STATE OF FLORIDA

PRECISION OF HIGH-SPEED PROFILERS FOR MEASUREMENT OF ASPHALT PAVEMENT SMOOTHNESS

Research Report
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STATE MATERIALS OFFICE

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EXECUTIVE SUMMARY

The Florida Department of Transportation (FDOT) initiated a field study to assess the feasibility and appropriateness of implementing the use of laser-based high-speed profilers to automate its process of ride acceptance. If a high-speed profiler is to be considered for ride acceptance, it is essential to assess its level of accuracy and precision. For such a purpose, profile measurements were acquired using five profilers concurrently on a large number of asphalt pavement sections. Also, in order to evaluate the effects of surface texture on these measurements, the test sections were randomly selected to include both open and dense-graded surface mixtures. The collected profile data was first analyzed to determine the profile indexes, in terms of Ride Number (RN) and International Roughness Index (IRI), at each test site. The results were then used as a basis for an evaluation of the repeatability and reproducibility of the profiling units. In addition, the effects of a profiler operating speed gradient as well as those of the pavement surface texture on roughness measurements were assessed.

This report presents a description of the testing program, the data collection effort and the subsequent analyses and findings.

BACKGROUND

Pavement smoothness/roughness is gaining growing importance as an indicator of a pavement condition, both in terms of performance, and as a major determinant of road user costs. Therefore, attaining acceptable surface smoothness on newly constructed or rehabilitated pavements is becoming a major concern to highway agencies. This need to quantify pavement surface smoothness has resulted in a number of measurement techniques and devices. Of greater interest to highway agencies are those that would provide for versatility, ease and speed of use. Considerable attention has been particularly focused on the height sensor-based technology. It is potentially well suited for surveying the surface condition of pavement sections while operating at highway speed.

High-speed pavement profiling technology was initially introduced in the 1960s at the General Motors Research Laboratory *(1)*. Although this technology has been available since then, it still has not fully matured. A considerable amount of research has been conducted to gain further understanding on the factors affecting high-speed profiling from both the analytical and experimental points of view. Still some problems have not fully been resolved, particularly in the interpretation of the measured data and selection of adequate sensing technology (or profiler designs) *(2)*. Comparative studies have indicated, for instance, that optical and laser-based profilers generally exhibited better performance, in terms of repeatability and accuracy, when used in network-level profiling. These studies have also shown that the use of ultrasonic-based profilers may not be appropriate for textured surfaces such as chip seal or open graded pavements, while ambient light could contaminate optical sensors *(3, 4, 5)*.

Once a longitudinal profile is measured, any profile-based roughness index may be calculated. Although a number of roughness indexes exist, the International Roughness Index (IRI) and Ride Number (RN) statistics are generally used as pavement surface condition indicators. IRI is defined as a mathematical transform (a property) of a true profile describing surface roughness that causes vehicle vibration *(6)*. The underlying IRI model is a series of differential equations that relate the motions of a simulated quarter-car to a road profile. The IRI is computed as a linear accumulation of the simulated suspension motion, normalized by the length of the profile. IRI has, therefore, units of slope and is computed from a single longitudinal wheel path profile. It has a demonstrated strong compatibility with the equipment used to develop pavement management systems. RN is obtained through a practical mathematical process of the longitudinal road surface profiles. The practice is the result of NCHRP work on the effect of road surface roughness on ride comfort conducted in the 1980s *(7)*. The objective of that work was to determine how road profiles were linked to the subjective opinion about the road ride quality from members of the public. Thus, RN is linked by statistical correlation to public opinion of ride quality *(7)*. The Federal Highway Administration (FHWA) currently requires the States to report IRI on a portion of their network for the national Highway Performance Monitoring System (HPMS) *(8)*.

Florida implemented the use of high speed profiling at the network level in 1985. It is still, however, requiring the use of a 15-ft rolling straightedge, for acceptance purposes of the final surface finish on asphalt pavements (project level). Testing with the rolling straightedge is slow, tedious, and labor intensive. Consequently, Florida intends to automate its process of ride acceptance. However, the project-level end use of the data requires higher measurement accuracy and precision. Therefore, if a high-speed profiler is to be considered for ride acceptance, it is essential to assess further its level of accuracy, repeatability, and reproducibility. Thus, FDOT initiated this field study to assess the feasibility of implementing the use of high-speed laser profilers for such a purpose. RN and IRI values were acquired using five profilers concurrently on a large number of asphalt sections. RN and IRI were both selected because some pavement features that affect IRI do not affect RN, and some features that affect RN do not affect IRI. In particular, RN is sensitive to shorter wavelengths. These test sections were randomly selected to include both open and dense-graded surface mixtures in order to evaluate the effects of surface texture on profile data collection. In addition, the profiler testing precision and the effects of its testing speed gradients on roughness measurements were also considered.

This report presents a description of the testing program, the data collection effort as well as the subsequent analyses and findings.

OBJECTIVE

The primary objective of this study was to assess the accuracy and precision of the high-speed laser profilers for determining the ride quality or smoothness of asphalt pavements in Florida. The testing repeatability and reproducibility of the laser-based profilers as well as their ease of use, field-worthiness, and ruggedness were considered. In addition, the effects of a profiler operating speed gradient as well as those of the surface texture on roughness measurements were also evaluated.

EXPERIMENTAL PROGRAM AND DATA COLLECTION

Smoothness-Measuring Devices

The present study focused on devices that collect profile data at ordinary traffic speeds. These are of the class known as “inertial profilers”. Inertial profilers consist of an instrumented vehicle with three essential transducers, namely, (1) accelerometer(s), (2) road sensing transducer(s), and (3) a distance- measuring instrument. The respective outputs of these three sensors are combined to compute a pavement surface profile. The accelerometer measures the vertical motion of the vehicle body. Data processing algorithms convert the acceleration signals to the elevation path followed by the body of the host vehicle as it travels along the road. The distance of the road surface below the elevation path of the vehicle is measured with non-contacting sensors such as lasers, optical, or infrared transducers. When this measurement is subtracted from the elevation of the vehicle body, the road profile is obtained. The distance-measuring instrument determines the position along the road, and is usually picked up from the vehicle speedometer or from direct measurements of rotation of one of the vehicle wheels. The longitudinal distance measurement is needed to associate a position with each profile elevation.

In the present investigation, longitudinal profiles were acquired using five FDOT-owned inertial profilers. Each of the five profilers consisted of a full-sized instrumented van. Three laser sensors were mounted in the front of a specially designed bumper of each vehicle. Two of the sensors were mounted 1750 mm (69 in) apart and equidistant from the bumper centerline to measure pavement profiles in the two wheel paths of the traveled surface. The third sensor, used primarily for rut measurement, is located exactly at the bumper centerline. Each profiler used two accelerometers mounted with the outward sensors to isolate vehicle motion. The vehicles were also equipped with data acquisition systems to collect and store elevation profile data of the traveled surface. Distance-measuring instruments were provided to monitor the traveled distance. All these measuring instruments comply with the ASTM E-950 standards for Class 1 profiling equipment in terms of longitudinal sampling and vertical resolution, as certified by the equipment manufacturer.

Data Collection

During this investigation, continuous longitudinal profiles were acquired on a large number of asphalt sections using the five inertial profilers concurrently (thus minimizing the environmental effects on the test results). Each vehicle was driven along the pavement sections to be tested. While the vehicle was driven at highway speed, the sensors measured the vertical acceleration of the vehicle, the vertical distance between the accelerometer and the pavement surface as well as the distance traveled. The sensor signals were combined through a computerized process to generate a record of the longitudinal profile along each individual wheel path. Such records were then analyzed to determine the rate of roughness (or smoothness) and to identify changes in the longitudinal pavement surface elevation along the pavement length traversed by the instrumented vehicle.

The profile data was collected at Rate 4 (as-collected profile data was averaged in 300-mm (12-in) intervals). All the raw ride data was first filtered to a 300-ft wavelength and then analyzed to determine IRI and RN at each test site in accordance with ASTM E-1926 and ASTM E-1489, respectively. The reported IRI and RN for each pavement section represent the average values as collected on the left and right wheel paths for the corresponding segment. The results were used for the purpose of this study. All the sites were randomly selected from eight different projects in an effort to achieve unbiased test site distribution. Within each test site, roughness data were continuously collected on predefined paths of the travel lane. The profilers were equipped with a photo-triggering device for automatic start/stop of data collection. The device was activated by reflective tape placed on the pavement surface at the beginning and ending points of each test section.

Profiler Accuracy and Precision

Two of the most important criteria of the usefulness of any testing device are accuracy and precision. Presently, there are no accepted standards or references with which the profiling results can be compared to determine the bias in the measurements. Several calibration studies have indeed been conducted throughout the years without the benefit of a reference measurement that is considered the true profile of the road *(2)*. According to a recent NCHRP study, the measurement of true profile is an elusive goal *(2)*. Therefore, without such a measurement, the accuracy of the profilers considered in this study could not be appropriately assessed. The precision was addressed in term of the level of testing repeatability and reproducibility. Within each site, three measurements were taken using each of the profilers along predetermined paths. The path was predefined on the pavement surface to control the longitudinal alignment of the testing operation. Eight test sections were selected to include both open and dense-graded surface mixtures. The profiler was operated at a speed of approximately 80 km/h (50 mph).

Speed Gradient Effect on Profiler Measurements

When measuring a pavement surface profile, a profiler may be effectively operated at speeds ranging from approximately 30 to 110 km/h (20 to 70 mph). An evaluation was performed to ensure that any test speed within this specified range would result in respectively comparable IRI and RN values. For this purpose, additional testing was conducted considering three profilers and five operating speeds.

DATA ANALYSIS

RN and IRI Relationship

The profile data as collected during the course of this investigation was first analyzed to determine the profile indexes, in terms of IRI and RN, at each test site. The respective values of RN and IRI were determined considering the continuous profile made along the entire length of each test section. The illustrative relationship between these indexes, as determined on the eight test sites using the five profiling units, is shown in Figure 1. Within each site, three longitudinal profile measurements (or runs) were taken using each of the units. Therefore, the comparison considered a total of 120 paired-data points. Figure 1 shows a good correlation between the two roughness indexes as reflected by the R-square value of 0.94. A regression analysis also indicated that, within the test limits, a simple exponential law equation was appropriate to define the roughness relationship between the two indexes. The relationship model obtained is as follows:

$$IRI = 563982.18e^{(-1.51RN)} \qquad (1)$$

Where:

IRI = International Roughness Index, mm/km; and

RN = Ride Number.

Testing Repeatability and Reproducibility

A statistical analysis was then performed to assess the data repeatability and reproducibility. This assessment was in statistical terms of range, standard deviations, and coefficients of variation. The range serves herein as a convenient measure of data dispersion, while the standard deviation and coefficient of variation provide, respectively, a convenient measure of deviation around the mean and a normalized way of expressing data variability.

The results, summarized in Table 1, as well as those of the pooled-statistics (pooled by test section) given in Table 2, indicate, in general, a high level of repeatability and reproducibility of the ride number measurements. The widest range recorded in RN data within any given unit was 0.14 (with the exception of unit 5 on project 3 and regardless of the surface texture type), while the widest ranges in RN between the five units were 0.25 and 0.15 on open and dense graded sections, respectively. Based on these range values, the maximum difference in RN data within any given unit was less than 3 percent (regardless of the surface texture type), while the maximum differences in RN between the five units were approximately 5 and 3 percent on open and dense graded sections, respectively. The maximum standard deviation value of RN measurements within any unit was 0.07 while that of between units was 0.1. Also, there seems to be relatively better RN repeatability and reproducibility on dense-graded than on open-graded sections. However, the statistical significance of this observation on the overall effect of surface texture may be negligible as shown by the pooled-variance (for all the various sections by surface texture type) and corresponding standard deviations values given in Table 3.

In terms of IRI measurements, the respective maximum differences within and between units were approximately 6 and 12 percent. Also, as seen in Table 1, the maximum standard deviations within and between units were 36 and 50 mm/km, respectively. Lower standard deviations indicate a higher degree of precision. Therefore, the level of repeatability and reproducibility of IRI data was generally lower as compared to that of RN. In addition, within the test range, similarly to RN, IRI measurements do not seem to be affected by the type of surface texture. The IRI between units (reproducibility) pooled-variance values and corresponding standard deviations were relatively lower for dense than for open-graded sections. However, for all practical purposes the difference may be negligible.

Speed Gradient effect on Profiler Measurements

The effects of profiler test speed gradients on the RN and IRI measurements were also evaluated. For this purpose 3 profiler units, and 5 operating speeds 50, 65, 80, 95, and 110 km/h were considered. Within a test site, 3 profile runs were conducted at each of the operating speeds with each of the three profilers. The resulting profile indexes were then analyzed as a factorial experiment with 3 profilers and 5 levels of testing speed using a two-way analysis of variance (ANOVA). The purpose of such an analysis was to evaluate, within each test section, if there was any evidence of real differences between and within the respective means of RN and IRI values as determined using the 5 test speeds with each of the profiling units. An important result of ANOVA is the P-value corresponding to the factor(s) considered (testing speeds and profilers in this case). The P-value for a particular factor indicates the probability of error of the hypothesis that the factor has a significant effect on the measured parameters.

The results of the ANOVA are presented in Table 4. The calculated F values are compared with the critical F value for the corresponding degrees of freedom to determine whether to accept the null hypothesis of no difference between the means of profile measurements (in terms of both RN and IRI). It can be inferred from these ANOVA results that, at 95 percent confidence level and within the test range, both profile indexes were affected by the testing speed of the profilers. The interaction effect between the two factors was also significant. In addition, contrastingly to those of IRI, the RN measurements within each test speed were not statically different, again at 95 percent confidence level.

Precision Statements

The pooled-statistics considering all the measurements obtained on 8 test sections using 5 profiler units operated at a speed of approximately 80 km/h (50 mph) are illustrated in Table 5. The profile indexes, in terms of RN and IRI, were respectively determined using the continuous profile made along the entire test section. Therefore, within this test range, the following precision statements are developed respectively for the repeatability and reproducibility of the profile index determination:

Repeatability (within-profiler) Precision

The respective RN and IRI results of two properly performed tests using the same profiler on the same test section should not differ by more than 0.09 and 36 mm/km (2.28 in/mile) at a 95 percent confidence level.

Reproducibility (between-profilers) Precision

The respective RN and IRI results of two properly performed tests using two profiler units on the same test section should not differ by more than 0.12 and 98 mm/km (6.21 in/mile) at a 95 percent confidence level.

CONCLUSIONS

The present study was conducted primarily to assess the level of precision of the high-speed laser profilers for determining the ride quality or smoothness of asphalt pavements in Florida. The profile data as collected during the course of this investigation were first analyzed to determine the profile indexes, in terms of RN and IRI, at each test site. The results were then used as a basis for an evaluation of repeatability and reproducibility of the profiling units. Also, the effects of a profiler operating speed gradient on roughness measurements were considered. Within the test range, the findings indicated the following:

- A comparison considering a total of 120 paired-data points showed a good correlation between RN and IRI as reflected by the R-square value of 0.94. A regression analysis indicated that a simple exponential law equation was appropriate to define this relationship.
- In general, a high level of repeatability and reproducibility of the ride number measurements was obtained. The maximum difference in RN data within any given unit was less than 3 percent, while the maximum difference in RN between the five units were approximately 5 and 3 percent on open and dense graded sections, respectively.
- IRI measurements were generally less repeatable and reproducible than those of RN. The respective maximum differences within and between units were approximately 6 and 12 percent.
- A comparison of the respective pooled-variances indicated that the effect of the surface texture on the profiler repeatability and reproducibility was negligible.
- A two-way ANOVA indicated that, at 95 percent confidence level, the profile indexes were affected by the testing speed of the profilers.
- The respective RN and IRI results of two properly conducted tests using the same profiler on

the same test section should not differ by more than 0.09 and 36 mm/km (2.28 in/mile), at a 95 percent confidence level.

- The respective RN and IRI results of two properly conducted tests using two profiler units on the same test section should not differ by more than 0.12 and 98 mm/km (6.21 in/mile), at a 95 percent confidence level.

One has to note that the above analysis assumed that, since the test sections were randomly selected, the potential for sampling error or bias is minimized. It is known that a biased selection (or sampling error) of test sites affects the representativeness of the test results. In addition, it was also assumed that the variability of the profile index results from a particular test site was randomly distributed around a correct mean value. It is also always possible that the variability will distribute randomly around an incorrect mean value. The difference between the two means represents an error in the mean itself, or a bias error. However, although the bias can change the mean value, it will not affect the evaluation of the relative testing variability as conducted in this study.

RECOMMENDATIONS

All the findings of the present study suggest that the high-speed profilers is a faster, more practical, and more reliable alternative to a rolling straightedge, for acceptance purposes of the final surface finish on asphalt pavements (project level). Also, because of its relatively higher level of repeatability and reproducibility, RN may be more appropriate for use on a project level. It is also recommended that, when developing acceptance criteria, the profiler testing speed be considered. In addition, it is suggested that the profiler level of accuracy be investigated once an external reference is standardized.

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Table 1 Repeatability and Reproducibility Statistics in Terms of Range, Standard Deviation, and Coefficient of Variation

Surface Texture Type	Project No.	Statistic	Ride Number							
			Repeatability					Reproducibility		
			Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Run 1	Run 2	Run 3
Open Graded	1	Range	0.01	0.01	0	0.01	0.03	0.08	0.07	0.07
		Std. Dev.	0.01	0.01	0	0.01	0.02	0.03	0.03	0.03
		COV	0.23	0.23	0	0.23	0.46	0.69	0.69	0.69
	2	Range	0.01	0.01	0.04	0.03	0.01	0.07	0.09	0.12
		Std. Dev.	0.01	0.01	0.02	0.02	0.01	0.02	0.04	0.05
		COV	0.25	0.24	0.48	0.49	0.24	0.49	0.98	1.22
	3	Range	0.03	0.03	0.02	0.05	0.21	0.25	0.18	0.11
		Std. Dev.	0.02	0.02	0.01	0.03	0.12	0.1	0.07	0.04
		COV	0.45	0.45	0.22	0.69	2.76	2.29	1.59	0.91
	4	Range	0.02	0.01	0.01	0.13	0.02	0.19	0.07	0.05
		Std. Dev.	0.01	0.01	0.01	0.07	0.01	0.07	0.03	0.02
		COV	0.24	0.24	0.23	1.69	0.24	1.67	0.71	0.47
Dense Graded	5	Range	0.05	0.01	0.05	0.01	0	0.08	0.13	0.1
		Std. Dev.	0.03	0.01	0.03	0.01	0	0.03	0.05	0.04
		COV	0.71	0.23	0.69	0.23	0	0.7	1.17	0.93
	6	Range	0.01	0.02	0.03	0.06	0.02	0.05	0.04	0.08
		Std. Dev.	0.01	0.01	0.02	0.03	0.01	0.02	0.02	0.03
		COV	0.25	0.25	0.5	0.76	0.25	0.5	0.5	0.75
	7	Range	0.02	0.01	0.01	0.1	0	0.1	0.03	0.03
		Std. Dev.	0.01	0.01	0.01	0.05	0	0.04	0.01	0.01
		COV	0.22	0.22	0.22	1.1	0	0.88	0.22	0.22
	8	Range	0.01	0.14	0.07	0.02	0.13	0.07	0.15	0.07
		Std. Dev.	0.01	0.07	0.04	0.01	0.07	0.03	0.07	0.03
		COV	0.23	1.61	0.91	0.23	1.6	0.68	1.61	0.68

Table 1 (Cont.)

Surface Texture Type	Project No.	Run	International Roughness Index, mm/km							
			Repeatability					Reproducibility		
			Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Run 1	Run 2	Run 3
Open Graded	1	Range	15	31	15	16	0	94	79	64
		Std. Dev.	9	18	9	9	0	38	41	29
		COV	0.99	2.14	1.09	1.01	0	4	5	3
	2	Range	0	16	64	32	15	47	111	111
		Std. Dev.	0	9	33	16	9	20	43	47
		COV	0	0.79	3.04	1.37	0.8	2	4	4
	3	Range	0	16	16	0	0	111	111	95
		Std. Dev.	0	9	9	0	0	43	44	40
		COV	0	1.34	1.38	0	0	6	6	6
	4	Range	16	15	16	32	15	111	95	63
		Std. Dev.	9	9	9	16	9	41	36	24
		COV	0.9	0.91	0.96	1.56	0.91	4	4	2
Dense Graded	5	Range	16	32	31	16	15	110	126	95
		Std. Dev.	9	16	16	9	9	43	50	39
		COV	0.96	1.88	1.91	1.02	1.08	5	6	4
	6	Range	0	32	15	32	16	64	47	79
		Std. Dev.	0	18	9	18	9	24	21	28
		COV	0	1.36	0.71	1.36	0.68	2	2	2
	7	Range	16	0	16	15	16	48	47	48
		Std. Dev.	9	0	9	9	9	18	20	21
		COV	1.71	0	1.8	1.66	1.8	4	4	4
	8	Range	0	15	63	16	16	79	63	63
		Std. Dev.	0	9	36	9	9	33	23	29
		COV	0	1.18	4.72	1.1	1.2	4	3	4

Table 2 Summary of Statistics Pooled by Test Section

Surface Texture Type	Project No.	Ride Number							
		Component of Variance		Variance		Standard Deviation		Coef. of Variation	
		W/Unit	B/Units	W/Unit	B/Units	W/Unit	B/Units	W/Unit	B/Units
Open Graded	1	0.000	0.001	0.000	0.001	0.01	0.03	0.19	0.68
	2	0.000	0.001	0.000	0.001	0.01	0.04	0.30	0.88
	3	0.003	0.003	0.003	0.006	0.05	0.08	1.23	1.71
	4	0.001	0.001	0.001	0.002	0.03	0.05	0.79	1.11
Dense Graded	5	0.000	0.001	0.000	0.002	0.02	0.04	0.41	0.96
	6	0.000	0.000	0.000	0.001	0.02	0.02	0.46	0.56
	7	0.001	0.000	0.001	0.001	0.02	0.03	0.52	0.58
	8	0.002	0.000	0.002	0.002	0.05	0.05	1.14	1.09
International Roughness Index, mm/km									
Open Graded	1	111.1	1209.7	111.1	1320.8	10.54	36.34	1.23	4.23
	2	305.1	1164.5	305.1	1469.6	17.47	38.34	1.54	3.37
	3	34.1	1746.9	34.1	1781.0	5.84	42.20	0.85	6.16
	4	115.3	1074.8	115.3	1190.1	10.74	34.50	1.09	3.49
Dense Graded	5	148.4	1807.2	148.4	1955.6	12.18	44.22	1.41	5.10
	6	168.6	432.1	168.6	600.7	12.98	24.51	0.99	1.88
	7	66.2	337.6	66.2	403.8	8.14	20.09	1.58	3.90
	8	313.7	497.2	313.7	811.0	17.71	28.48	2.29	3.68

Table 3 Pooled Variances and Standard Deviations by Surface Texture Type

Surface Texture Type	Ride Number			
	Variance		Standard Deviation	
	Repeatability	Reproducibility	Repeatability	Reproducibility
Open Graded	0.001	0.003	0.03	0.05
Dense Graded	0.001	0.001	0.03	0.04
	IRI, mm/km			
Open Graded	141	1440	12	38
Dense Graded	174	943	13	31

Table 4 ANOVA Results on the Effects of Speed Gradient on Profile Indexes

Source of Variation	Deg. of Freedom	Sum of Squares	Mean Squares	F-value	*P-value*	*F-crit*
			RN			
Speed	4	0.00890	0.00222	14.94	7.97E-07	2.69
Profiler	2	0.00369	0.00185	12.40	0.000119	3.32
Interaction	8	0.00206	0.00026	1.73	0.131757	2.27
Within	30	0.00447	0.00015			
Total	44	0.01912				
			IRI			
Speed	4	157676.72	39419.18	74.18	4.07E-15	2.69
Profiler	2	4417.43	2208.71	4.16	0.02551	3.32
Interaction	8	17559.00	2194.87	4.13	0.002031	2.27
Within	30	15942.60	531.42			
Total	44	195595.75				

Table 5 Summary of Profiler Precision

Profile Index	Variance		Std Deviation		Precision (D2S)	
	Repeatability	Reproducibility	Repeatability	Reproducibility	Repeatability	Reproducibility
RN	0.001	0.002	0.03	0.04	0.09	0.12
IRI, mm/km	158	1192	12.6	34.5	36	98

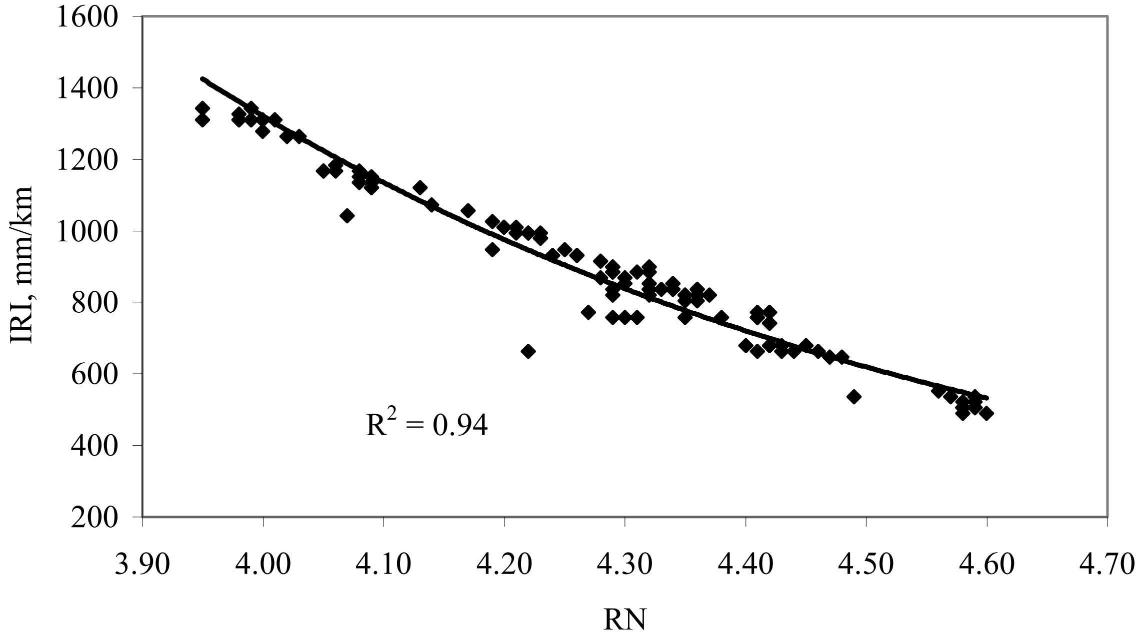

Figure 1 Illustrative relationship between RN and IRI