maximum Differences of RN Values between Repeated Runs of FDOT High-Speed Profiler**

| | | 30 mph | 45 mph | 60 mph | Average |
|---|---|---|---|---|---|
| Section 1 | Rate 1 | 0.01 | 0.06 | 0.02 | |
| | Rate 2 | 0.03 | 0.02 | 0.06 | |
| | Rate 3 | 0.05 | 0.01 | 0.01 | |
| | Rate 4 | 0.02 | 0.02 | 0.00 | |
| | | | | | Ave.=0.03 |
| Section 4 | Rate 1 | 0.12 | 0.13 | 0.25 | |
| | Rate 2 | 0.02 | 0.16 | 0.05 | |
| | Rate 3 | 0.06 | 0.04 | 0.10 | |
| | Rate 4 | 0.02 | 0.04 | 0.01 | |
| | | | | | Ave.=0.08 |
| Section 6 | Rate 1 | 0.05 | 0.02 | 0.05 | |
| | Rate 2 | 0.02 | 0.16 | 0.05 | |
| | Rate 3 | 0.03 | 0.02 | 0.04 | |
| | Rate 4 | 0.04 | 0.04 | 0.07 | |
| | | | | | Ave.=0.05 |
| Section 7 | Rate 1 | 0.04 | 0.02 | 0.04 | |
| | Rate 2 | 0.04 | 0.02 | 0.01 | |
| | Rate 3 | 0.04 | 0.04 | 0.06 | |
| | Rate 4 | 0.03 | 0.03 | 0.02 | |
| | | | | | Ave.=0.03 |

**Over-All Ave. = 0.05**

## IMPACT OF OPERATING SPEED

Since the FDOT High-Speed Profiler uses an accelerometer to measure vehicle vertical acceleration, the operating speed of the FDOT High-Speed Profiler could have certain impact on the roughness measurements because a regular accelerometer usually is sensitive to speed. To evaluate the speed impact of the FDOT High-Speed Profiler, different operating speeds were used in field data collection. Actually, for a given operating speed and sampling rate, three repeated runs were used on a calibration section. Thus, average value from the repeated runs was used. Meanwhile, for a given operating speed, four different sampling rates were tested. In order to evaluate the speed impact, the average value from different sampling rates was used. Table 4.3 shows the RN values of FDOT High-Speed Profiler at different operating speeds. Figure 4.1 graphically presents the same data. The values in the table were the average values of RN from repeated runs and at different sampling rates. From the table and the figure, it can be concluded that the operating speed did not have significant impact on RN value because there were no significant differences among these RN values for a given calibration section. In fact, theoretically, the roughness measuring devices with the use of vertical accelerometer and laser distance sensor should not be sensitive to operating speed. However, since the field test only included the operating speeds of 30 mph, 45 mph, and 60 mph, the conclusion is not valid for the operating speed beyond this range. Further tests may be needed to evaluate whether higher speed (faster than 60 mph) and lower speed (lower than 30 mph) has certain impact on RN measurements.

**Table 4.3. RN Values of FDOT High-Speed Profiler at Different Operating Speeds (Average of Different Sampling Rates)**

| | 30 mph | 45 mph | 60 mph |
|---|---|---|---|
| Section 1 | 4.33 | 4.33 | 4.35 |
| Section 4 | 3.52 | 3.51 | 3.42 |
| Section 6 | 3.06 | 3.03 | 3.02 |
| Section 7 | 3.56 | 3.54 | 3.53 |

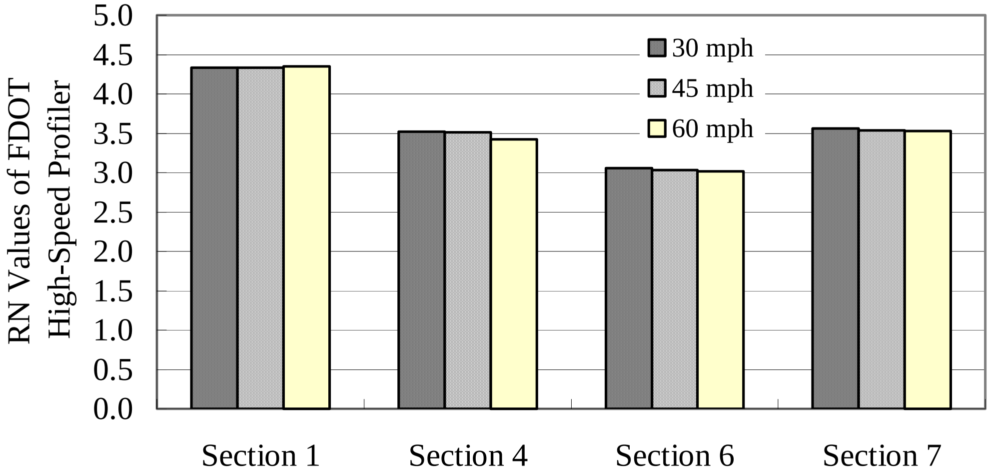


Figure 4.1. Operating Speed Impact of FDOT High-Speed Profiler on RN in Each Section

To further evaluate the impact of the operating speed on RN measurement, one-way variance analysis (ANOVA test) was performed. Since Section 6 had the most rough condition as compared to other test sections, the RN data from Section 6 at different sampling rates were used for the ANOVA test. Table 4.4 shows the ANOVA test results. In the table, $F_{0.05}$=5.14 and $F_{0.01}$=10.92 are the critical F values at significance levels of 0.05 and 0.01, respectively. The critical F values are checked from F tables in any statistics book and calculated F values shown in the table were calculated from ANAOVA test. If the calculated F value is smaller than the critical F value, the impact of speed is statistically not significant. Otherwise, the impact of speed is significant. From the table, it can be concluded that the impact of operating speed was not significant except at sampling rates 3 and 4 with significance level of 0.05.

**Table 4.4. ANOVA Test Results to Test the Impact of Speed on RN (Test Section 6, Significance Levels of 0.05 and 0.01)**

| | Rate 1 | Rate 2 | Rate 3 | Rate 4 |
|---|---|---|---|---|
| Calculated F Values | F=0.2 | F=1.14 | F=8.68 | F=6.65 |
| $F_{0.05}$=5.14 | no | no | yes | yes |
| $F_{0.01}$=10.92 | no | no | no | no |

## IMPACT OF SAMPLING RATE

Sampling interval may have certain impact on the roughness output, RN, of the FDOT High-Speed Profiler. This research tried different sampling rates to test whether the sampling rate had impact on RN. Since the operating speed did not have impact on RN and the FDOT High-Speed Profiler showed good repeatability, RN values from different runs and different operating speeds on a given calibration section were averaged so that the only factor, sampling rate, could be evaluated. Table 4.5 presents the RN values at different sampling rates on FDOT calibration sections. From the table, it is clearly seen that as the sampling rate increased, RN value also increased. This is mainly due to the characteristics of RN model. As seen in Figure 2.5 shown in Chapter 2, at high frequency (short wavelength), as frequency decreases (wavelength increases), the magnitude of the spectral density correspondingly increases, meaning RN value increases for given pavement section roughness condition. More specifically, as sampling interval increases, profile data with short wavelength may be lost and long wavelength information is kept, resulting RN value increased, as shown in Figure 2.5. Therefore, it is anticipated that as sampling interval increases, RN value on the same pavement section could increase too. However, the field data collection only covered the sampling rate from rate 1 to rate 4. Any conclusion based on sampling rate beyond this range should be further tested.

**Table 4.5. RN Values of FDOT High-Speed Profiler at Different Sampling Rates (Average of Different Operating Speeds)**

| | Rate 1 | Rate 2 | Rate 3 | Rate 4 |
|---|---|---|---|---|
| Section 1 | 4.11 | 4.32 | 4.39 | 4.51 |
| Section 4 | 3.01 | 3.46 | 3.59 | 3.86 |
| Section 6 | 2.85 | 3.00 | 3.07 | 3.23 |
| Section 7 | 3.34 | 3.52 | 3.57 | 3.73 |

Similar to the operating speed, ANOVA test was performed to statistically analyze the impact of sampling rate on RN measurements. Table 4.6 summarizes the ANOVA test result. Actually, all calculated F values were much larger than the critical F values at significance levels of 0.05 and 0.01. Statistically, it can be concluded that the sampling rate had a significant impact on RN measurements. Therefore, the sampling rate should be specified when RN values are to be measured.

**Table 4.6. ANOVA Test Results to Test the Impact of Sampling Rate on RN (Test Section 6, Significance Levels of 0.05 and 0.01)**

| | 30 mph | 45 mph | 60 mph |
|---|---|---|---|
| Calculated F Values | F=164.27 | F=214.38 | F=101.48 |
| $F_{0.05}$=4.066 | yes | yes | yes |
| $F_{0.01}$=7.59 | yes | yes | yes |

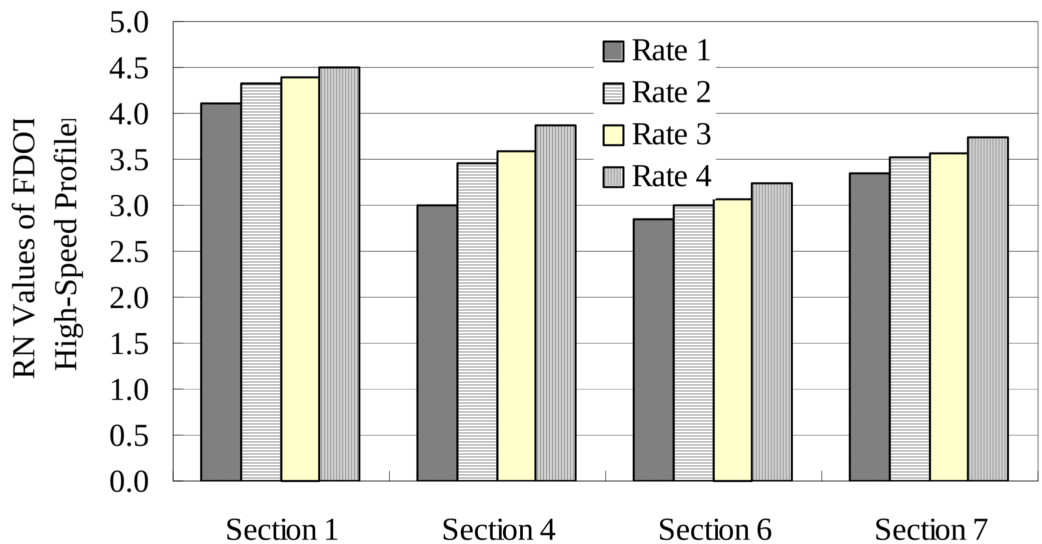


Figure 4.2. Sampling Rate Impact of FDOT High-Speed Profiler on RN in Each Section

Figure 4.2 (shown above) graphically presents the difference of RN values at different sampling rates. For a given pavement section, it could be anticipated that RN values at different sampling intervals could be estimated if sufficient modeling data (including sampling intervals and corresponding RN values) are available. However, the models to estimate RN values at different sampling intervals should be developed based on field experiments with the supports of sufficient field data. Actually, as recommended by NCHRP (National Cooperative Highway Research Program), RN should be obtained at a smaller sampling interval and IRI at a larger sampling interval [7]. This makes it much more complicated when RN and IRI are needed at the same measurement. A feasible approach to measure IRI and RN from the same run is to estimate RN value at different sampling intervals. That is to say that the RN value measured at larger sampling interval could be used to estimate the RN value measured at smaller sampling interval. Again, to make the approach feasible, more field experiments with more test sections should be conducted to cover the entire range of different roughness.

## CORRELATION ANALYSIS

A reliable measuring device should have good correlation with standard reference. If a measuring device has a good correlation with standard reference and good repeatability, this device is said to be reliable with good measuring performance.

The correlation curves between the USF Walking Profiler and the FDOT High-Speed Profiler operated at different sampling rates and speeds are shown in Figures 4.3 through 4.14. The corresponding correlation coefficients ($R^2$ values) are presented in Table 4.7. From these figures and the table, it is clearly shown that the correlation between the USF Walking Profiler and the FDOT High-Speed Profiler is good, meaning the FDOT High-Speed Profiler can be calibrated by the USF Walking Profiler.

**Table 4.7. $R^2$ Values (Correlation Between USF Walking Profiler and FDOT High-Speed Profiler) at Different Operating Speeds and Sampling Rates**

| | 30 mph | 45 mph | 60 mph |
|---|---|---|---|
| Rate 1 | 0.9891 | 0.9745 | 0.9298 |
| Rate 2 | 0.9911 | 0.9889 | 0.9918 |
| Rate 3 | 0.9686 | 0.9611 | 0.9955 |
| Rate 4 | 0.9315 | 0.9223 | 0.9484 |

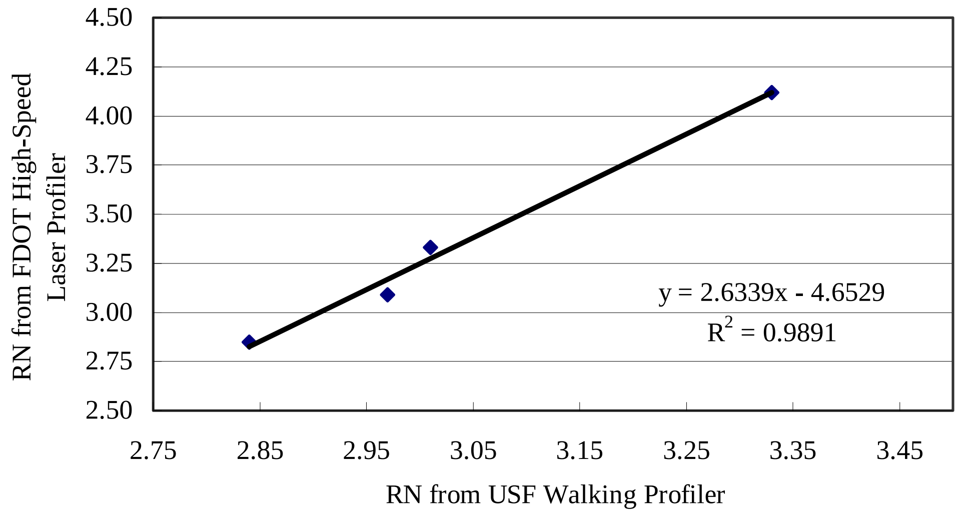


Figure 4.3. Correlation Between FDOT High-Speed Laser Profiler and USF Walking Profiler (RN, 30 mph, Rate1)

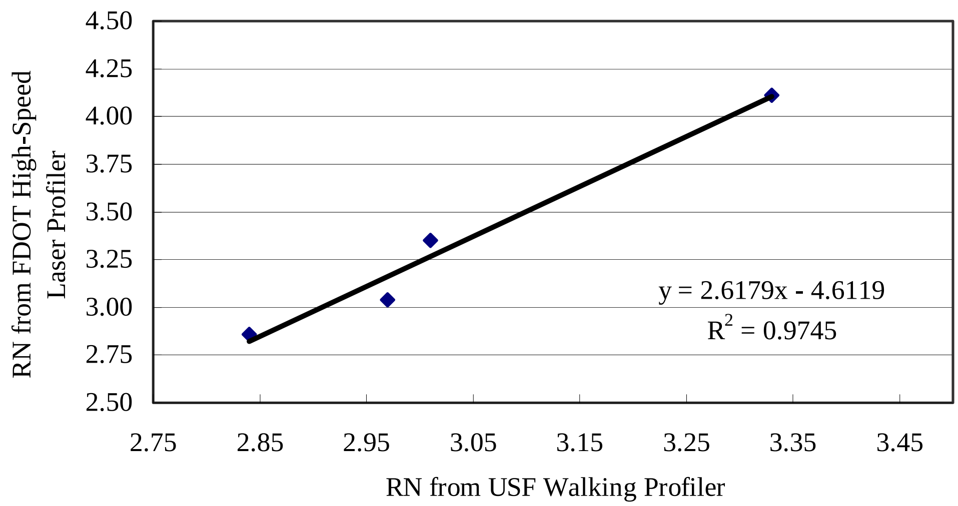


Figure 4.4. Correlation Between FDOT High-Speed Laser Profiler and USF Walking Profiler (RN, 45 mph, Rate1)

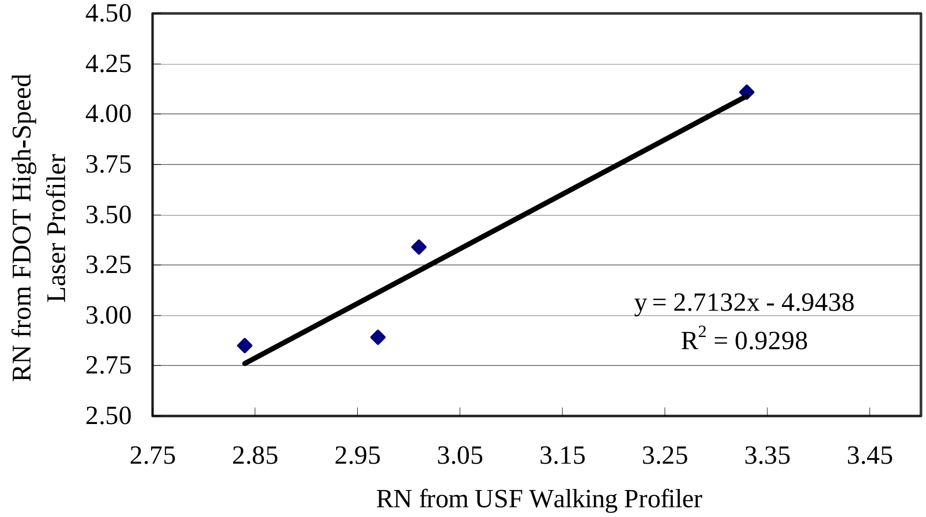


Figure 4.5. Correlation Between FDOT High-Speed Laser Profiler and USF Walking Profiler (RN, 60 mph, Rate1)

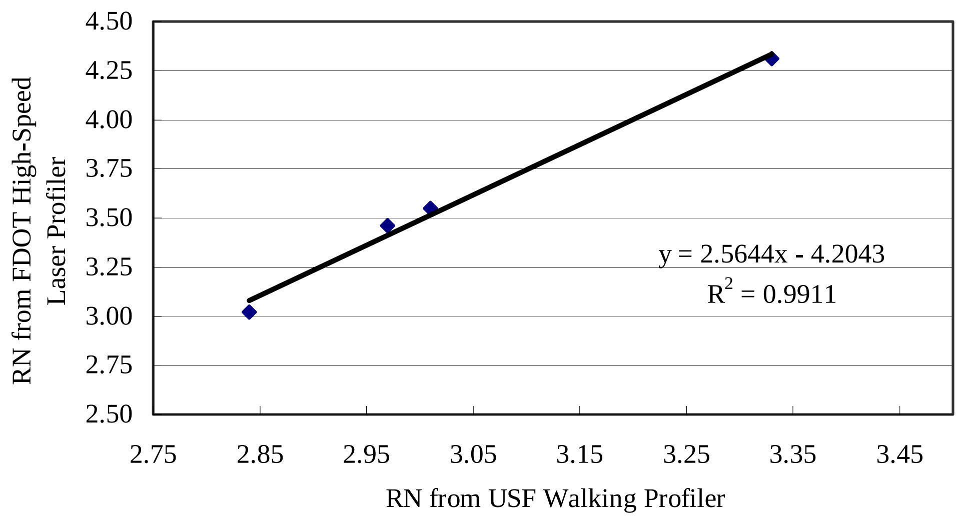


Figure 4.6. Correlation Between FDOT High-Speed Laser Profiler and USF Walking Profiler (RN, 30 mph, Rate2)

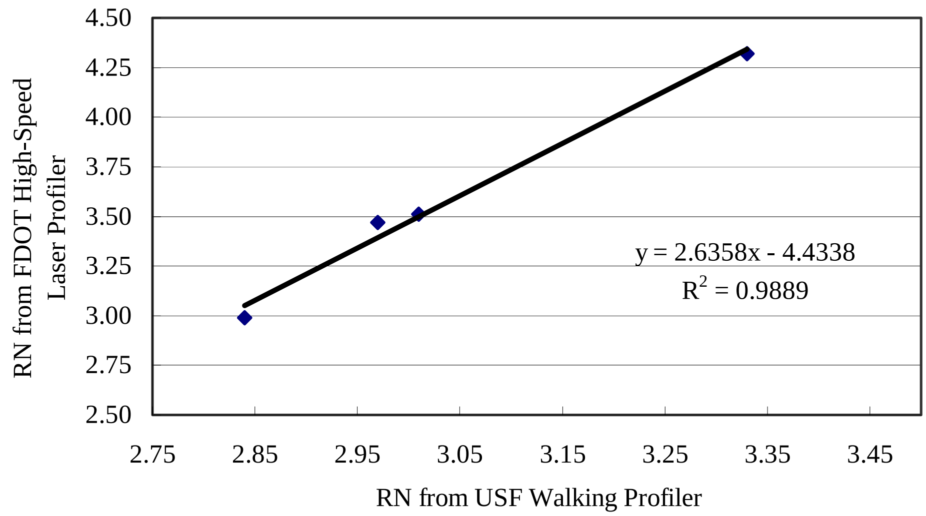


Figure 4.7. Correlation Between FDOT High-Speed Laser Profiler and USF Walking Profiler (RN, 45 mph, Rate2)

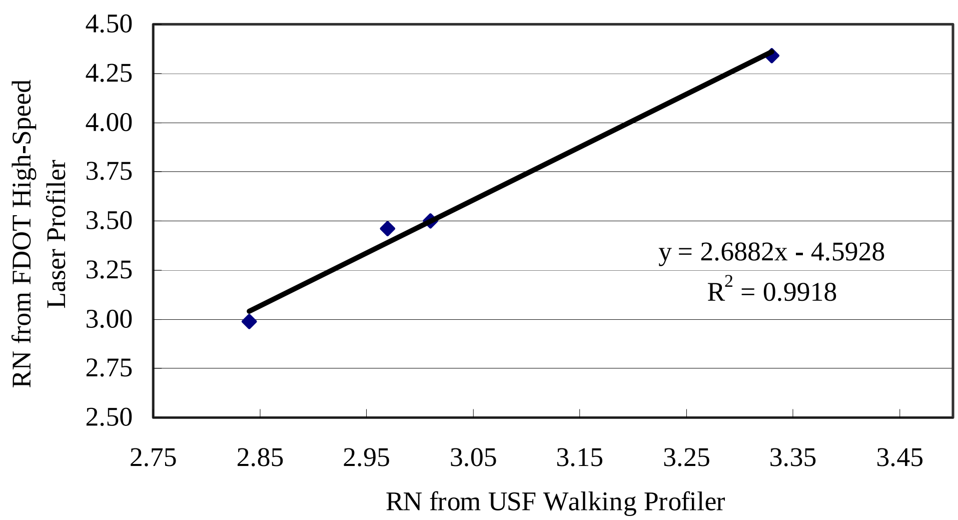


Figure 4.8. Correlation Between FDOT High-Speed Laser Profiler and USF Walking Profiler (RN, 60 mph, Rate2)

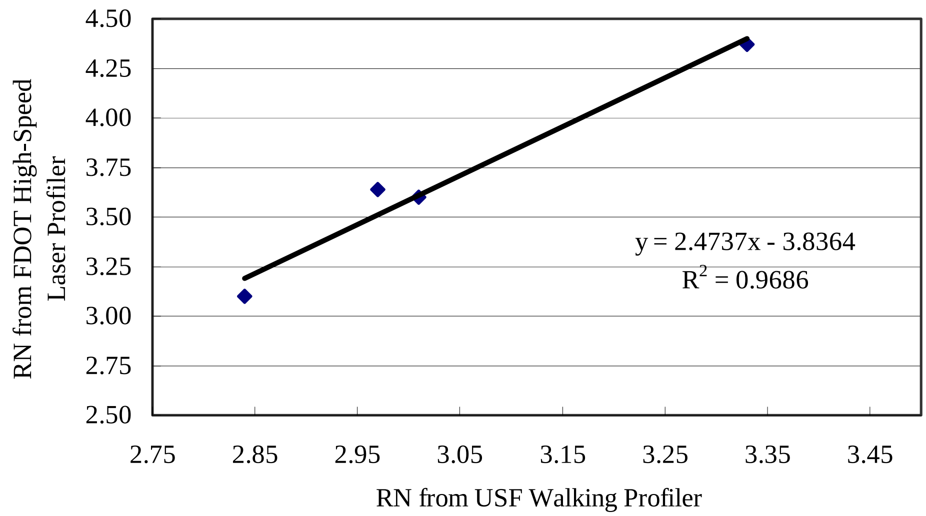


Figure 4-9. Correlation Between FDOT High-Speed Laser Profiler and USF Walking Profiler (RN, 30 mph, Rate3)

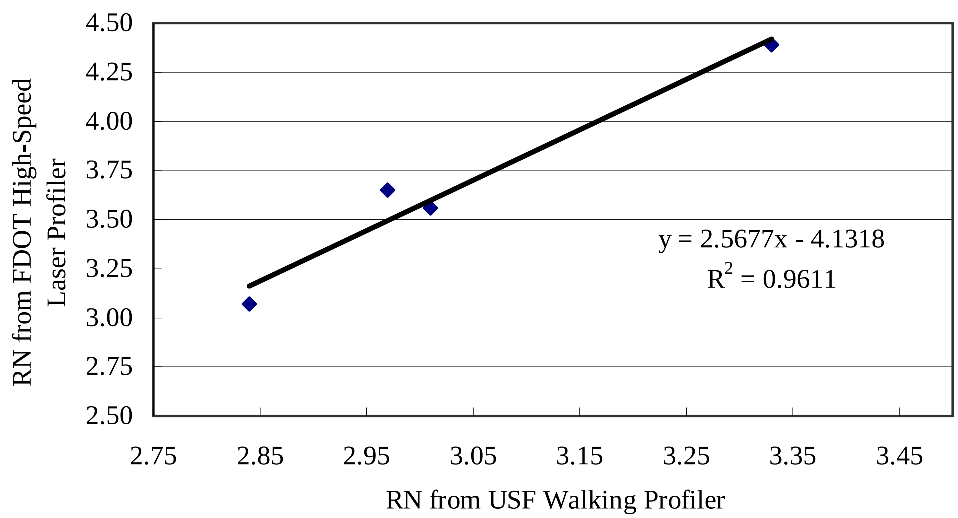


Figure 4-10. Correlation Between FDOT High-Speed Laser Profiler and USF Walking Profiler (RN, 45 mph, Rate3)

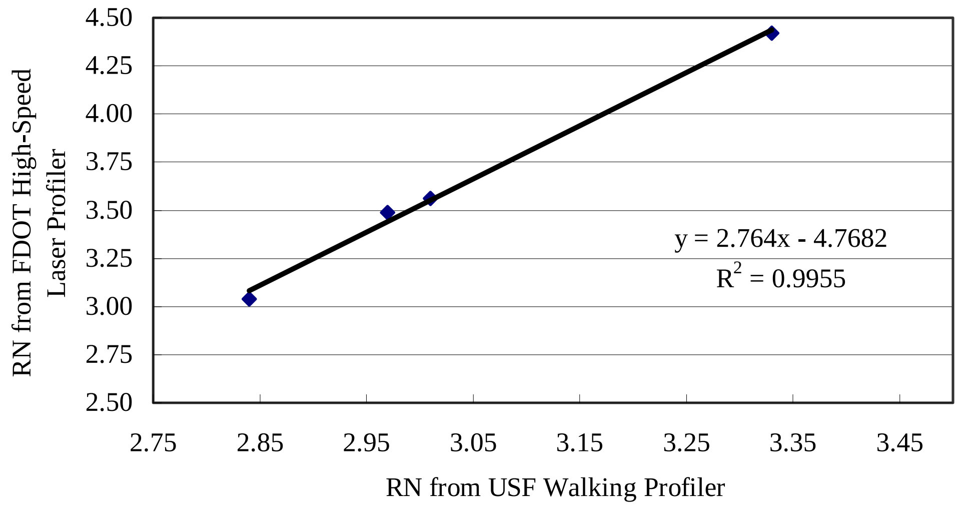


Figure 4-11. Correlation Between FDOT High-Speed Laser Profiler and USF Walking Profiler (RN, 60 mph, Rate3)

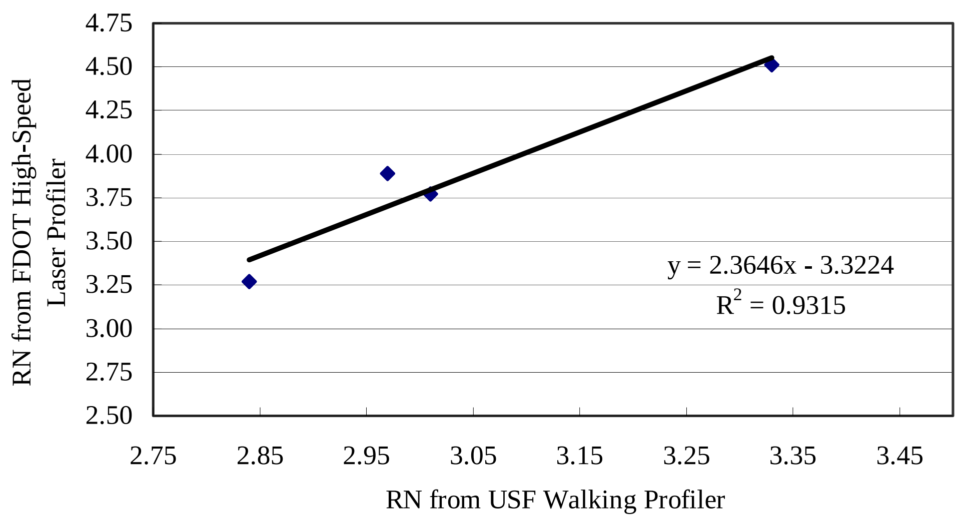


Figure 4-12. Correlation Between FDOT High-Speed Laser Profiler and USF Walking Profiler (RN, 30 mph, Rate4)

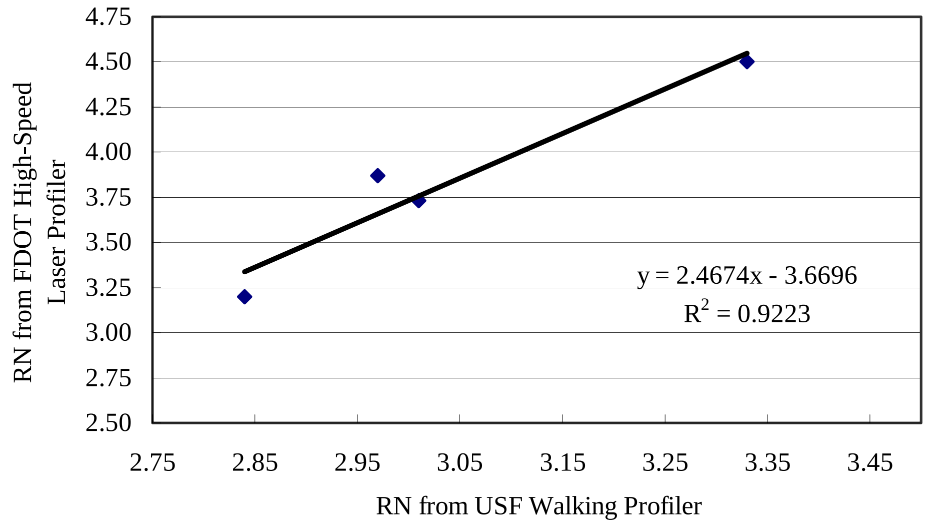


Figure 4-13. Correlation Between FDOT High-Speed Laser Profiler and USF Walking Profiler (RN, 45 mph, Rate4)

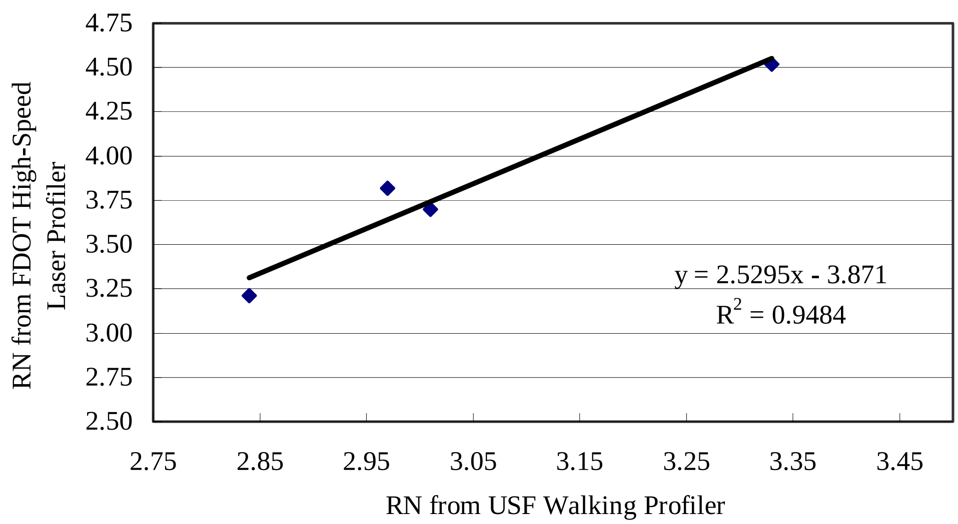


Figure 4-14. Correlation Between FDOT High-Speed Laser Profiler and USF Walking Profiler (RN, 60 mph, Rate4)

# CHAPTER 5. EVALUATION ON IRI

All roughness measuring devices used in the project have the function to produce IRI. Although this project focused on the FDOT High-Speed Profiler and USF Walking Profiler, the ICC Walking Profiler and the FACE Dipstick were operated in these test sections to obtain IRI. The roughness measurements from these devices were used as references to evaluate the correlation performance of the FDOT High-Speed Profiler and USF Walking Profiler. The evaluation of IRI focused on the correlation between these roughness measuring devices. Other performances such as repeatability and accuracy of these devices have been proved to be acceptable in practice. This chapter presents the IRI correlativity between these devices including the FDOT High-Speed Profiler, USF Walking Profiler, the ICC Walking Profiler, and the FACE Dipstick.

## FIELD DATA

All the devices were operated in FDOT test sections 1, 4, 6, and 7. Repeated runs were performed and the average values from the repeated runs were used for correlation analysis. Table 5.1 presents the average IRI values from USF Walking Profiler, the ICC Walking Profiler, and the FACE Dipstick. Table 5.2 presents the IRI values from the FDOT High-Speed Profiler.

**Table 5.1. IRI Values Collected by FACE Dipstick, USF Walking Profiler, and ICC Walking Profiler**

| Sections | FACE Dipstick | USF Walking Profiler | ICC Walking Profiler |
|---|---|---|---|
| 1 | 48.56 | 53.27 | 54.06 |
| 4 | 86.76 | 89.53 | 98.52 |
| 6 | 167.67 | 170.40 | 174.28 |
| 7 | 104.63 | 94.43 | 109.49 |

**Table 5.2. IRI Values Collected by FDOT High-Speed Profiler at Different Sampling Rates and Speeds**

| | | Filtered to 300 foot Wavelength | | | Unfiltered | | |
|---|---|---|---|---|---|---|---|
| Sections | Rate | 30 mph | 45 mph | 60 mph | 30 mph | 45 mph | 60 mph |
| Section 1 | 1 | 49 | 49 | 48 | 50 | 50 | 49 |
| | 2 | 47 | 47 | 47 | 48 | 49 | 49 |
| | 3 | 46 | 46 | 46 | 49 | 49 | 48 |
| | 4 | 44 | 44 | 43 | 47 | 48 | 48 |
| Section 4 | 1 | 95 | 97 | 98 | 96 | 98 | 99 |
| | 2 | 91 | 94 | 95 | 94 | 96 | 98 |
| | 3 | 88 | 89 | 96 | 93 | 94 | 102 |
| | 4 | 83 | 84 | 89 | 90 | 92 | 100 |
| Section 6 | 1 | 172 | 171 | 177 | 173 | 172 | 178 |
| | 2 | 165 | 166 | 174 | 168 | 170 | 178 |
| | 3 | 160 | 163 | 175 | 168 | 171 | 184 |
| | 4 | 152 | 157 | 166 | 164 | 170 | 180 |
| Section 7 | 1 | 107 | 108 | 109 | 108 | 110 | 111 |
| | 2 | 103 | 104 | 110 | 105 | 107 | 113 |
| | 3 | 100 | 103 | 109 | 106 | 109 | 115 |
| | 4 | 94 | 97 | 105 | 103 | 106 | 115 |

**CORRELATION BETWEEN FACE DIPSTICK, USF WALKING PROFILER, ICC WALKING PROFILER**

FACE Dipstick has been considered standard device for field calibration because it has beast accuracy performance as compared with other automated roughness measuring devices. If a roughness measuring device has good correlativity with FACE Dipstick, this device is considered having good correlation with standard reference.

Figure 5.1 shows the correlation between FACE Dipstick and USF Walking Profiler. From this figure, it can be seen that the USF Walking Profiler had good correlativity with FACE Dipstick ($R^2$ = 0.981). Figure 5.2 presents the correlation between FACE Dipstick and ICC Walking Profiler. Similar to USF Walking Profiler, ICC Walking Profiler had good correlativity with FACE Dipstick ($R^2$ = 0.996). In fact, USF Walking Profiler and ICC Walking Profiler all measure the longitudinal profile based on the similar principle as FACE Dipstick uses. Thus, it is reasonable that the correlation between FACE Dipstick and USF Walking Profiler and the correlation between FACE Dipstick and ICC Walking Profiler are good.

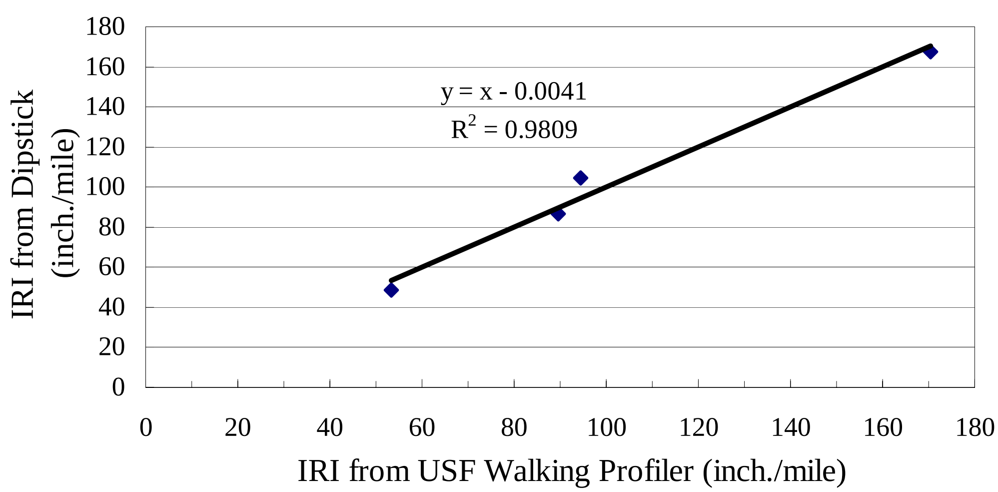


Figure 5.1. Correlation between Face Dipstick and USF Walking Profiler (IRI)

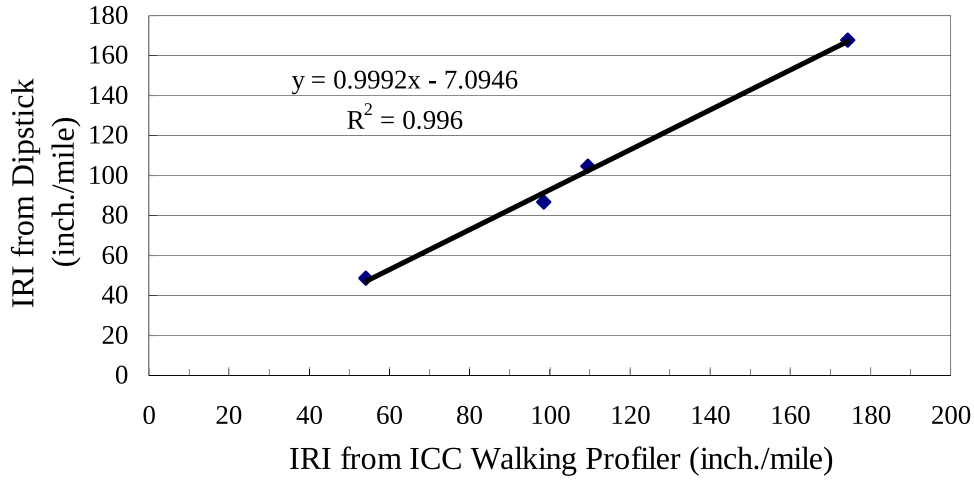


Figure 5.2. Correlation between Face Dipstick and ICC Walking Profiler (IRI)

To further evaluate the correlation performance of USF Walking Profiler with standard reference, the correlativity between USF Walking Profiler and ICC Walking Profiler was analyzed. Figure 5.3 shows the correlation analysis result. From this figure, it can be seen that the correlativity between the two devices was good ($R^2$ = 0.984).

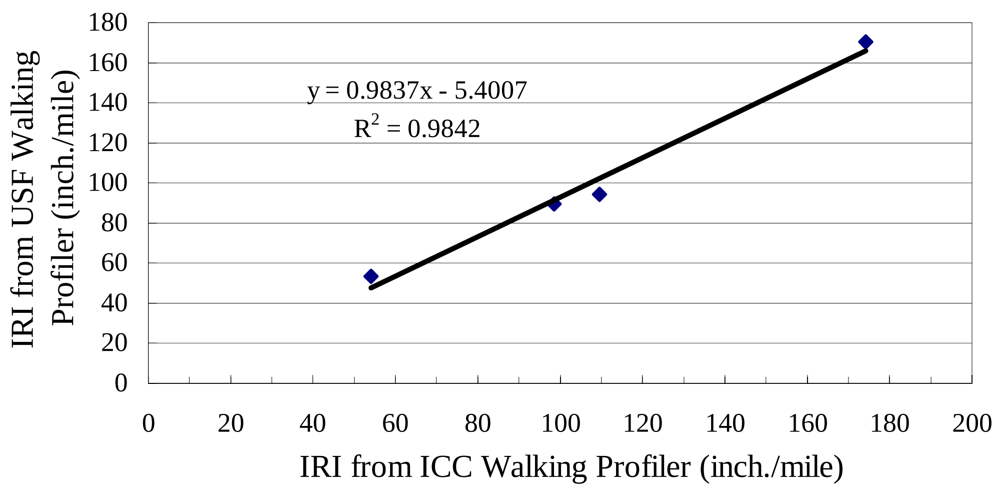


Figure 5.3. Correlation between USF Walking Profiler and ICC Walking Profiler (IRI)

## CORRELATION BETWEEN FDOT HIGH-SPEED PROFILER AND USF WALKING PROFILER

Since the USF Walking Profiler showed good correlation with FACE Dipstick and ICC Walking Profiler as presented previously, USF Walking Profiler could be used as a standard reference to calibrate FDOT High-Speed Profiler. In this project, one of the main purposes was to analyze the correlativity between USF Walking Profiler and FDOT High-Speed Profiler. IRI data from FDOT High-Speed Profiler were collected at different sampling rates (rates 1 – 4) and at different speeds (30 mph, 45 mph, and 60 mph). Original data showed that the operating speed had no significant impact on the IRI measurements. However, to analyze the correlativity, correlation results were obtained under different combinations of sampling rate and speed.

During field data collection, the FDOT High-Speed Profiler produced roughness data at different wavelengths (bandwidth), including 300 foot-wavelength and full wavelength (unfiltered bandwidth). Usually, IRI should be processed from pavement surface longitudinal profile with wavelength bandwidth in the range of 200 feet to 500 feet. Thus, the correlation analysis was based on the filtered data with 300 foot-wavelength.

### Correlation for Sampling Rate 1

Figures 5.4 – 5.6 present the correlation analysis results for sampling rate 1 at 30 mph, 45 mph, and 60 mph, respectively. From these figures, it is found that the correlation between FDOT High-Speed Profiler and USF Walking Profiler at sampling rate 1 under different operating speeds was good.

### Correlation for Sampling Rate 2

Figures 5.7 – 5.9 show the correlation analysis results for sampling rate 2 at 30 mph, 45 mph, and 60 mph, respectively. Similar to the correlation at sampling rate 2, the correlation between FDOT High-Speed Profiler and USF Walking Profiler at sampling rate 2 under different operating speeds was good.

**Correlation for Sampling Rate 3**

Figures 5.10 – 5.12 summarize the correlation analysis results for sampling rate 3 at 30 mph, 45 mph, and 60 mph, respectively. Again, based on the correlation analysis results, it is found that the correlation between FDOT High-Speed Profiler and USF Walking Profiler at sampling rate 3 under different operating speeds was good.

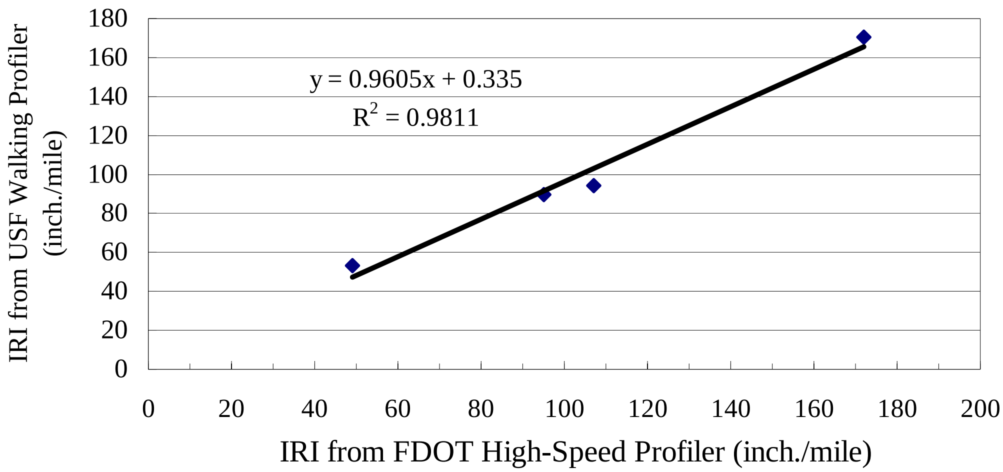


Figure 5.4. Correlation between USF Walking Profiler and FDOT High-Speed Profiler (30 mph, Sampling Rate 1)

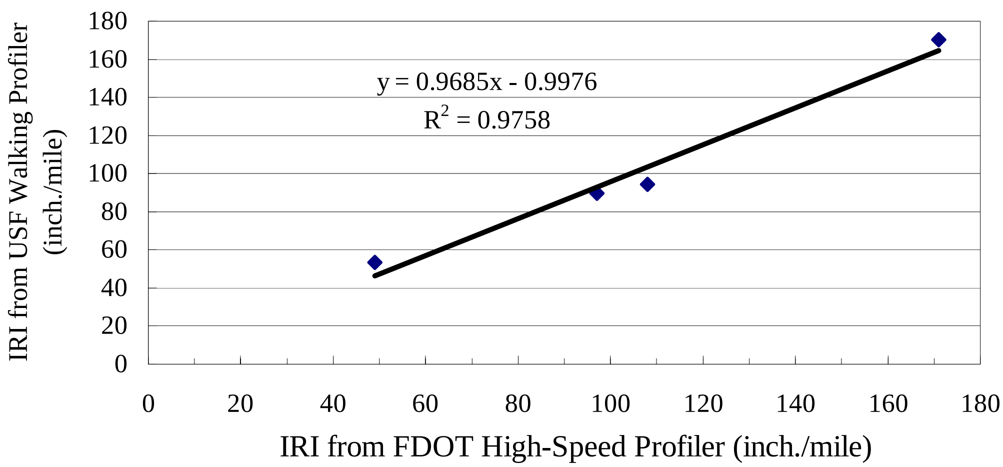


Figure 5.5. Correlation between USF Walking Profiler and FDOT High-Speed Profiler (45 mph, Rate 1)

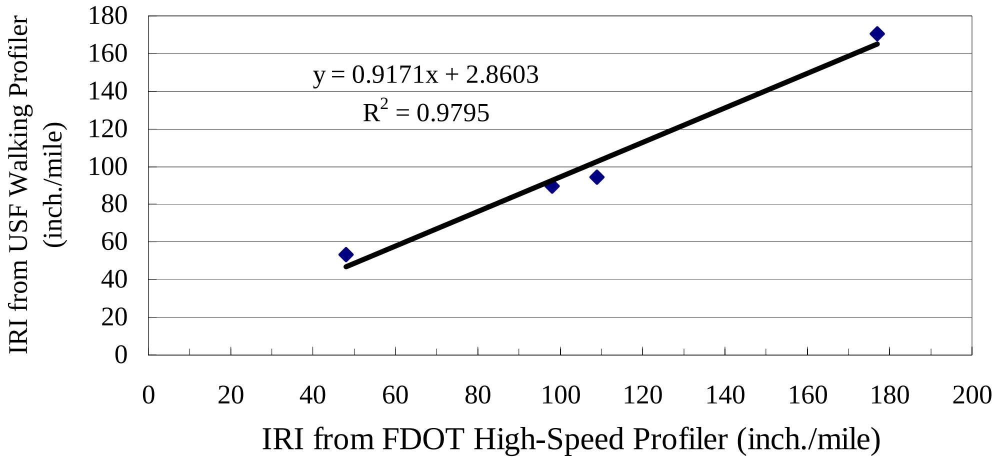


Figure 5.6. Correlation between USF Walking Profiler and FDOT High-Speed Profiler (60 mph, Rate 1, 300-ft.)

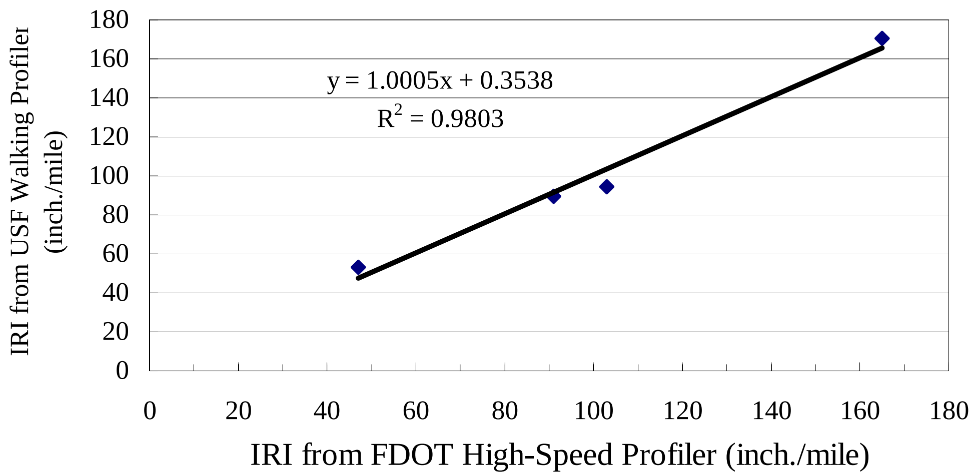


Figure 5.7. Correlation between USF Walking Profiler and FDOT High-Speed Profiler (30 mph, Rate 2, 300-ft.)

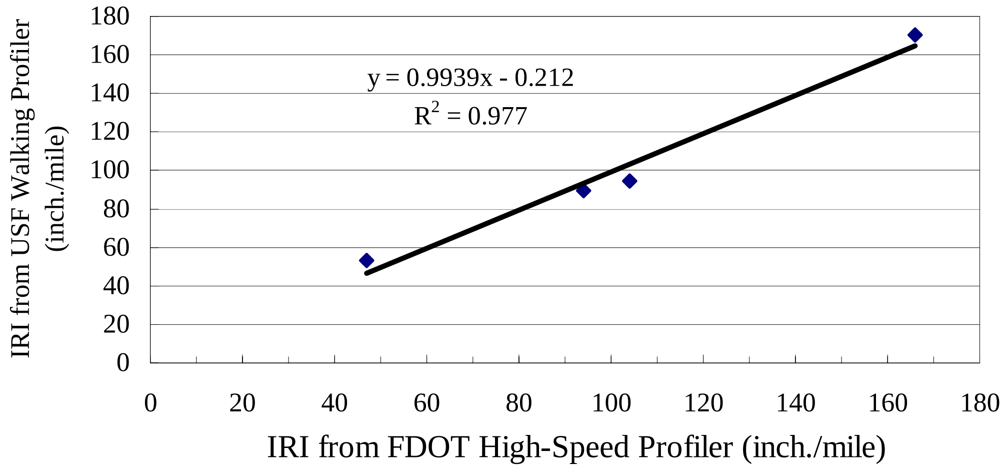


Figure 5.8. Correlation between USF Walking Profiler and FDOT High-Speed Profiler (45 mph, Rate 2)

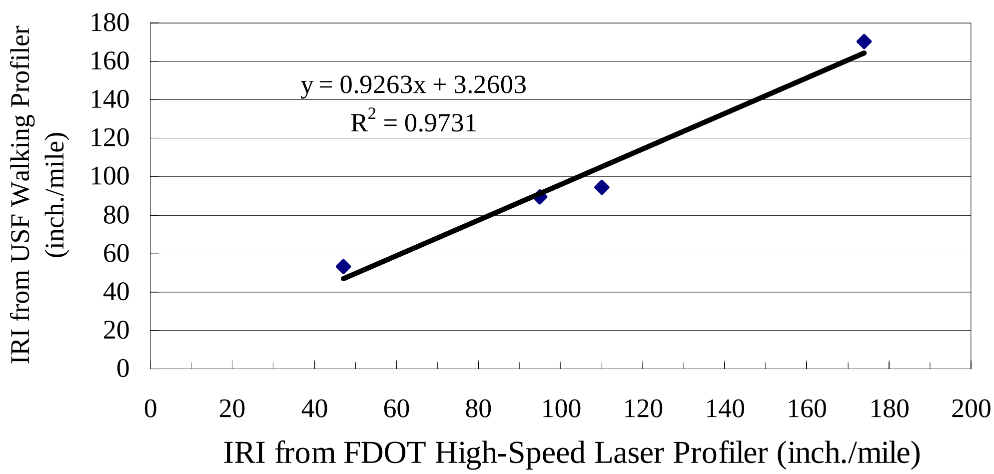


Figure 5.9. Correlation between USF Walking Profiler and FDOT High-Speed Profiler (60 mph, Rate 2)

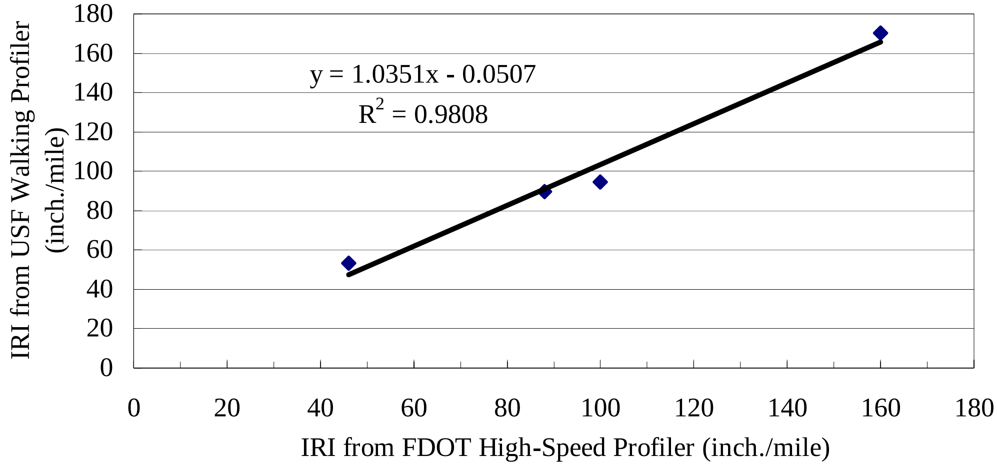


Figure 5.10. Correlation between USF Walking Profiler and FDOT High-Speed Profiler (30 mph, Rate 3)

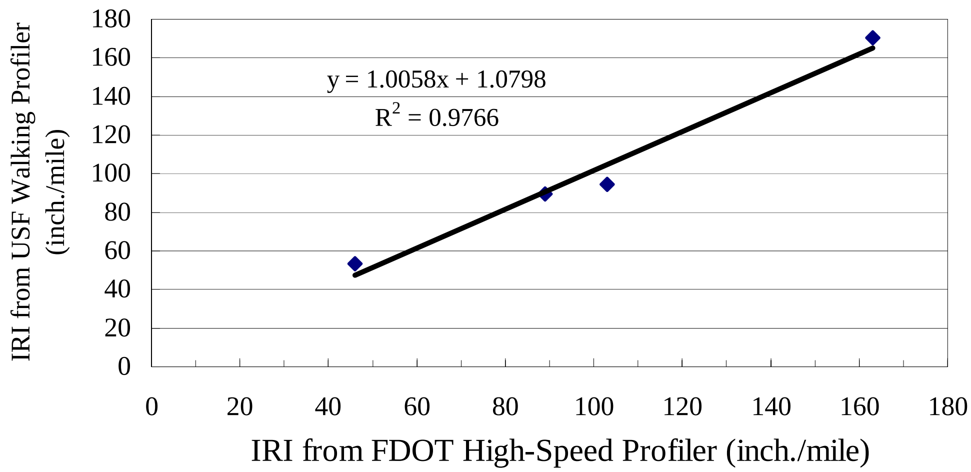


Figure 5.11. Correlation between USF Walking Profiler and FDOT High-Speed Profiler (45 mph, Rate 3)

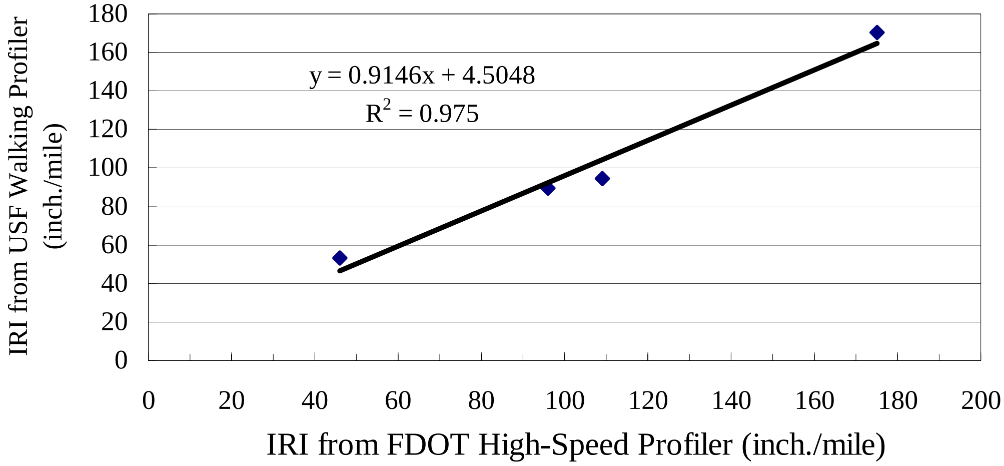


Figure 5.12. Correlation between USF Walking Profiler and FDOT High-Speed Profiler (60 mph, Rate 3)

**SUMMARY**

Based on the correlation analysis results, it was found that the correlativity between all these devices was good. It appears that USF Walking Profiler had good correlation with FACE Dipstick (the standard device for calibrating roughness measuring systems) and with ICC Walking Profiler. Also, the USF Walking Profiler had good correlation with FDOT High-Speed Profiler according to the correlation analysis results. Thus, it was proved that the USF Walking Profiler could be used to calibrate FDOT High-Speed Profiler in terms of IRI.

However, since the correlation analysis was based on field data collected from FDOT test sections 1, 4, 6, and 7, with limited roughness condition range, the correlation functions (linear regression functions shown in Figures 5.1 – 5.12) have limited application ranges. To practically use these functions, more test sites with worse roughness conditions may be needed for calibration purpose.

# CHAPTER 6. DISCUSSIONS ON SAMPLING INTERVAL

## IMPACTS OF SAMPLING INTERVAL ON MEASUREMENTS

Sampling interval of a roughness measuring system does have some impacts on the outputs of the measuring system. Based on the discussions presented in Refs. 2, 4, and 6 [2, 4, 6], small sampling interval may cause "aliasing", resulting measurement bias error; However, if the sampling interval is too large, details on vertical elevation of longitudinal profile could be ignored, resulting in too low measurement on IRI.

As shown in Figures 2.2 and 2.5, IRI has a wavelength bandwidth of 1.2 to 30 meters while RN has a wavelength bandwidth of 0.5 to 11 meters. Thus, RN is sensitive to shorter wavelengths than the IRI, meaning RN needs shorter sampling interval to reflect short-wavelength roughness than IRI needs.

## RECOMMENDATIONS BY LITERATURES

In this research project, literature review was performed to search recommendations on sampling intervals for measuring RN and IRI. However, as a result of literature search, no specific recommendations on the selections of sampling intervals were found. In the paper by Sayers, it is recommended that the maximum sampling interval when measuring IRI should not be more than 300 mm [2]. The same recommendation is also listed in ASTM E 1926-98 [8]. However, for RN, ASTM E 1489-98 states: "The distance interval over which the Ride Number is computed is discretionary" [9]. Conceptually, measurement of RN should take a smaller sampling interval as compared to the measurement of IRI. This is stated in Research Results Digest No. 244 [7].

## INDICATION FROM THIS RESEARCH

The original RN values obtained from field measurements in the research clearly indicates that different sampling rates resulted in different RN measurements with the other conditions given. More specifically, at lower sampling rate, the FDOT High-Speed

Profiler produced higher RN values as compared at higher sampling rate. Statistical tests (ANOVA tests) were performed in the research and test results also indicated that the sampling rate could affect RN measurements. Practically, smaller sampling interval (higher sampling rate) should be used when measuring RN values. As stated previously, RN has a wavelength bandwidth of 0.5 to 11 meters. According to signal sampling theory, to obtain signal with wavelength bandwidth of 0.5 meters, the sampling interval should not be longer than 0.25 meters or 0.82 feet. Since the FDOT High-Speed Profiler has four different sampling rates, i.e. sampling intervals of 0.273 ft. (rate 1), 0.545 ft. (rate 2), 0.818 ft. (rate 3), and 1.091ft. (rate 4), to effectively measure RN without losing details of roughness information, sampling rates 1 and 2 would be more adequate.

# CHAPTER 7. SUMMARY, CONCLUSION, & RECOMMENDATION

## SUMMARIES

The main purpose of this research project was to evaluate whether the FDOT High-Speed Profiler could effectively measure RN values with satisfactory performance. With such an assumption, the research project was to determine which type-I pavement surface longitudinal profiler could be used to calibrate the FDOT High-Speed Profiler in terms of RN. To reach the purpose, standard roughness measuring systems were used as references in fields to evaluate whether the FDOT High-Speed Profiler had good correlation with these standard references. The reference measurements included IRI valuates collected by FACE Dipstick, ICC Walking Profiler, and USF Walking Profiler from FDOT test sections 1, 4, 6, and 7 in Gainesville, Florida. However, since FACE Dipstick and ICC Walking Profiler do not have the function to produce RN values, only the USF Walking Profiler was used to evaluate the FDOT High-Speed Profiler's performance in measuring RN values.

Field tests were performed in April 2002 in Gainesville, Florida. Four FDOT calibration sections (sections 1, 4, 6, and 7) were measured by the FDOT High-Speed Profiler, USF Walking Profiler, FACE Dipstick, and ICC Walking Profiler to obtain corresponding IRI values and by the FDOT High-Speed Profiler and USF Walking Profiler to obtain corresponding RN values. The FDOT High-Speed Profiler was operated at different sampling rates (rates 1 – 4) and at different speeds (30 mph, 45 mph, and 60 mph). All devices were operated for at least three repeated runs.

After field data were obtained, data analysis was performed to evaluate the measuring performance of the FDOT High-Speed Profiler in obtaining RN values. The performance was evaluated based on: the impact of sampling rate, the impact of operating speed, repeatability, and correlativity with USF Walking Profiler, etc. The repeatability of the USF Walking Profiler was also evaluated.

Linear regression analysis (correlation analysis) was performed to evaluate the IRI correlativity between the FDOT High-Speed Profiler, USF Walking Profiler, ICC Walking Profiler, and FACE Dipstick. Again, the FDOT High-Speed Profiler was operated at different sampling rates and different speeds.

## CONCLUSIONS

From data analysis, it was found that the FDOT High-Speed Profiler could be operated at different operating speeds (30 mph – 60 mph) with very little difference in RN values for a given test section and sampling rate. However, any speeds beyond the speed range may not produce the same conclusion because the analysis was based on the speed range and no conclusion is supported if the speed is beyond the speed range.

The factor of sampling rate did show some impact on RN outputs of the FDOT High-Speed Profiler. Thus, for a given test section, the data sampling rate should be specified. In fact, if sufficient field data are available, models could be developed to calibrate the impact of sampling rate on RN outputs.

Both FDOT High-Speed Profiler and USF Walking Profiler showed satisfactory repeatability performances. Thus, for real data collection by these two devices, if the data collection procedure is well controlled, there is no need to run these devices more than three repeated runs because the difference between different runs could be ignored.

The FDOT High-Speed Profiler and USF Walking Profiler had good correlations at different sampling rates and operating speeds of the FDOT High-Speed Profiler. Since the USF Walking Profiler is considered the type I roughness measuring device, it can be used to calibrate the FDOT High-Speed Profiler’s RN outputs. This conclusion could make the procedure to measure pavement surface RN values more efficiently and effectively.

Correlation analysis showed that all the roughness measuring devices used in the project had good correlations between them in terms of IRI. Thus, the FDOT Walking Profiler could be calibrated by any of these devices because these walking profilers are considered the type-I roughness measuring devices.

## RECOMMENDATIONS

The FDOT High-Speed Profiler could be used to measure pavement RN values with satisfactory performance based on the analysis done in the research. To calibrate the FDOT High-Speed Profiler in terms of RN values, future research is needed to develop the ways for RN calibration.

Since the impact of sampling rate of the FDOT High-Speed Profiler had significant impact on its RN output, to measure RN values, the FDOT High-Speed Profiler should be operated at a specified sampling rate. Any change in sampling rate would change the RN outputs. To best use the FDOT High-Speed Profiler to measure RN values, further research is needed to verify the best sampling rate that the FDOT High-Speed Profiler should use for measuring RN values.

Based on the discussions presented in Chapter 6, it is recommended that sampling rate 1 or sampling rate 2 be used when measuring RN values.

# REFERENCES


1. Sayers, M. W., Thomas D. Gillespie, and William D. O. Paterson. "Guideline for Conducting and Calibrating Road Roughness Measurements." *World Bank Technical Paper*, Number 46, The World Bank, Washington, D.C., U.S.A., 1986

2. Sayers, M. W., “On the Calculation of International Roughness Index from Longitudinal Road Profile”, Transportation Research Record 1501, Transportation Research Board, 1995, pp. 1- 12

3. Transportation Research Board, Guidelines for Longitudinal Pavement Profile Measurement, NCHRP Report 434, 1999

4. Sayers, M. W., The Little Book of Profiling, University of Michigan, September 1998

5. Gillespie,T.D., M.W. Sayers, and L. Segel. "Calibration of Response-type Road Roughness Measuring Systems." NCHRP Report 228.Washington D.C. 1980

6. Transportation Research Board, Pavement Roughness and Reliability Field Evaluation, NCHRP Report 308, July 1988

7. Research Results Digest, “Operational Guidelines for Longitudinal Pavement Measurement”, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, No. 244, November 1999

8. ASTM, “Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements, ASTM Designation E 1926-98, March 1999, pp. 1015 – 1032

9. ASTM, “Standard Practice for Computing Ride Number of Roads from Longitudinal Profile Measurements Made by an Inertial Profile Measuring Device”, ASTM Designation E 1489-98, March 1999, pp. 926 – 941

# APPENDIX A

Roughness Data Obtained from the FDOT High Speed Profiler

RATE VALIDATION STUDY INTERNATIONAL ROUGHNESS INDEX ENGLISH UNITS / DOT 24725
HIGH-SPEED LASER PROFILER DATA SECTION 1 WESTBOUND FILTERED TO 300 FOOT WAVELENGTH

| RATE | PASS | TEST SPEEDS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 30 MPH | | | 45 MPH | | | 60 MPH | | |
| | | IRI 1 | IRI 2 | IRI AVG. | IRI 1 | IRI 2 | IRI AVG. | IRI 1 | IRI 2 | IRI AVG. |
| | | | | | | | | | | |
| 1 | 1 | 41 | 56 | 49 | 42 | 55 | 49 | 41 | 56 | 48 |
| 1 | 2 | 42 | 57 | 49 | 44 | 53 | 48 | 41 | 54 | 48 |
| 1 | 3 | 42 | 54 | 48 | 43 | 56 | 50 | 42 | 54 | 48 |
| AVERAGE | | 42 | 56 | 49 | 43 | 55 | 49 | 41 | 55 | 48 |
| DIFFERENCE | | 1 | 3 | 1 | 2 | 3 | 2 | 1 | 2 | 0 |
| | | | | | | | | | | |
| 2 | 1 | 40 | 53 | 47 | 41 | 53 | 47 | 41 | 50 | 46 |
| 2 | 2 | 40 | 54 | 47 | 40 | 53 | 47 | 44 | 53 | 48 |
| 2 | 3 | 41 | 55 | 48 | 41 | 54 | 48 | 43 | 51 | 47 |
| AVERAGE | | 40 | 54 | 47 | 41 | 53 | 47 | 43 | 51 | 47 |
| DIFFERENCE | | 1 | 2 | 1 | 1 | 1 | 1 | 3 | 3 | 2 |
| | | | | | | | | | | |
| 3 | 1 | 41 | 53 | 47 | 40 | 52 | 46 | 41 | 51 | 46 |
| 3 | 2 | 40 | 52 | 46 | 43 | 50 | 46 | 43 | 49 | 46 |
| 3 | 3 | 38 | 54 | 46 | 43 | 50 | 46 | 40 | 50 | 45 |
| AVERAGE | | 40 | 53 | 46 | 42 | 51 | 46 | 41 | 50 | 46 |
| DIFFERENCE | | 3 | 2 | 1 | 3 | 2 | 0 | 3 | 2 | 1 |
| | | | | | | | | | | |
| 4 | 1 | 36 | 51 | 44 | 37 | 49 | 43 | 38 | 49 | 43 |
| 4 | 2 | 37 | 50 | 44 | 37 | 51 | 44 | 38 | 48 | 43 |
| 4 | 3 | 36 | 50 | 43 | 38 | 49 | 44 | 38 | 50 | 44 |
| AVERAGE | | 36 | 50 | 44 | 37 | 50 | 44 | 38 | 49 | 43 |
| DIFFERENCE | | 1 | 1 | 1 | 1 | 2 | 1 | 0 | 2 | 1 |

RATE VALIDATION STUDY RIDE NUMBER / DOT 24725
HIGH-SPEED LASER PROFILER DATA SECTION 1 WESTBOUND FILTERED TO 300 FOOT WAVELENGTH

| RATE | PASS | TEST SPEEDS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 30 MPH | | | 40 MPH | | | 60 MPH | | |
| | | RN 1 | RN 2 | RN AVG. | RN 1 | RN 2 | RN AVG. | RN 1 | RN 2 | RN AVG. |
| | | | | | | | | | | |
| 1 | 1 | 4.16 | 4.10 | 4.13 | 4.19 | 4.06 | 4.12 | 4.20 | 4.05 | 4.12 |
| 1 | 2 | 4.15 | 4.09 | 4.12 | 4.15 | 4.12 | 4.14 | 4.18 | 4.03 | 4.10 |
| 1 | 3 | 4.19 | 4.05 | 4.12 | 4.15 | 4.02 | 4.08 | 4.17 | 4.08 | 4.12 |
| AVERAGE | | 4.17 | 4.08 | 4.12 | 4.16 | 4.07 | 4.11 | 4.18 | 4.05 | 4.11 |
| DIFFERENCE | | 0.04 | 0.05 | 0.01 | 0.04 | 0.10 | 0.06 | 0.03 | 0.05 | 0.02 |
| | | | | | | | | | | |
| 2 | 1 | 4.36 | 4.27 | 4.32 | 4.39 | 4.28 | 4.33 | 4.41 | 4.34 | 4.37 |
| 2 | 2 | 4.37 | 4.26 | 4.31 | 4.37 | 4.27 | 4.32 | 4.35 | 4.27 | 4.31 |
| 2 | 3 | 4.35 | 4.24 | 4.29 | 4.38 | 4.25 | 4.31 | 4.38 | 4.33 | 4.35 |
| AVERAGE | | 4.36 | 4.26 | 4.31 | 4.38 | 4.27 | 4.32 | 4.38 | 4.31 | 4.34 |
| DIFFERENCE | | 0.02 | 0.03 | 0.03 | 0.02 | 0.03 | 0.02 | 0.06 | 0.07 | 0.06 |
| | | | | | | | | | | |
| 3 | 1 | 4.41 | 4.29 | 4.35 | 4.42 | 4.35 | 4.39 | 4.45 | 4.39 | 4.42 |
| 3 | 2 | 4.45 | 4.36 | 4.40 | 4.40 | 4.38 | 4.39 | 4.43 | 4.40 | 4.41 |
| 3 | 3 | 4.41 | 4.30 | 4.35 | 4.40 | 4.40 | 4.40 | 4.46 | 4.39 | 4.42 |
| AVERAGE | | 4.42 | 4.32 | 4.37 | 4.41 | 4.38 | 4.39 | 4.45 | 4.39 | 4.42 |
| DIFFERENCE | | 0.04 | 0.07 | 0.05 | 0.02 | 0.05 | 0.01 | 0.03 | 0.01 | 0.01 |
| | | | | | | | | | | |
| 4 | 1 | 4.58 | 4.46 | 4.52 | 4.54 | 4.48 | 4.51 | 4.57 | 4.48 | 4.52 |
| 4 | 2 | 4.56 | 4.45 | 4.50 | 4.54 | 4.45 | 4.49 | 4.56 | 4.49 | 4.52 |
| 4 | 3 | 4.56 | 4.46 | 4.51 | 4.55 | 4.48 | 4.51 | 4.57 | 4.48 | 4.52 |
| AVERAGE | | 4.57 | 4.46 | 4.51 | 4.54 | 4.47 | 4.50 | 4.57 | 4.48 | 4.52 |
| DIFFERENCE | | 0.02 | 0.01 | 0.02 | 0.01 | 0.03 | 0.02 | 0.01 | 0.01 | 0.00 |

RATE VALIDATION STUDY INTERNATIONAL ROUGHNESS INDEX ENGLISH UNITS / DOT 24725
HIGH-SPEED LASER PROFILER DATA SECTION 4 EASTBOUND FILTERED TO 300 FOOT WAVELENGTH

| RATE | PASS | TEST SPEEDS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 30 MPH | | | 45 MPH | | | 60 MPH | | |
| | | IRI 1 | IRI 2 | IRI AVG. | IRI 1 | IRI 2 | IRI AVG. | IRI 1 | IRI 2 | IRI AVG. |
| | | | | | | | | | | |
| 1 | 1 | 93 | 97 | 95 | 91 | 101 | 96 | 94 | 99 | 96 |
| 1 | 2 | 89 | 103 | 96 | 98 | 97 | 97 | 99 | 96 | 98 |
| 1 | 3 | 88 | 101 | 95 | 95 | 99 | 97 | 106 | 96 | 101 |
| AVERAGE | | 90 | 100 | 95 | 95 | 99 | 97 | 100 | 97 | 98 |
| DIFFERENCE | | 5 | 6 | 1 | 7 | 4 | 1 | 12 | 3 | 5 |
| | | | | | | | | | | |
| 2 | 1 | 85 | 98 | 91 | 91 | 97 | 94 | 98 | 92 | 95 |
| 2 | 2 | 90 | 91 | 90 | 95 | 97 | 96 | 89 | 99 | 94 |
| 2 | 3 | 87 | 98 | 92 | 89 | 95 | 92 | 90 | 102 | 96 |
| AVERAGE | | 87 | 96 | 91 | 92 | 96 | 94 | 92 | 98 | 95 |
| DIFFERENCE | | 5 | 7 | 2 | 6 | 2 | 4 | 9 | 10 | 2 |
| | | | | | | | | | | |
| 3 | 1 | 82 | 97 | 89 | 84 | 93 | 89 | 104 | 88 | 96 |
| 3 | 2 | 89 | 90 | 89 | 88 | 91 | 89 | 98 | 94 | 96 |
| 3 | 3 | 78 | 94 | 86 | 86 | 93 | 89 | 103 | 88 | 96 |
| AVERAGE | | 83 | 94 | 88 | 86 | 92 | 89 | 102 | 90 | 96 |
| DIFFERENCE | | 11 | 7 | 3 | 4 | 2 | 0 | 6 | 6 | 0 |
| | | | | | | | | | | |
| 4 | 1 | 74 | 89 | 81 | 79 | 88 | 83 | 96 | 84 | 90 |
| 4 | 2 | 75 | 94 | 84 | 80 | 90 | 85 | 95 | 85 | 90 |
| 4 | 3 | 79 | 89 | 84 | 78 | 92 | 85 | 89 | 88 | 88 |
| AVERAGE | | 76 | 91 | 83 | 79 | 90 | 84 | 93 | 86 | 89 |
| DIFFERENCE | | 5 | 5 | 3 | 2 | 4 | 2 | 7 | 4 | 2 |

RATE VALIDATION STUDY RIDE NUMBER / DOT 24725

HIGH-SPEED LASER PROFILER DATA SECTION 4 EASTBOUND FILTERED TO 300 FOOT WAVELENGTH

| RATE | PASS | TEST SPEEDS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 30 MPH | | | 40 MPH | | | 60 MPH | | |
| | | RN 1 | RN 2 | RN AVG. | RN 1 | RN 2 | RN AVG. | RN 1 | RN 2 | RN AVG. |
| | | | | | | | | | | |
| 1 | 1 | 2.95 | 3.09 | 3.02 | 3.02 | 3.11 | 3.06 | 2.93 | 3.10 | 3.01 |
| 1 | 2 | 3.07 | 3.16 | 3.12 | 2.84 | 3.12 | 2.97 | 2.82 | 2.97 | 2.89 |
| 1 | 3 | 3.16 | 3.12 | 3.14 | 3.03 | 3.18 | 3.10 | 2.60 | 2.94 | 2.76 |
| AVERAGE | | 3.06 | 3.12 | 3.09 | 2.96 | 3.14 | 3.04 | 2.78 | 3.00 | 2.89 |
| DIFFERENCE | | 0.21 | 0.07 | 0.12 | 0.19 | 0.07 | 0.13 | 0.33 | 0.16 | 0.25 |
| | | | | | | | | | | |
| 2 | 1 | 3.49 | 3.44 | 3.47 | 3.47 | 3.50 | 3.48 | 3.37 | 3.50 | 3.43 |
| 2 | 2 | 3.43 | 3.50 | 3.47 | 3.29 | 3.47 | 3.38 | 3.47 | 3.50 | 3.48 |
| 2 | 3 | 3.42 | 3.48 | 3.45 | 3.56 | 3.52 | 3.54 | 3.50 | 3.45 | 3.48 |
| AVERAGE | | 3.45 | 3.47 | 3.46 | 3.44 | 3.50 | 3.47 | 3.45 | 3.48 | 3.46 |
| DIFFERENCE | | 0.07 | 0.06 | 0.02 | 0.27 | 0.05 | 0.16 | 0.13 | 0.05 | 0.05 |
| | | | | | | | | | | |
| 3 | 1 | 3.66 | 3.60 | 3.63 | 3.69 | 3.65 | 3.67 | 3.36 | 3.62 | 3.48 |
| 3 | 2 | 3.58 | 3.63 | 3.61 | 3.60 | 3.69 | 3.64 | 3.52 | 3.57 | 3.54 |
| 3 | 3 | 3.74 | 3.61 | 3.67 | 3.64 | 3.62 | 3.63 | 3.29 | 3.62 | 3.44 |
| AVERAGE | | 3.66 | 3.61 | 3.64 | 3.64 | 3.65 | 3.65 | 3.39 | 3.60 | 3.49 |
| DIFFERENCE | | 0.16 | 0.03 | 0.06 | 0.09 | 0.07 | 0.04 | 0.23 | 0.05 | 0.10 |
| | | | | | | | | | | |
| 4 | 1 | 3.95 | 3.86 | 3.90 | 3.93 | 3.85 | 3.89 | 3.76 | 3.87 | 3.81 |
| 4 | 2 | 3.98 | 3.79 | 3.88 | 3.90 | 3.82 | 3.86 | 3.77 | 3.88 | 3.82 |
| 4 | 3 | 3.94 | 3.83 | 3.88 | 3.88 | 3.81 | 3.85 | 3.84 | 3.80 | 3.82 |
| AVERAGE | | 3.96 | 3.83 | 3.89 | 3.90 | 3.83 | 3.87 | 3.79 | 3.85 | 3.82 |
| DIFFERENCE | | 0.04 | 0.07 | 0.02 | 0.05 | 0.04 | 0.04 | 0.08 | 0.08 | 0.01 |

RATE VALIDATION STUDY INTERNATIONAL ROUGHNESS INDEX ENGLISH UNITS / DOT 24725
HIGH-SPEED LASER PROFILER DATA SECTION 6 WESTBOUND FILTERED TO 300 FOOT WAVELENGTH

| RATE | PASS | TEST SPEEDS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 30 MPH | | | 45 MPH | | | 60 MPH | | |
| | | IRI 1 | IRI 2 | IRI AVG. | IRI 1 | IRI 2 | IRI AVG. | IRI 1 | IRI 2 | IRI AVG. |
| | | | | | | | | | | |
| 1 | 1 | 168 | 174 | 171 | 171 | 169 | 170 | 175 | 181 | 178 |
| 1 | 2 | 171 | 177 | 174 | 170 | 172 | 171 | 172 | 181 | 176 |
| 1 | 3 | 168 | 173 | 171 | 173 | 173 | 173 | 173 | 181 | 177 |
| AVERAGE | | 169 | 175 | 172 | 171 | 171 | 171 | 173 | 181 | 177 |
| DIFFERENCE | | 3 | 4 | 3 | 3 | 4 | 3 | 3 | 0 | 2 |
| | | | | | | | | | | |
| 2 | 1 | 165 | 168 | 167 | 168 | 167 | 167 | 172 | 179 | 175 |
| 2 | 2 | 166 | 170 | 168 | 170 | 165 | 167 | 169 | 176 | 173 |
| 2 | 3 | 160 | 163 | 161 | 163 | 164 | 164 | 169 | 181 | 175 |
| AVERAGE | | 164 | 167 | 165 | 167 | 165 | 166 | 170 | 179 | 174 |
| DIFFERENCE | | 6 | 7 | 7 | 7 | 3 | 3 | 3 | 5 | 2 |
| | | | | | | | | | | |
| 3 | 1 | 158 | 161 | 160 | 164 | 159 | 161 | 170 | 180 | 175 |
| 3 | 2 | 162 | 160 | 161 | 166 | 161 | 164 | 174 | 178 | 176 |
| 3 | 3 | 162 | 158 | 160 | 165 | 160 | 163 | 169 | 179 | 174 |
| AVERAGE | | 161 | 160 | 160 | 165 | 160 | 163 | 171 | 179 | 175 |
| DIFFERENCE | | 4 | 3 | 1 | 2 | 2 | 3 | 5 | 2 | 2 |
| | | | | | | | | | | |
| 4 | 1 | 151 | 151 | 151 | 163 | 151 | 157 | 170 | 170 | 170 |
| 4 | 2 | 152 | 149 | 151 | 159 | 152 | 156 | 159 | 166 | 162 |
| 4 | 3 | 156 | 151 | 153 | 160 | 154 | 157 | 166 | 167 | 167 |
| AVERAGE | | 153 | 150 | 152 | 161 | 152 | 157 | 165 | 168 | 166 |
| DIFFERENCE | | 5 | 2 | 2 | 4 | 3 | 1 | 11 | 4 | 8 |

RATE VALIDATION STUDY RIDE NUMBER / DOT 24725
HIGH-SPEED LASER PROFILER DATA SECTION 6 WESTBOUND FILTERED TO 300 FOOT WAVELENGTH

| | | TEST SPEEDS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 30 MPH | | | 40 MPH | | | 60 MPH | | |
| RATE | PASS | RN 1 | RN 2 | RN AVG. | RN 1 | RN 2 | RN AVG. | RN 1 | RN 2 | RN AVG. |
| | | | | | | | | | | |
| 1 | 1 | 2.88 | 2.81 | 2.84 | 2.92 | 2.81 | 2.86 | 2.82 | 2.82 | 2.82 |
| 1 | 2 | 2.89 | 2.77 | 2.83 | 2.90 | 2.85 | 2.87 | 2.92 | 2.83 | 2.87 |
| 1 | 3 | 2.92 | 2.83 | 2.88 | 2.88 | 2.82 | 2.85 | 2.89 | 2.83 | 2.86 |
| AVERAGE | | 2.90 | 2.80 | 2.85 | 2.90 | 2.83 | 2.86 | 2.88 | 2.83 | 2.85 |
| DIFFERENCE | | 0.04 | 0.06 | 0.05 | 0.04 | 0.04 | 0.02 | 0.10 | 0.01 | 0.05 |
| | | | | | | | | | | |
| 2 | 1 | 3.05 | 2.95 | 3.00 | 3.00 | 2.96 | 2.98 | 3.02 | 2.95 | 2.98 |
| 2 | 2 | 3.06 | 2.94 | 3.00 | 3.00 | 2.96 | 2.98 | 3.05 | 2.97 | 3.01 |
| 2 | 3 | 3.09 | 3.00 | 3.05 | 3.06 | 2.97 | 3.02 | 2.98 | 2.98 | 2.98 |
| AVERAGE | | 3.07 | 2.96 | 3.02 | 3.02 | 2.96 | 2.99 | 3.02 | 2.97 | 2.99 |
| DIFFERENCE | | 0.04 | 0.06 | 0.05 | 0.06 | 0.01 | 0.04 | 0.07 | 0.03 | 0.03 |
| | | | | | | | | | | |
| 3 | 1 | 3.16 | 3.08 | 3.12 | 3.11 | 3.05 | 3.08 | 3.09 | 3.01 | 3.05 |
| 3 | 2 | 3.11 | 3.07 | 3.09 | 3.09 | 3.03 | 3.06 | 3.00 | 3.04 | 3.02 |
| 3 | 3 | 3.12 | 3.07 | 3.09 | 3.10 | 3.03 | 3.07 | 3.05 | 3.06 | 3.06 |
| AVERAGE | | 3.13 | 3.07 | 3.10 | 3.10 | 3.04 | 3.07 | 3.05 | 3.04 | 3.04 |
| DIFFERENCE | | 0.05 | 0.01 | 0.03 | 0.02 | 0.02 | 0.02 | 0.09 | 0.05 | 0.04 |
| | | | | | | | | | | |
| 4 | 1 | 3.30 | 3.26 | 3.28 | 3.14 | 3.21 | 3.18 | 3.16 | 3.20 | 3.18 |
| 4 | 2 | 3.32 | 3.26 | 3.29 | 3.21 | 3.22 | 3.22 | 3.28 | 3.21 | 3.25 |
| 4 | 3 | 3.26 | 3.24 | 3.25 | 3.19 | 3.21 | 3.20 | 3.19 | 3.24 | 3.21 |
| AVERAGE | | 3.29 | 3.25 | 3.27 | 3.18 | 3.21 | 3.20 | 3.21 | 3.22 | 3.21 |
| DIFFERENCE | | 0.06 | 0.02 | 0.04 | 0.07 | 0.01 | 0.04 | 0.12 | 0.04 | 0.07 |

RATE VALIDATION STUDY INTERNATIONAL ROUGHNESS INDEX ENGLISH UNITS / DOT 24725
HIGH-SPEED LASER PROFILER DATA SECTION 7 EASTBOUND FILTERED TO 300 FOOT WAVELENGTH

| RATE | PASS | TEST SPEEDS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 30 MPH | | | 40 MPH | | | 60 MPH | | |
| | | IRI 1 | IRI 2 | IRI AVG. | IRI 1 | IRI 2 | IRI AVG. | IRI 1 | IRI 2 | IRI AVG. |
| | | | | | | | | | | |
| 1 | 1 | 113 | 103 | 108 | 111 | 106 | 108 | 115 | 106 | 110 |
| 1 | 2 | 110 | 101 | 105 | 111 | 107 | 109 | 116 | 102 | 109 |
| 1 | 3 | 110 | 106 | 108 | 111 | 105 | 108 | 113 | 104 | 109 |
| AVERAGE | | 111 | 103 | 107 | 111 | 106 | 108 | 115 | 104 | 109 |
| DIFFERENCE | | 3 | 5 | 3 | 0 | 2 | 1 | 3 | 4 | 1 |
| | | | | | | | | | | |
| 2 | 1 | 103 | 100 | 101 | 109 | 102 | 105 | 112 | 106 | 109 |
| 2 | 2 | 105 | 100 | 102 | 106 | 98 | 102 | 117 | 104 | 111 |
| 2 | 3 | 107 | 102 | 105 | 107 | 103 | 105 | 115 | 105 | 110 |
| AVERAGE | | 105 | 101 | 103 | 107 | 101 | 104 | 115 | 105 | 110 |
| DIFFERENCE | | 4 | 2 | 4 | 3 | 5 | 3 | 5 | 2 | 2 |
| | | | | | | | | | | |
| 3 | 1 | 104 | 95 | 100 | 108 | 101 | 105 | 113 | 100 | 107 |
| 3 | 2 | 102 | 97 | 100 | 106 | 97 | 102 | 121 | 105 | 113 |
| 3 | 3 | 103 | 99 | 101 | 104 | 99 | 102 | 112 | 102 | 107 |
| AVERAGE | | 103 | 97 | 100 | 106 | 99 | 103 | 115 | 102 | 109 |
| DIFFERENCE | | 2 | 4 | 1 | 4 | 4 | 3 | 9 | 5 | 6 |
| | | | | | | | | | | |
| 4 | 1 | 97 | 92 | 95 | 97 | 98 | 98 | 112 | 99 | 106 |
| 4 | 2 | 99 | 90 | 94 | 100 | 92 | 96 | 113 | 97 | 105 |
| 4 | 3 | 96 | 93 | 94 | 97 | 96 | 97 | 112 | 98 | 105 |
| AVERAGE | | 97 | 92 | 94 | 98 | 95 | 97 | 112 | 98 | 105 |
| DIFFERENCE | | 3 | 3 | 1 | 3 | 6 | 2 | 1 | 2 | 1 |

RATE VALIDATION STUDY RIDE NUMBER / DOT 24725
HIGH-SPEED LASER PROFILER DATA SECTION 7 EASTBOUND FILTERED TO 300 FOOT WAVELENGTH

| | | TEST SPEEDS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 30 MPH | | | 40 MPH | | | 60 MPH | | |
| RATE | PASS | RN 1 | RN 2 | RN AVG. | RN 1 | RN 2 | RN AVG. | RN 1 | RN 2 | RN AVG. |
| | | | | | | | | | | |
| 1 | 1 | 3.23 | 3.43 | 3.32 | 3.29 | 3.43 | 3.36 | 3.26 | 3.40 | 3.33 |
| 1 | 2 | 3.25 | 3.39 | 3.32 | 3.28 | 3.40 | 3.34 | 3.23 | 3.45 | 3.33 |
| 1 | 3 | 3.29 | 3.43 | 3.36 | 3.27 | 3.43 | 3.35 | 3.29 | 3.47 | 3.37 |
| AVERAGE | | 3.26 | 3.42 | 3.33 | 3.28 | 3.42 | 3.35 | 3.26 | 3.44 | 3.34 |
| DIFFERENCE | | 0.06 | 0.04 | 0.04 | 0.02 | 0.03 | 0.02 | 0.06 | 0.07 | 0.04 |
| | | | | | | | | | | |
| 2 | 1 | 3.50 | 3.65 | 3.57 | 3.37 | 3.65 | 3.50 | 3.41 | 3.62 | 3.51 |
| 2 | 2 | 3.52 | 3.60 | 3.56 | 3.40 | 3.65 | 3.52 | 3.38 | 3.63 | 3.50 |
| 2 | 3 | 3.45 | 3.63 | 3.53 | 3.42 | 3.62 | 3.51 | 3.40 | 3.62 | 3.50 |
| AVERAGE | | 3.49 | 3.63 | 3.55 | 3.40 | 3.64 | 3.51 | 3.40 | 3.62 | 3.50 |
| DIFFERENCE | | 0.07 | 0.05 | 0.04 | 0.05 | 0.03 | 0.02 | 0.03 | 0.01 | 0.01 |
| | | | | | | | | | | |
| 3 | 1 | 3.48 | 3.71 | 3.59 | 3.44 | 3.67 | 3.54 | 3.44 | 3.73 | 3.58 |
| 3 | 2 | 3.53 | 3.74 | 3.63 | 3.43 | 3.73 | 3.57 | 3.37 | 3.71 | 3.52 |
| 3 | 3 | 3.49 | 3.71 | 3.59 | 3.47 | 3.71 | 3.58 | 3.47 | 3.70 | 3.58 |
| AVERAGE | | 3.50 | 3.72 | 3.60 | 3.45 | 3.70 | 3.56 | 3.43 | 3.71 | 3.56 |
| DIFFERENCE | | 0.05 | 0.03 | 0.04 | 0.04 | 0.06 | 0.04 | 0.10 | 0.03 | 0.06 |
| | | | | | | | | | | |
| 4 | 1 | 3.65 | 3.89 | 3.76 | 3.64 | 3.84 | 3.74 | 3.58 | 3.87 | 3.71 |
| 4 | 2 | 3.63 | 3.92 | 3.76 | 3.56 | 3.88 | 3.71 | 3.52 | 3.90 | 3.69 |
| 4 | 3 | 3.68 | 3.91 | 3.79 | 3.64 | 3.84 | 3.74 | 3.55 | 3.87 | 3.70 |
| AVERAGE | | 3.65 | 3.91 | 3.77 | 3.61 | 3.85 | 3.73 | 3.55 | 3.88 | 3.70 |
| DIFFERENCE | | 0.05 | 0.03 | 0.03 | 0.08 | 0.04 | 0.03 | 0.06 | 0.03 | 0.02 |