Evaluation of Smoothness of Louisiana Pavements Based on International Roughness Index and Ride Number

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ABSTRACT

This paper presents the results of research conducted to develop smoothness specifications for asphalt concrete pavements in Louisiana based on the International Roughness Index (IRI) and Ride Number (RN). Measurements of longitudinal profiles were conducted using the high-speed inertial road profiler along 98.7 km of pavements in 23 different projects. Profile Index (PI) with 5.1 and 0 mm blanking bandwidth, IRI and RN were determined. Statistical analyses were conducted to establish relationships between the different smoothness indices. The mathematical models were used to establish IRI based smoothness specifications for construction control of pavements in Louisiana.

KEYWORDS: Pavement smoothness, International roughness index, Ride number, Pavement ride quality.

INTRODUCTION

The ride quality is one of the most important conditions used by the traveling public to judge roadway pavements. Rough pavements have a significant impact on public satisfaction, safety and also on the economy. Pavements with rough surfaces cause driving discomfort, magnify impact loads on pavement structures such as bridges, damage sensitive transported goods, increase vehicle wear and require expensive maintenance, which will impede traffic flow.

Louisiana Department of Transportation and Development (LA DOTD) recognizes the benefits of having smooth pavement surfaces. These benefits are usually observed in terms of users' satisfaction and monetary savings. Pavement smoothness specifications are the means used to guarantee the construction of pavements with excellent ride quality. Therefore, standard smoothness specifications are used for quality control during the construction of roadway pavements. Current LA DOTD standard specifications of pavement smoothness are based on the profile index with 5.1 mm blanking bandwidth ($PI_{5.1}$). The California-Type Profilograph is the device approved by LA DOTD to measure pavement profiles for construction acceptance of pavements. While the profilograph is pushed on the pavement surface, the longitudinal roadway profile is recorded on paper. The longitudinal profile trace is then analyzed to determine the profile index with 5.1 mm blanking bandwidth. This index is used to set the pay schedule for pavement contractors.

There is a concern regarding the use of the profile index with 5.1 mm blanking bandwidth to evaluate the

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smoothness of pavement surfaces. Evaluation of pavement smoothness using the $PI_{5.1}$ results in filtering a portion of the pavement roughness and therefore, shows smoother roads than in reality. This situation led to a search for more acceptable measures of pavement smoothness. With the advancement in roadway profiling equipment and technology, attention is focused on the International Roughness Index (*IRI*) as the rational measure of pavement smoothness. After measuring the longitudinal roadway profile, the *IRI* is determined using a mathematical model by accumulating the output of quarter-car model and dividing by the profile length. The *IRI* is expressed in mm/km or inch/mile. The *IRI* is described as a rational indicator that reflects the smoothness of pavements and the ride quality. Figure 1 depicts the *IRI* scale for different pavements.

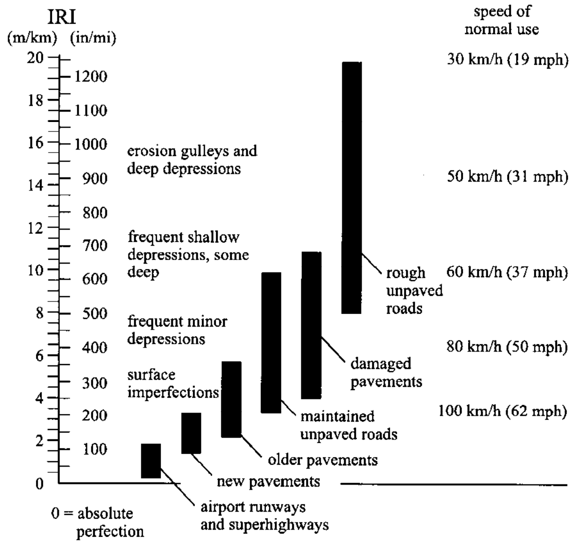


Figure (1): The international roughness index scale for different pavements (Sayers and Karamihas, 1998).

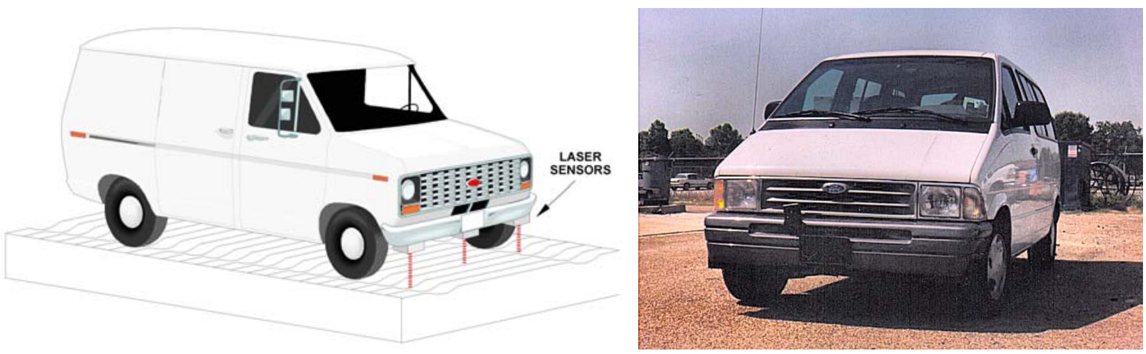


Figure (2): The ICC full size inertial profiler used in this study.

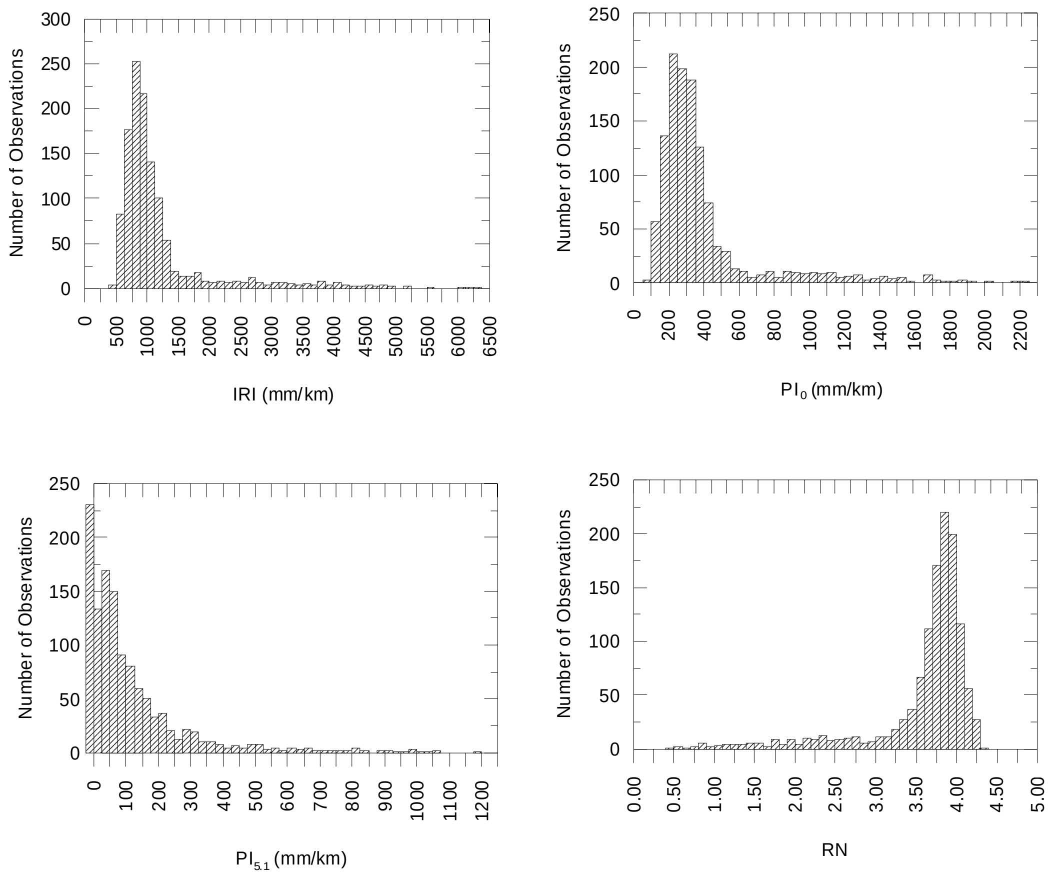


Figure (3): Preliminary statistical analysis of the pavement smoothness indices determined from the measured roadway profiles.

There is an ongoing effort by LA DOTD to switch to *IRI* based pavement smoothness specifications. It is believed that this step will lead to reliable evaluation of pavement smoothness in Louisiana and will produce smoother roadway pavements. In order for LA DOTD to switch the smoothness specifications from $PI_{5.1}$ to more accurate measures such as *IRI*, research is needed to develop mathematical models based on actual data collected from Louisiana roadway pavements. The objective of this research is to establish and validate correlations between different smoothness indices to help LA DOTD set new *IRI* smoothness based specifications for asphalt concrete pavements.

BACKGROUND

Different smoothness indices are available to quantify the smoothness of roadway pavements. Some of these indices are descriptive with no numerical values. Among the commonly used ones is the profile index with 5.1 mm blanking bandwidth, which is a quantitative smoothness index. Due to the concern regarding the use of $PI_{5.1}$ as a reliable smoothness index, state highway agencies started to search for rational methods to characterize pavement smoothness. In 1982, the International Roughness Index was developed under sponsorship of the World Bank (Sayers et al., 1986). The Federal Highway Administration (FHWA) has adopted the *IRI* for Highway Pavement Monitoring System.

Table (1): Ride Number Rating Scale (ASTM, 2000).

Description	Ride Number
Perfect	5.0
Very good	4.5
	4.0
Good	3.5
	3.0
Fair	2.5
	2.0
Poor	1.5
	1.0
Very poor	0.5
Impassable	0.0

The ride number (*RN*) is a descriptive index used to describe pavement smoothness. The ride number is determined from the measurement of the longitudinal roadway profile according to the standard procedure described by ASTM E 1489. Table 1 presents the scale of the ride number as described by ASTM (2000). which ranges between 0 for impassable pavement surface and 5 for the perfect one.

Previously, initial smoothness of constructed pavements in Louisiana was evaluated by the straightedge test. Then, LA DOTD moved towards using California-Type Profilograph for quality control of pavement smoothness. LA DOTD also used the Mays Ride Meter but only for research purposes. Currently, LA DOTD is in the process of switching towards using the lightweight and full size inertial road profilers to evaluate/control pavement smoothness.

The use of *IRI* for pavement smoothness characterization is becoming increasingly popular among the state highway departments. Few state highway departments have developed new specifications for roadway smoothness based on *IRI*. As an example, Virginia Department of Transportation (V DOT) developed special provisions regarding the smoothness of asphalt pavement surfaces based on IRI. Their method is administered with a laser-equipped South Dakota-style inertial road profiler (McGhee, 2000). Many state highway departments are eager to adopt new *IRI* based specifications. However, there are difficulties associated with this move, such as the lack of rational methods to establish new specifications based of *IRI* or profile index with 0 mm blanking bandwidth (PI_0).

Research studies have been initiated to help state highway departments establish new smoothness specifications. Most of the research was focused on establishing correlations between the old and new pavement smoothness indices. Models were developed to predict *IRI* using the profile index $PI_{5.1}$ obtained from the measurements of roadway profiles using manual profilographs, computerized profilographs, lightweight inertial profilers, ultrasonic–type inertial profilers and laser-type inertial profilers. These models were developed by investigators such as Florida DOT (1997), Fernando (2000) and Hossain et al. (2000), based on data collected from specific climatic regions (e.g., Kansas, where conditions are wet with winter freeze), using specific equipment (e.g., lightweight inertial profiler) and specific pavement type (e.g., Portland Cement Concrete). Therefore, these models may or may not be valid for characterization of pavement smoothness in Louisiana where the climatic conditions are wet with no winter freeze.

RESEARCH METHODOLOGY

Twenty-three sections on asphalt concrete pavements were identified for this research. These sections are located on major highways in Louisiana and represent a wide range of pavement smoothness. The high-speed inertial profiler of Louisiana Transportation Research Center (LTRC) was used to collect field data on the pavement test sections. The profiler, shown in Figure 2, is the International Cybernetics Corporation (ICC) type with an infrared laser and precision accelerometer to obtain road profile measurement at speeds up to 105 kph (65 mph). Three laser height sensors are used to measure the distance between the road and a vehicle reference point while the vehicle is being driven over the road. The laser sensors mounted over the wheel paths produce longitudinal roadway profiles. The third laser sensor mounted between the wheelpaths gives a reference elevation so that an average rut depth can be calculated for the wheelpaths. Accelerometers matched with the wheelpath laser sensors measure the vertical acceleration of the vehicle as it bounces in response to the road profile. Computer software called WINPRO (Windows Profiling Software) is used to analyze the data measured by the profiler. The software eliminates the vertical vehicle movement, leaving the true vertical profile of the road. Smoothness indices like International Roughness Index, Profile Index and Ride Number are then determined from the measured roadway profile.

Table (2): Statistical parameters for the smoothness indices used in this study.

Smoothness Index	Statistical Parameter (mm/km)			
	Minimum Value	**Maximum Value**	**Mean μ**	**Standard Deviation σ**
International Roughness Index, *IRI*	472	6287	1192.4	829.6
Profile Index with 0 mm Blanking Bandwidth, PI_0	67	2396	399.5	328.5
Profile Index with 5.1 mm Blanking Bandwidth, $PI_{5.1}$	0	1793	129.4	197.9
Ride Number, *RN*	0.66	4.42	3.76	0.64

Table (3): LA DOTD pay adjustment criteria based on $PI_{5.1}$ in mm/km (LA DOTD, 2000).

Payment Adjustment (%) Current Specifications Based on $PI_{5.1}$	100	95	80	50 or Remove
Multi-lift new construction and overlays more than two lifts	# 46	47 – 61	62 – 91	> 91
Single-lift construction over cold planed surfaces and two lift overlays	# 76	77 – 91	92 – 152	> 152
Single-lift overlays over existing surfaces	#122	123 – 152	153 – 228	> 228

INITIAL DATA ANALYSIS

Longitudinal profiles (at wheel paths) were measured at twenty-three sections of asphalt concrete pavements with a total length of 98.7 km (61.3 miles). Data points were measured every 76.2 mm along each wheel path for each test section. Analysis was conducted on the measured profiles to determine the smoothness indices *IRI*, $PI_{5.1}$, PI_0 and *RN*. These indices are the average values for 80.47m intervals along each test section. A preliminary statistical analysis was conducted on these indices to evaluate the quality of the collected data.

Figure 3 depicts histograms of the distribution of the calculated pavement smoothness indices. The *IRI* data shown in Figure 3 cover a wide range of pavement smoothness that extends from 472 to 6287 mm/km. This is expected, since the pavement sections tested consist of new and old asphaltic concrete pavements. Statistical parameters such as the mean (μ), standard deviation (σ), minimum value and maximum value for the smoothness indices are calculated and are summarized in Table 2.

To achieve the objective of this research, correlations between the different smoothness indices need to be developed and validated. Figure 4 depicts the relationship between *IRI* and $PI_{5.1}$ determined from the longitudinal profiles of the pavement test sections. Examination of Figure 4 shows that there is high variability in the data. However, an attempt was made to obtain and evaluate the correlation between *IRI* and $PI_{5.1}$. Regression analysis was conducted to find the best relationship between *IRI* and $PI_{5.1}$ in which four different functions were used. The following exponential, linear, polynomial and hyperbolic functions were obtained as a result of the regression analysis:

$$IRI = \begin{cases} 802.79e^{0.002PI_{5.1}} \\ 712.06 + 3.71PI_{5.1} \\ 681.97 + 4.15PI_{5.1} - 0.00047PI_{5.1}^2 \\ \dfrac{7.25PI_{5.1}}{1 + 0.000536PI_{5.1}} \end{cases} \quad (1)$$

where *IRI* is the International Roughness Index and $PI_{5.1}$ is the Profile Index with 5.1 mm blanking bandwidth. The linear function has a coefficient of determination R^2=0.78 and a standard error of estimation *SEE*=385.2. R^2 values for the exponential, polynomial and hyperbolic functions are 0.78, 0.79 and 0.70, respectively. The linear function appears to be the best obtained correlation. However, it has a high value of *SEE*.

The models developed in Equation 1 were used to backpredict the *IRI* values obtained from the profile measurements. Comparisons of predicted and measured *IRI* values are depicted in Figure 5. It is evident that these models show large scatter of predicted versus measured values of *IRI* and therefore might not be appropriate to set up the threshold specification limit for pavement smoothness control.

Based on this evaluation, the research team concluded that even though the results of the initial regression analysis showed that *IRI* could be estimated from $PI_{5.1}$ with an acceptable margin of uncertainty, it is not appropriate to set up the criteria for *IRI* based smoothness specifications.

STATISTICAL ANALYSIS

The results of the initial regression analysis on the data did not yield acceptable correlations between *IRI* and $PI_{5.1}$. This is due to the high variability of the *IRI* and $PI_{5.1}$ data, especially at high $PI_{5.1}$ values. The variability of the data at high $PI_{5.1}$ values is normal, since the pavement test sections were comprised of old pavements with rough surfaces. The outcome of the analysis in this study will be used to set smoothness criteria for pavement construction. The current LA DOTD specifications do not allow the acceptance of any pavement constructed with more than $PI_{5.1}$=228 mm/km. At this level of $PI_{5.1}$, the pavement surface is rough and might be neither safe nor functional. Therefore, statistical analysis will be conducted on the data with a range of acceptable pavement smoothness.

Analysis of variance was conducted on the collected data of the smoothness indices. The *IRI* values corresponding to $PI_{5.1}$ range from 0 to 7.6 mm/km were grouped together in a group G_1. Then, the number of data points, mean, standard deviation and coefficient of variation for *IRI* values were determined. Calculations were also conducted for the next $PI_{5.1}$ range from >7.6 to 15.2 mm/km, which is group G_2. All data were grouped using the 7.6 mm/km range up till the maximum value of $PI_{5.1}$ was reached. The mean *IRI* values for each group are plotted against $PI_{5.1}$ as shown in Figure 6. Examination of Figure 6 indicates that there is a well-defined relationship between *IRI* and $PI_{5.1}$ up to $PI_{5.1}$ = 300 mm/km. For $PI_{5.1}$>300, the data exhibit a high degree of variability. Therefore, the analysis will consider only the well-defined portion of the data with $PI_{5.1} \leq$ 300 mm/km. This is acceptable, since the objective of the research was to establish criteria of pavement smoothness for acceptance and pay for pavement construction and maintenance. Therefore, the analysis will focus on low values of *IRI* and $PI_{5.1}$, which indicate smooth pavements.

Figure 7a depicts the variation of mean *IRI* versus $PI_{5.1}$. The shaded area in Figure 7a denotes 95% confidence intervals. Different correlations were attempted to develop correlations between *IRI* and $PI_{5.1}$ for the data presented in Figure 7b. The correlations consist of linear, polynomial and exponential functions, as shown in Figure 7b. The mathematical formulas for these functions are:

$$\mathrm{IRI} = \begin{cases} 705.2 + 3.43\mathrm{PI}_{5.1} \\ 766.1e^{0.0029\mathrm{PI}_{5.1}} \\ 783.1 + 1.67\mathrm{PI}_{5.1} + 0.006\mathrm{PI}_{5.1}^2 \end{cases} \quad (2)$$

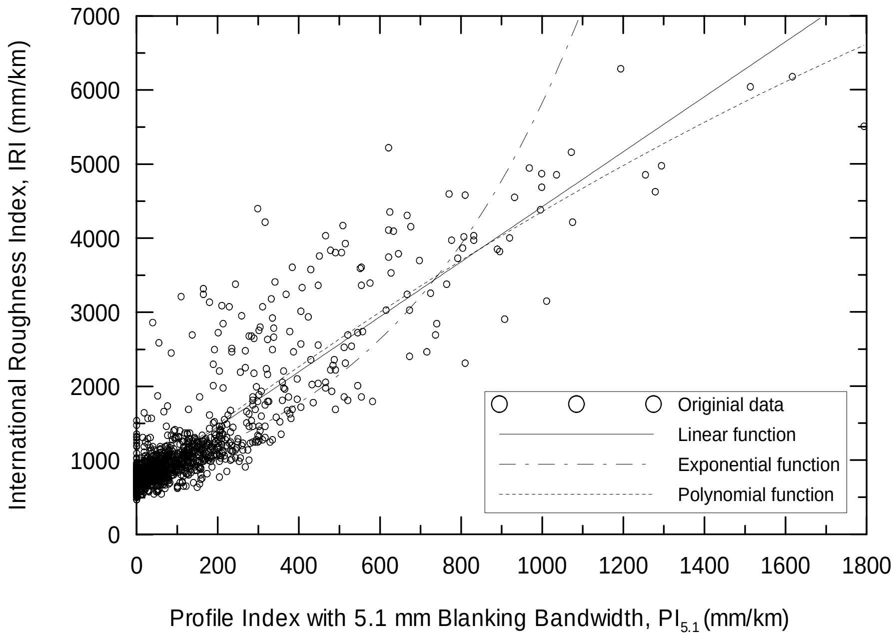


Figure (4): *IRI* versus *PI*$_{5.1}$ for the pavement test sections.

Table (4): *IRI* values predicted using the models developed in this study.

LA DOTD Specifications		RN Predicted from $PI_{5.1}$	Predicted *IRI* (mm/km)	
$PI_{0.2}$ (in/mi)	$PI_{5.1}$ (mm/km)		Linear model Eqn. 1	Linear model RN
0	0	4.3	705	654
3	45.6708	4.1	862	801
4	60.8944	4.1	914	851
5	76.118	4	966	900
6	91.3415	3.9	1019	949
8	121.789	3.8	1123	1048
10	152.236	3.7	1227	1146
15	228.354	3.4	1488	1392

These correlations have a high coefficient of determination, where R^2=0.96 for the linear function and R^2=0.98 for both the polynomial as well as the exponential function. The linear function is selected for the purpose of developing *IRI* based smoothness specifications for simplicity. The standard error of estimate for the linear functions *EES*=27.6 mm/km. Table 3 presents the current Louisiana smoothness specifications, which are based on $PI_{5.1}$. Also, these specifications are presented in Table 4 to verify the developed correlations. The *IRI* values were predicted using the linear function model in Equation 2 from the $PI_{5.1}$ values corresponding to LADOTD smoothness specification limits. These values are shown in Table 4, column 4.

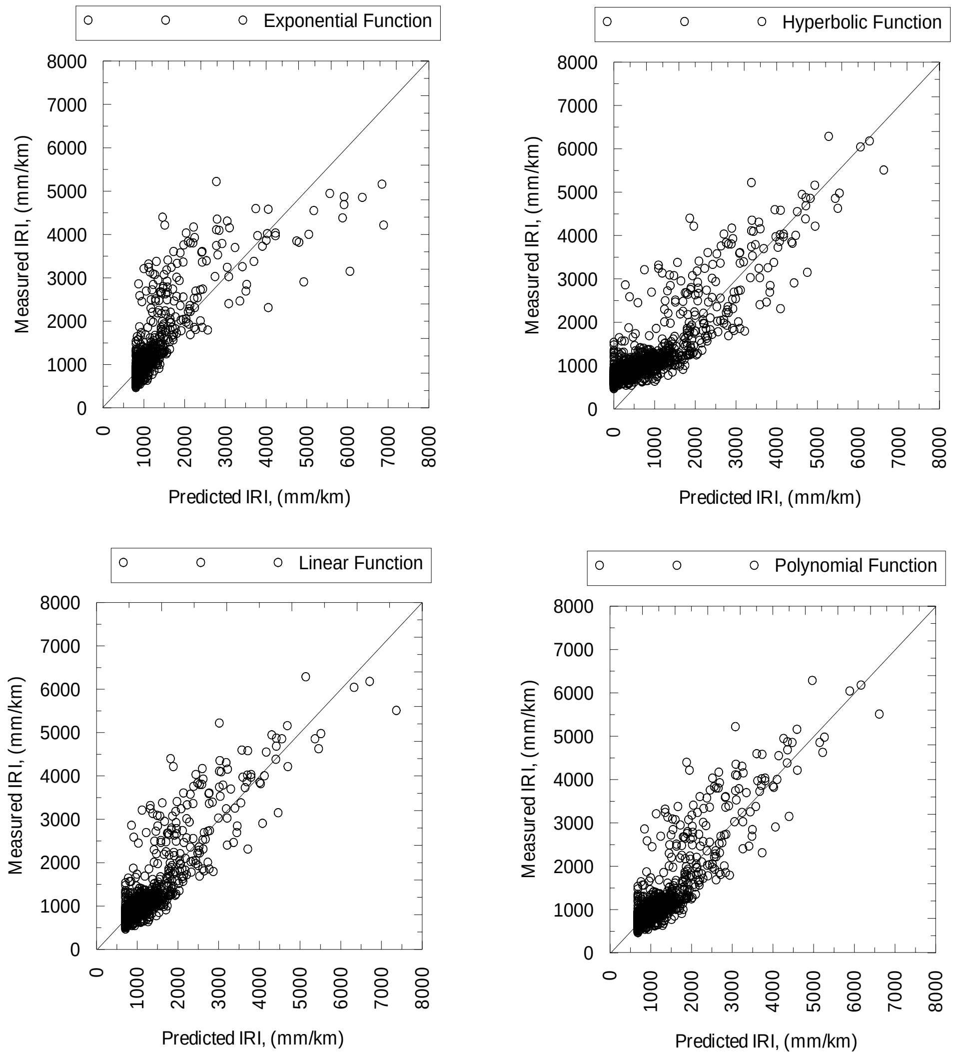


Figure (5): Comparison of *IRI* determined by the high-speed inertial profiler and that predicted by different models through correlations with $PI_{5.1}$.

Similar statistical analyses were also conducted to evaluate the relationships between *IRI* and *RN* and between $PI_{5.1}$ and *RN*. The correlations between these smoothness indices will help in developing the smoothness specifications based on multivariable data analysis. The relationship between $PI_{5.1}$ and *RN* is shown in Figure 8. The data quality is good to warrant the development of an accurate predictive model. Regression analysis was conducted to find the best model among linear, polynomial and exponential functions. The results are given in the following equation:

$$RN = \begin{cases} 4.31 - 0.0041PI_{5.1} \\ 4.33e^{-0.0011PI_{5.1}} \\ 4.4 - 0.0064PI_{5.1} + 7.95PI_{5.1}^{2} \end{cases} \quad (3)$$

The coefficient of determination for the linear, polynomial and exponential function are 0.97, 0.98 and 0.99, respectively. All these models are considered good based on the smoothness range used in the analysis. The linear function is selected to represent the relationship between *RN* and $PI_{5.1}$. The linear function was used to predict the ride number corresponding to the $PI_{5.1}$ values specified by LA DOTD specifications. The results are presented in Table 4, column 3. The values of *IRI* and *RN* obtained from the models developed using the field data will form the base for the development of new *IRI* and *RN* based smoothness specifications for asphalt concrete pavement in Louisiana.

Table (5): The new *IRI* based smoothness specifications currently under review for implementation for construction control of asphalt concrete pavements.

Percent of Contract Unit Price/Lot*					
Percent of contract unit price (by sublot)	Units	100%	90%	80%	50%** or remove
Category A Multi-lift new construction and overlays of more than two lifts	mm/km	< 990	990 - 1142	NA	> 1142
	in/mi	< 65	65 - 75	NA	> 75
Category B One or two lift overlay construction over cold planed surfaces and two-lift overlays	mm/km	< 1142	1142 - 1355	NA	> 1355
	in/mi	< 75	75 - 89	NA	> 89
Category C Single-lift overlays over existing surfaces	mm/km	< 1294	1294 - 1446	1446- 1674	> 1674
	in/mi	< 85	85 - 95	95 - 110	> 110
Shoulders	mm/km	< 1675	NA	NA	> 1675 Pay 70% or remove
	in/mi	< 110	NA	NA	> 110 Pay 70% or remove
Incentive pay, final completion, average of all travel lanes (with no lot less than 100% pay)	mm/km	≤ 685 +10% of the value of the wearing course (plan quantities)			
	in/mi	≤ 45 +10% of the value of the wearing course (plan quantities)			

* or Portion of lot placed on the Project.
** At the option of the engineer.

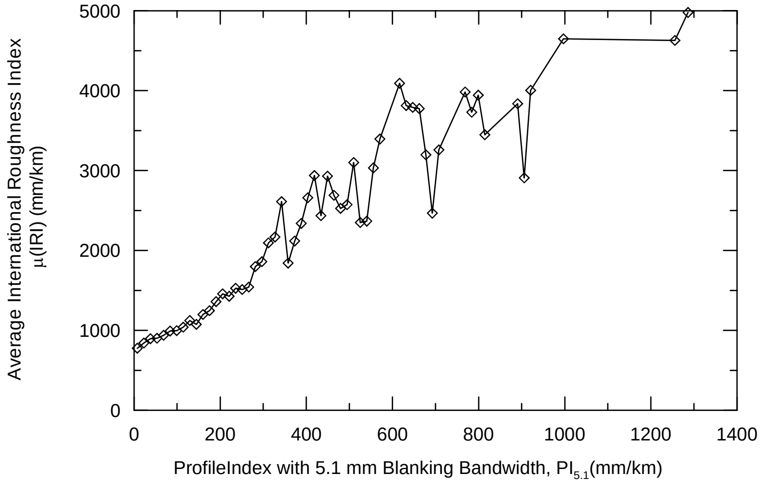
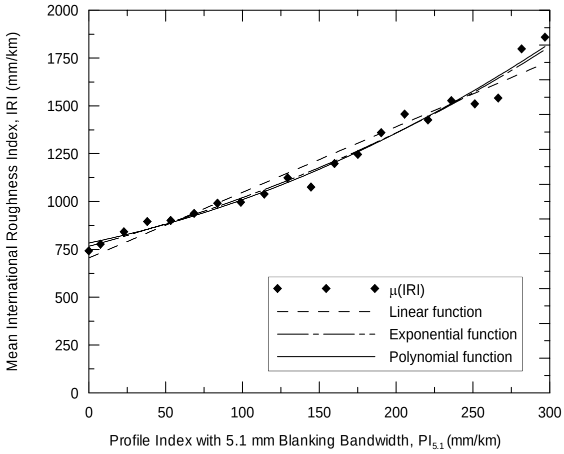
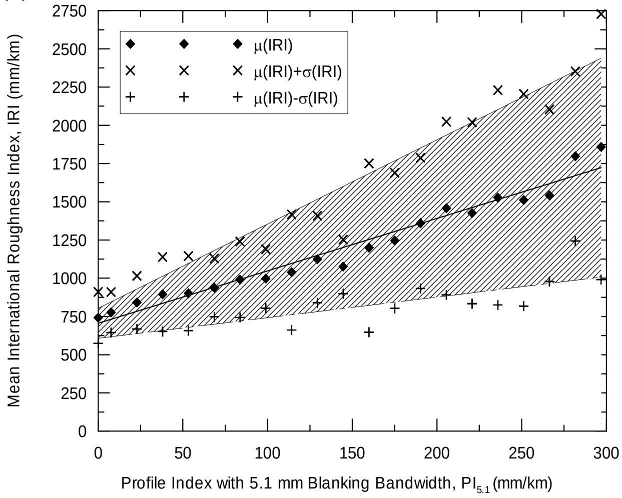


Figure (6): Relationship between mean *IRI* and *PI*$_{5.1}$ obtained via analysis of variance.



(a) Mean *IRI* versus *PI*$_{5.1}$ with the 95% confidence interval



(b) Mean *IRI* versus *PI*$_{5.1}$with the different regression functions.

Figure (7): Analysis of variance of the smoothness indices of the collected data.

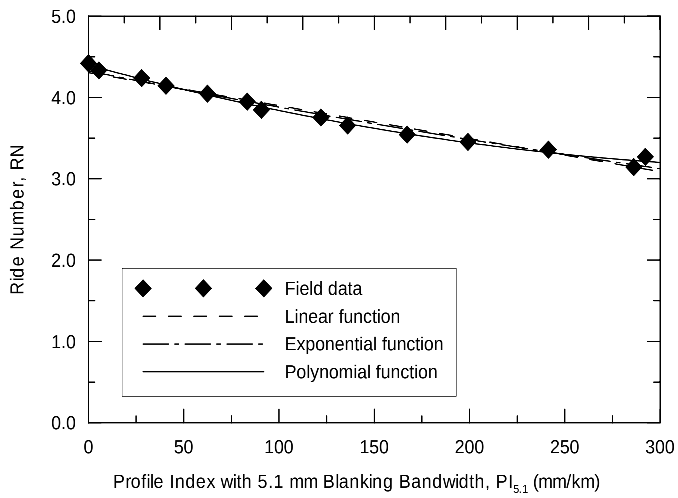


Figure (8): Ride number versus the profile index with 5.1 mm blanking bandwidth.

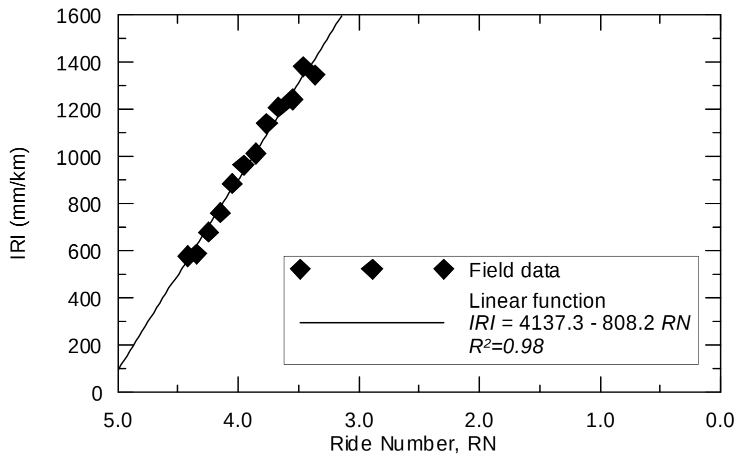


Figure (9): Relationship between *IRI* and *RN* for the pavement test sections.

Statistical analysis was also conducted to evaluate the relationship between *IRI* and *RN*. The results are depicted in Figure 9. The best function that correlates *IRI* to *RN* is a linear function with R^2=0.98, as shown in Figure 9. The linear model was used to predict the *IRI* limits corresponding to the specifications limits of LA DOT, as presented in Table 4, column 5. The linear models used to predict *IRI* from $PI_{5.1}$ and *RN* produced reasonable values that can be used to guide a selection of new *IRI* based smoothness specifications.

Based on this analysis, *IRI* based smoothness specifications were developed for asphalt concrete pavement in Louisiana and are summarized in Table 5. These specifications are currently under processing for approval by LA DOTD.

CONCLUSIONS

Statistical analyses were conducted to establish mathematical relationships between *IRI*, $PI_{5.1}$ and *RN*. The data used in the analyses were collected from measurement of longitudinal profiles along 98.7 km of asphalt concrete pavements in Louisiana. Relationships between the different indices were evaluated. The linear models that relate *IRI* to $PI_{5.1}$ and *IRI* to *RN* were selected. These models were used to develop smoothness criteria based on *IRI* for asphalt pavements in Louisiana.

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