Establishing International Roughness Indices for a dense urban area – case study in Washington, DC

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Abstract

The Federal Highway Administration (FHWA) requires each state in the United States to report the International Roughness Indices (IRI) of their road network in the annual Highway Performance Monitoring System (HPMS). The reported IRI for road segments are compared to the national standards developed by the FHWA based on national data. Deviations from the national standards are used to identify road segments that need to be included in repair or maintenance programs. The FHWA IRI thresholds for all road classes range between 170 in/mi and 96 in/mi for "acceptable" pavements, and 95 in/mi or less for "good" pavements. The use of the IRI for identifying sections of highways for repair and rehabilitation has been under review in several states. There is the concern that the national values of the IRI often do not reflect the ride smoothness perceived by citizens in the specific jurisdictions. This research obtained the ride quality ratings of residents of a dense urban area (Washington, DC) and correlated those with the IRI values for selected road segments. This research presents the IRI thresholds developed for the urban area based on the regression models obtained and the standard IRI thresholds for newly constructed pavement.

Keywords: International Roughness Index, deceleration, braking.

1 Introduction

Since the development of the International Roughness Index (IRI) in the early 1990s, all states have been required by the Federal Highway Administration (FHWA) to report bi-annually IRI results through their Highway Performance

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Monitoring System. International Roughness Index is a standardized measure of the response of a standard vehicle to roadway profile and roadway roughness. The index is typically expressed in "inches per mile". Higher IRI values generally represent rougher roads, while lower IRI values mean smoother roads. Over the past several years substantial progress has been made in improving ride quality through pavement management programs thereby reducing IRI values. Increasingly, modification of FHWA's IRI standards is being used as a strategy for improving the ability of states to identify road segments for repair or maintenance programs. There is concern that the pure values of the IRI are often in conflict with the ride perceived by the occupants of vehicles. A few states [1–3, 8] states are establishing IRI thresholds based on the ride quality perceptions of motorists. The problem appears to be more acute in urban areas where the dominant features are arterials, collectors and local streets and where the public's tolerance for pavement roughness is relatively higher because of low operating speeds.

Currently, the District Department of Transportation (DDOT) uses the IRI standards set by FHWA for HPMS reporting. There was concern among the District's engineers that the IRI data collected in bi-annual surveys may exaggerate the extent of maintenance needed since manhole covers and similar roadway features may skew IRI values. This paper presents the establishment of IRI thresholds that are based on the level of satisfaction of the ride quality experienced by vehicle occupants on the District's roads, automated IRI survey data, and IRI specifications used for deciding payments for newly constructed pavements in the District of Columbia. The developed IRI thresholds have the potential for reducing maintenance cost by reducing the number of road segments that may fail the basic FHWA IRI thresholds. This research is aimed at using citizens' perception to establish the IRI thresholds for urban roads (the District of Columbia). In particular, the following objectives formed the basis of this research:

- developed a relationship between the subjective ride quality rating (PSR) provided by citizen subjects and the objective ride quality data (IRI) for various roadway classifications.
- developed IRI thresholds based on the relationship established and acceptable IRI standards for newly constructed pavement.

2 Literature review

Pavement smoothness or roughness can be expressed as the extent of the non-existence or existence of surface irregularities that affect the ride quality of road users. Research has shown that smooth roads, on the whole, costs highway agencies less over the life of the pavement resulting in decreased highway user operating costs, delay costs, fuel consumption and maintenance costs. Pavement roughness is measured by various automatic multifunctional measuring instruments or devices and is quantified using the International Roughness Index (IRI), an internationally accepted parameter. IRI was first defined in the late 70s by NCHRP Report 228 [1] and was adopted as a universal scale.

IRI is typically measured by automation using a road profiler, which produces a series of numbers to represent the profile of the road by combining a reference elevation, height relative to the reference, and longitudinal distance. Examples of road profilers include the Profilograph, Dipstick Auto-Read Road, and Inertial Profilers [2]. Response-type road roughness meters or profilers are typically used to collect IRI data and are usually mounted in specialized vehicles with computer technology to monitor pavement roughness. The device records the displacement of the vehicle chassis relative to the rear axle per unit distance traveled, usually in terms of counts per mile or foot [3].

Road smoothness may also be quantified in the form of the Present Serviceability Rating (PSR), which depends on subjective human evaluation of ride quality. The PSR was developed in 1962 by the AASHO Road Test. The rating ranges from zero (impassable) to 5 (perfect). It has been established through studies conducted by FHWA that the smoothness index of highway systems obtained through automation (IRI) can be correlated with the subjective ride experience or evaluation of road users (PSR rating).

Pavement surface roughness is a major indicator of drive quality, and can induce stress into the pavement structure that could cause premature pavement fatigue and accelerated pavement deterioration. Pavement roughness indices (together with other pavement measurements) are often indicators of pavement surface deformation. Pavement distress, whether originating from above or below, undermines pavement drainage and thereby compromises highway safety. Pavement distress also results in a deterioration of the pavement roughness index value. This therefore suggests that the extent of pavement distress could be correlated with pavement roughness indices, including the IRI.

The FHWA recommended a threshold of 170 in/mi (2.7 m/km) for acceptable ride quality in its 1998 strategic plan for the National Highway System. The lower the IRI number the smoother the ride and vice versa. Table 1 provides the pavement condition criteria for all functional road classifications in the national highway system, together with the estimated PSR rating [4].

Table 1: FHWA pavement condition criteria [4].

Road Quality Terms	**IRI Threshold (in/mi)**	**PSR Rating**
Good	≤ 95	> 3.5
Acceptable	≥ 95 and ≤ 170	≥ 2.5 and ≤ 3.5

Most jurisdictions in the United States rely on pavement indices to determine which road segments on their road network need maintenance or improvement. These indices include the IRI and the Pavement Condition Index. Since 1990, FHWA has required states to report road roughness on the basis of the IRI thresholds (and other pavement indices) in Table 1. This mandatory report has caused most states to take a second look at the national IRI thresholds, which may or may not truly reflect actual pavement roughness or smoothness perceived by motorists in local jurisdictions. The application of the national IRI standards has been challenging to dense urban jurisdictions due to heavy traffic volumes, expected traffic interruptions and considerably lower travel speeds.

The Minnesota Department of Transportation (MnDOT) developed a mathematical model for converting the IRI to the PSR for bituminous and concrete pavements [5]. In the process of developing this model in 1997, MnDOT asked 32 citizens to rate the smoothness of more than 120 pre-selected test sections on the state's highway system. The range of the ratings was from zero (very poor) to 5 (very good), with grades in-between for good, fair and poor. Using simple regression analysis, the following regression equations were developed for bituminous and concrete pavements respectively:

$$PSR = 5.697 - (2.104.\sqrt{IRI}) \text{ , and } PSR = 6.634 - (2.813.\sqrt{IRI}) \qquad (1)$$

where IRI = International Roughness Index, in m/km. These regression models enabled MnDOT to set its own IRI thresholds for acceptable pavement conditions.

The City of New York, along with the New York State Department of Transportation (NYSDOT), began an assessment of the quality of the pavements in various jurisdictions using 151 motorists in different community districts [6]. This study was conducted in 1995 and enlisted the services of an independent research firm which asked members of focus groups to rate a list of pre-selected roadways on a scale from 1 (good) to 4 (terrible) as they were driven through each segment. However, instead of using the traditional IRI values, NYSDOT measured the smoothness of the same segments in terms of "City Roughness Index" (CRI). The reported indices were obtained using the same procedures for obtaining IRI values, except that the CRI is a number that is dependent on the number of "jolts" encountered per mile on short distance segments with high speeds of travel. The tests were applied only to city streets. A regression analysis was conducted for the data obtained from the motorists' perception and the CRI. The percentages of motorists who rated the smoothness of roadways as "good", "fair", "poor" and "terrible" were also reported for each jurisdiction. The results of the study were used to establish the CRI thresholds for city streets in the State of New York.

In 2008, DDOT established standards for IRI for newly constructed pavement to be used in identifying the payment mechanism for pavement contractors [7]. The standards for accepting new pavements are based on IRI surveys of 25 ft segments of roads. The threshold averages for good pavement are equivalent to IRI_c, defined as the maximum IRI for full pay. These values are presented for

Table 2: DDOT's IRI thresholds for new pavement [11].

New Pavement IRI Limits	**ROAD TYPES**		
	Freeways	**Arterials/ Collectors**	**Local Roads**
IRI_c (Good)	≤80	≤160	≤180
IRI_f (Acceptable)	81-160	161-300	181-350

freeways, arterials and collectors, and local roads. Similarly, IRI_f is equivalent to the threshold for defect correction on new pavements. From the definitions, IRI_c could be classified as “good” while IRI_f could be classified as “acceptable”. The thresholds are presented in Table 2.

3 Methodology

In establishing IRI benchmarks for the District of Columbia (DC), a survey was conducted using DC residents who gave their opinions on the smoothness of selected road segments, based on the Weaver/AASHO Scale. The ratings were obtained while the subjects were driven over selected road segments in the City. Using simple regression analysis methods, the average ratings of the drivers' perception of the smoothness for each segment were correlated with the corresponding segments' IRI values obtained from recent DDOT pavement smoothness surveys. Based on the resulting regression models and acceptable IRI schedules for newly constructed pavement, benchmark IRI values for each roadway classification were obtained. A 5% level of significance was used for the analyses. The average of the thresholds obtained from the regression models and the established values for IRI_c and IRI_f (for each road classification) were then calculated and presented as IRI thresholds for the District of Columbia.

3.1 Data collection

DDOT provided the IRI data for selected segments that represented the various functional roadway classifications in the District. For each segment, the specific lane, direction of travel, and corresponding IRI observations were obtained. In all, 122 segments were selected and were grouped into the following 3 classes: interstate/freeways (30), arterials (62) and collectors (30). The segments selected had IRI values raging from 97 to 499 in/mi.

Sixty-six subjects participated in the survey with ages ranging between 21 and 61. Three groups were formed (22 subjects each) for the survey for each of the three roadway classes. Prior to the commencement of the survey, instructions on how to provide ratings using the AASHO/Weaver form were given to all the subjects. Each group was driven over the selected lane of each segment and each member recorded his/her individual perception of the ride using the survey for provided. The Weaver/AASHO form was used by the subjects for rating the smoothness of the segments. The scale ranges from 0 (“impassable”) to 5 (“perfect”). The scale also has intermediate ratings which are labeled as “very good,” “good,” “fair,” “poor” and “very poor”. For each segment driven, the subjects were asked to indicate on the scale the position that corresponded with their best description of their feeling about the segment smoothness. A survey form was provided for each segment and for each subject. The subjects familiarized themselves with the survey form before being driven over the selected segments.

3.2 Statistical analysis

For each segment, the average of the subjects' rating was computed. The average ratings for the segments were correlated to the IRI values using regression analysis methods. After a series of data transformations, the following generalized regression model was deemed to be adequate:

$$ln\ (IRI) = \alpha + \beta\ (PSR) + \varepsilon, \quad (2)$$

where IRI is the dependent variable and PSR is the independent variable. The constants α and β are the coefficients of the regression model with an associated error of ε [$\varepsilon \sim N(0, \sigma^2)$]. The statistical significance of the regression coefficients were tested at 5% level of significance. The overall statistical significance of each regression model for each classification of roadway segment was tested using the F-test at 5% level of significance. In addition, the regression model was checked for homoscedasticity (constant variance) using residual plots while checking for normality using the normal probability plots. For each regression model, the coefficient of determination or the R^2 value is also reported. This is the amount of variability in the data explained or accounted for by the regression model.

4 Results

4.1 Descriptive statistics

Table 3 presents a summary of descriptive statistics of interest for the various types of roadways.

Table 3: Descriptive statistics for IRI values.

Classification	Mean IRI (in/mi)	Mean PSR Rating	IRI Standard Deviation(in/mi)	PSR Standard Deviation
Freeways/Interstates	207.88	3.40	101.24	0.23
Arterials	225.52	3.20	55.32	0.45
Collectors	285.45	2.58	72.43	0.23

A PSR rating between 2 and 3 on the AASHO/Weaver scale was considered as fair while a rating above 3 indicated a good ride quality. Thus, on the average, motorists' in DC considered road segments with a high IRI value of about 285 in/mi as fair. Interstate and local freeways had the lowest mean IRI value (207.88 in/mi) with a corresponding high PSR rating (3.40) which represents a good ride quality. Collectors had the highest mean IRI value (approximately 286 in/mi) with a mean PSR rating of 2.58. However, on the Weaver/AASHO scale, a rating of 2.58 corresponds to a fair ride quality.

4.2 Regression model for freeways/interstates

Data for the 30 freeway segments surveyed were analyzed and the results showed that the regression model is adequate at 5% level of significance. The summary of the regression analysis indices is presented in Table 4. The scatter plot with fit and residual plot for the model are presented in Figures 1 and 2 respectively.

Since the p-value for the F-statistic is less that 5%, it indicates that the regression model is adequate based on the data collected. In addition, the t-statistics of the coefficients β_0 and β_1 were found to be statistically significant at 5% level of significance. The resultant regression equation is:

$$ln \text{ IRI} = 6.672 - 0.4202 \text{ (PSR)} \tag{3}$$

Table 4: Summary of regression analysis for freeways/interstates.

Test Statistic	Value	P-Value
R^2 Value	0.58	n/a
ANOVA: Regression ***F-Value***	34.07	0.00
Significance of Regression Coefficients (***t- Statistic)***	β_0 : 6.672	0.00
	β_1 : -0.4202	0.00

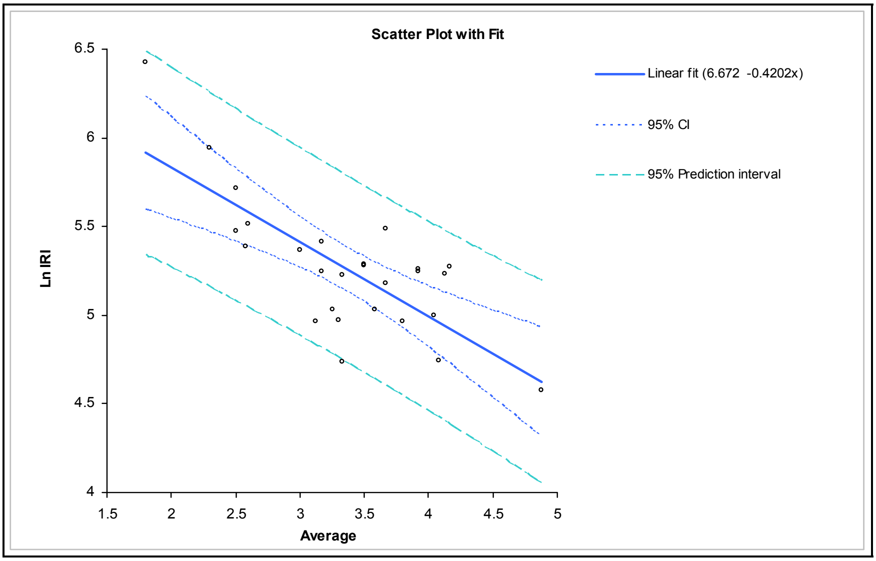

Figure 1: Scatter plot with fit for freeway regression model.

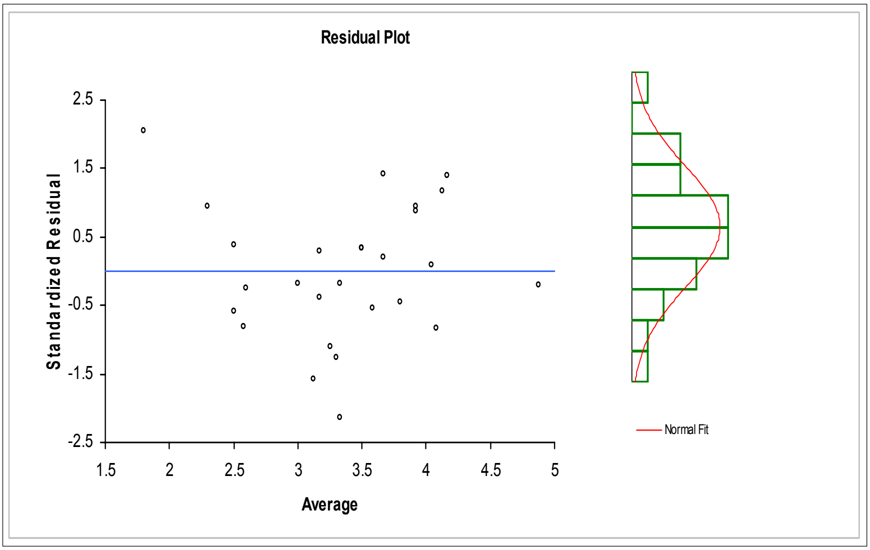

Figure 2: Residual plot for freeway regression model.

4.3 Regression model for arterials

Based on the regression analysis conducted on the 62 arterial segments, the results indicate a statistically significant regression model at 5% level of significance. This is indicated by the summary in Table 5. Presented in Figures 3 and 4 are respectively the scatter plot with fit and residual plot for the regression model.

The *p*-values for all the major regression indices were found to be less than 5%, thus indicating an adequate regression model. The model only explains about 48% of the variations in the data (based on the R^2 value). The resulting regression equation was determined to be:

$$\ln \text{IRI} = 6.191 - 0.2483\ (\text{PSR}) \tag{4}$$

Table 5: Summary of regression analysis for arterials.

Test Statistic	**Value**	**P-Value**
R^2 Value	0.48	n/a
ANOVA: Regression ***F-Value***	53.64	0.00
Significance of Regression Coefficients ***(t- Statistic)***	β_0 : 6.191	0.00
	β_1 : -0.2483	0.00

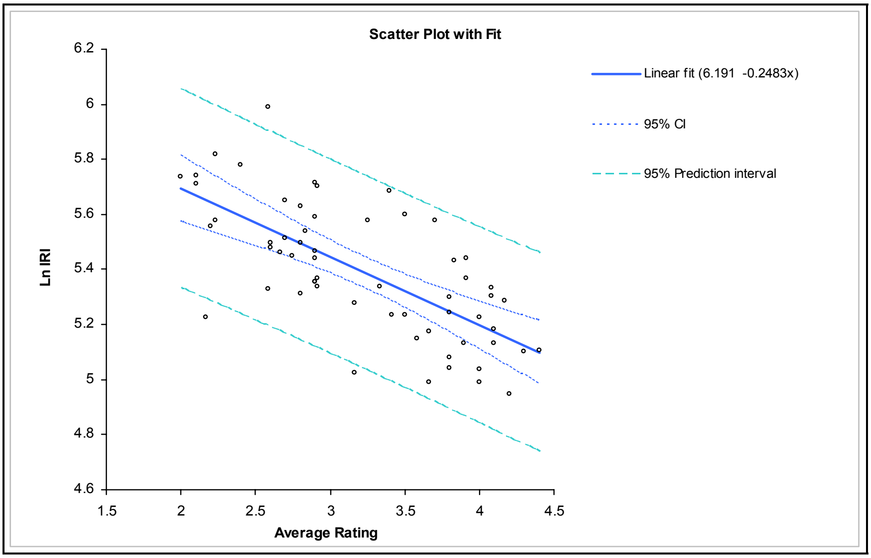

Figure 3: Scatter plot with fit for arterials regression model.

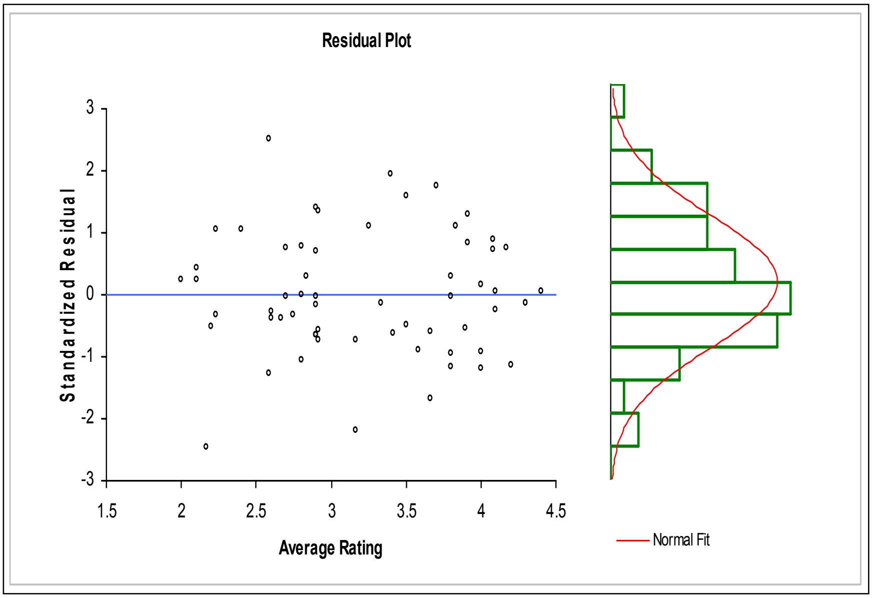

Figure 4: Residual plot for arterial regression model.

4.4 Regression model for collectors

Similarly, a statistically significant regression model was developed for the correlation between the IRI and the PSR rating for the arterial roads surveyed. The analysis was conducted at 5% level of significance. The primary regression indicators, as in the previous cases, showed a statistically significant correlation between the independent variable and the dependent variable. The summary of the results are presented in Table 6 with scatter plot with fit and residual plot for the regression model presented in Figures 5 and 6 respectively. The analysis resulted in the following regression equation:

$$\ln \text{IRI} = 6.599 - 0.3772\ (\text{PSR}) \qquad (5)$$

Table 6: Summary of regression analysis for collectors.

Test Statistic	Value	P-Value
R^2 Value	0.51	n/a
ANOVA: Regression ***F-Value***	29.63	0.00
Significance of Regression Coefficients ***(t- Statistic)***	β_0 : 6.599	0.00
	β_1 : -0.3772	0.00

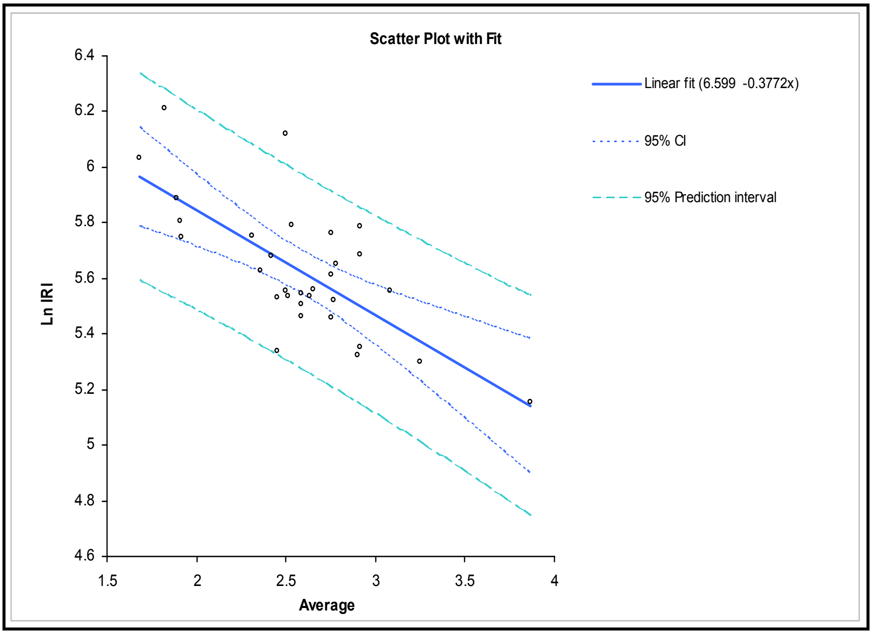

Figure 5: Scatter plot with fit for collector regression model.

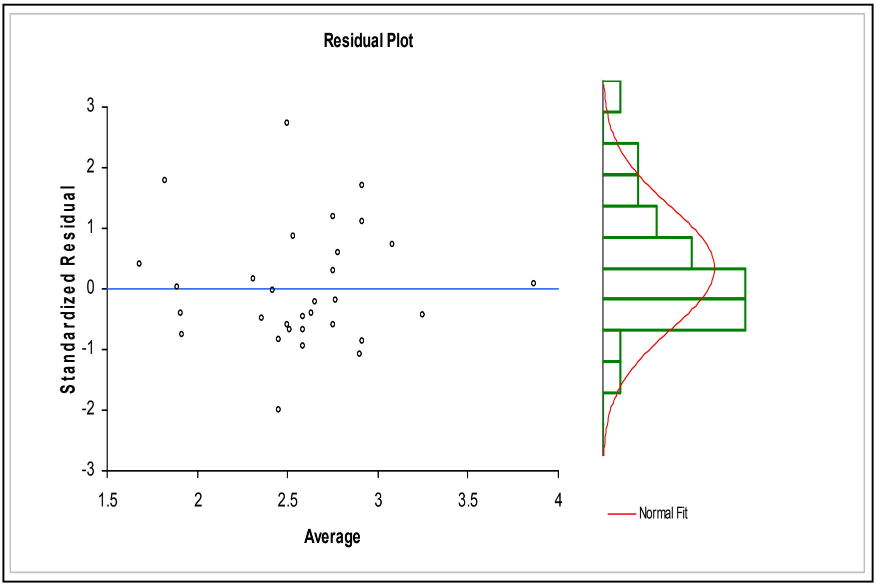

Figure 6: Residual plot for collector regression model.

The plots also validate the underlying regression assumptions presented earlier.

5 Developing IRI thresholds for DC

Based on the regression analyses conducted at 5% level of significance, the threshold IRI values (based on motorists' perception of ride quality) can be inferred. The thresholds derived from the analyses are presented in two-fold: based on FHWA pavement condition scale as presented in Table 1 and on the Weaver/AASHO scale range. The regression equations were used in arriving at these thresholds for each type of roadway. The minimum PSR ratings of 3.5 and 2.5 were used to characterize "good" and "acceptable" IRI thresholds, respectively. These limits were substituted into the regression equations to produce the corresponding IRI limits presented in Table 7.

Using the limits in Table 3 and Table 7, the following threshold values were obtained by computing the average of the limits for each roadway classification. The results, representing the IRI thresholds for the DC, are presented in Table 9.

Table 7: IRI limits based on regression models.

Ride Quality	**IRI Threshold (in/mi) by Roadway Classification**		
	Freeways	***Arterials***	***Collectors***
Good	< 167	< 204	< 196
Acceptable	167- 276	204- 262	196- 286

Table 8: IRI thresholds for DC.

Ride Quality	IRI Threshold (in/mi) by Roadway Classification		
	Freeways	*Arterials*	*Collectors*
Good	<124	<182	<188
Acceptable	124-218	182-281	188-318

6 Conclusion

The IRI thresholds recommended by FHWA are 95 and 170 for good and acceptable conditions respectively. These values, however, do not generally reflect the perception of dense urban environments. In addition, since roadway geometrics and pavement durability vary considerably from state to state, as expected, many states have embarked upon a similar research to establish their own smoothness tolerance levels which the driving public is willing to accept, based on prevailing driving conditions. Within the margin of error, the thresholds derived can be adequately generalized for the three roadway classes in the District of Columbia. The IRI thresholds derived in this study could be used to select road segments for pavement maintenance and rehabilitation programs.

Acknowledgement

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