Journal of Civil Engineering Research 2015, 5(1): 10-17
DOI: 10.5923/j.jce.20150501.02

Predicting Pavement Condition Index Using International Roughness Index in a Dense Urban Area

Stephen A. Arhin[1,*], Lakeasha N. Williams[2], Asteway Ribbiso[2], Melissa F. Anderson[3]

[1]Corresponding Author, Department of Civil and Environmental Engineering, Howard University, Washington, D.C., USA
[2]Graduate Students, Department of Civil and Environmental Engineering, Howard University, Washington, D.C., USA
[3]Graduate Student, Sustainable Urban Planning Program, George Washington University, Washington, D.C., USA

Abstract A number of pavement condition indices are obtained and used to conduct pavement management assessments, two of which are the International Roughness Index (IRI) and Pavement Condition Index (PCI). The IRI is typically obtained using specialized equipment which indicates the smoothness of the roadway segment based on established computer algorithms, while the PCI is based on subjective rating of the number of pavement distresses. The literature suggests that most of these pavement indices are related as a result of which several jurisdictions have developed models to predict one index from the other. This study used 2 years of IRI-PCI data sets to develop models that predict PCI from IRI by functional classification and by pavement type in the District of Columbia. The results of the descriptive statistics, based on the mean IRI and PCI values, suggest that highways have a smoother ride than arterials, followed by collectors and local roads. Similarly, when the data was analyzed by pavement type, the results show that Composite Pavements were smoother than Asphalt Pavements followed by Concrete Pavement. The regression models between the IRI and PCI by functional classification and pavement type were determined to be statistically significant within the margin of error (5% level of significance), with R^2 values between 0.56 and 0.82. The results of the ANOVA tests also showed statistically significant F - statistics ($p < 0.05$) in addition to statistically significant regression coefficients (from the t-tests, with $p < 0.05$). The residual plots for all the models also showed randomness about the zero line indicating their viability, in addition to the normal probability plots showing points near a straight line.

Keywords Pavement Condition Index, International Roughness Index, Ride Quality, Prediction, Urban Areas

1. Introduction

Departments of Transportation (DOTs) across the United States conduct pavement condition assessments each year to determine the health status of the roadway network and program improvements such as maintenance, resurfacing, rehabilitation and reconstruction. The type of pavement improvements is dictated by the extent of the distress severity. The annual condition assessment is typically conducted using specialized equipment to collect distress data as well as ride quality data. The specialized equipment comprises of a specialized camera mounted at the back of the survey vehicle which takes photographs of the pavement at varying speeds. The distress photographs are reviewed by trained pavement engineers and technicians on the basis of which the distress (if any) of the sections of the pavement are quantified by type, severity and extent. Using an established equation, and based on the engineers (or technicians) subjective evaluations, the distresses found on the sections of the pavement are combined and the overall Pavement Condition Index (PCI) for the block is then computed. Attempts are being made to use 3-D technology for automatic distress evaluations that are expected to reduce the subjectivity in PCI computations.

PCI ranges from zero to one hundred, with zero indicating poor/failed pavements and one hundred being excellent. In addition to distress data, the specialized equipment also obtains ride quality information at the same time. The ride quality indicates the smoothness of the roadway segment which is reported as the International Roughness Index (IRI). The IRI is calculated based on established computer algorithms, and thus, not subjective. Both pavement measurements are very important since they collectively provide a comprehensive indication of the structural and functional condition of the pavement. Only IRI is required as part of the Highway Performance Monitoring System (HPMS) reporting to the Federal Highway Administration.

The literature suggests that distresses in pavement surface (PCI) influence the smoothness (IRI) of a pavement. As a result, in order to eliminate the subjectivity in reporting the PCI, some jurisdictions and states have established relationships or models between IRI and PCI

* Corresponding author:
saarhin@howard.edu (Stephen A. Arhin)
Published online at http://journal.sapub.org/jce

based on which the PCI can be predicted from the IRI. This research is geared toward developing a model for pavement distress conditions (PCI) in terms of IRI for the District of Columbia.

2. Objectives and Benefits

The objective of this study is to use previously obtained distress (PCI) and smoothness (IRI) data of sections of roadways in the District to establish a relationship between PCI and IRI for various roadway classifications and pavement types. It is anticipated that the outcome of this research could potentially eliminate or reduce the time for collecting, reviewing and processing distress photographs for PCI and thereby the subjective rating of pavement distress. In addition, the expense for conducting the field data collection for PCI, and man-hours potentially could be reduced after the models have been validated with additional field data.

3. 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, cost 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 70's by the National Cooperative Highway Research Program (NCHRP) Report 228 and adopted by the World Bank [1] as a universal scale. IRI is one of several pavement indices required for annual reporting to FHWA by each state on the annual HPMS report.

IRI is 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 on specialized vehicles with computer technology to monitor pavement roughness as shown in Figure 1.

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]. Other instruments measure pavement roughness in terms of the number of inches per mile that a laser, mounted on a vehicle, jumps as it is driven across roads at speeds of over 30 mph. These instruments are connected to calibrated computer models which are used to calculate and report a corresponding number indicating the roughness or smoothness of the roadway driven. This ensures that the IRI values reported are comparable and repeatable, regardless of the test vehicle [3].

Figure 1. Specialized Van for IRI Data Collection

FHWA recommends a threshold of 170 in/mi (2.7 m/km) for acceptable ride quality in its 2006 strategic plan for the National Highway System where the lower the IRI value is, the smoother the ride and vice versa. Table 1 provides the pavement condition criteria for all functional road classifications in the national highway system [4]. Several jurisdictions have explored PCI-IRIR relationships for highways with acceptable statistical validity.

Table 1. FHWA Pavement Condition Criteria

Road Quality Terms	IRI Threshold (in/mi)
Good	< 95
Acceptable	< 170

Source: Dewan, 2012

Park et al. [5] established a power relationship between PCI and IRI using data from nine states and provinces in Northern America. The IRI-PCI data set used in the study used were extracted from the DataPave program for highways in the regions of Delaware, Maryland, New Jersey, New York, Vermont, Virginia, Ontario, Quebec and Prince Edward Island and spanned the period from 1991 through 2000. The power model proposed was led to the following equation:

$$\log(PCI) = 2 - 0.436\log(IRI) \quad (1)$$

The R^2 value of the model was determined to be 59%. The plots of the residuals and normal scores were used to confirm the normality and homoscedasticity of the model's distribution.

In 2012, Shahnazri et al. [6] estimated PCI values from other pavement indices (other than IRI) based on different types of distresses and severity levels using two optimization techniques: artificial neural networks (ANN) and genetic programming (GP). The models were developed based on PCI data gathered from more than 1,250 km of highways in

Iran. A feed forward ANN was used with the network being trained using the back propagation method. In addition, the root-mean square error (RMSE) fitness function was used for the GP approach. From the results, the ANN- and GP-based projected values were determined to be in good agreement with the field-measured PCI values. The reported R^2, RSME and mean absolute error (MAE) for the ANN-based models were respectively 0.9986, 0.99, and 0.49, whereas they were equal to 0.9898, 2.63, and 1.79 respectively for the GP-based model.

Another model for IRI as a function of PCI was developed for the Bay Area cities and counties in California with the intent of using the model in estimating user costs/benefits in their pavement management system. The resulting model was:

$$IRI = 0.0171(153 - PCI) \quad (2)$$

where IRI is in m/km. The model's R^2 value was 0.53 with a coefficient of variation of 28%. The actual and predicted values of IRI were compared graphically to depict the dispersion of data and for model validation.

A 2002 study conducted using data from varied highway pavement sections from the North Atlantic region in the United States and Canada resulted in the development of a relationship between the PCI and IRI. The model confirms the acceptability of the IRI as a predictor variable of the PCI based on the existence of the resulting strong correlation between the two variables (from the ANOVA) and an R^2 value of 0.66 for the model. In addition, the results showed acceptable corresponding *p*-values from the ANOVA and *t*-tests for this model which also suggest the acceptability of IRI as a predictor variable of PCI at a 99% significance level.

A neural network model was developed to estimate IRI from PCI based on data obtained for construction work zones [8]. The predicted IRI values from the model were compared with the actual IRI values measured using MERLIN (Machine for Evaluating Roughness using Low-cost Instrumentation) within the construction work zones. The researchers used Levenberg-Marquardt back-propagation for the estimation of IRI from PCI. The neural network model developed was trained and tested resulting in an R^2 value of 0.86 and MSE of 0.041 which indicate that the performance of neural network was satisfactory and feasible for the prediction IRI [8].

The literature review uncovered a variety of statistically significant models or relationships between the IRI and PCI (and other pavement indices). Most of the studies reviewed indicate the acceptability of IRI as a predictor variable of PCI for highways with variations in the confidence level. IRI, which is a profile-based statistic, is shown to be an ideal predictor (or independent variable) since it has the advantage of being repeatable, reproducible, and stable with time. More importantly, IRI is not a subjective measure, compared to PCI. The statistical significance of some of these relationships or models developed also suggest that one variable can be predicted or estimated from the other, depending on data availability and quality.

The majority of the models were based on data compiled for highways or suburban areas. As a result, a model developed for one jurisdiction is often inappropriate for another jurisdiction, especially for a dense urban city (e.g. District of Columbia). Therefore, unique IRI-PCI prediction models for specific urban areas need to be explored.

4. Research Methodology

4.1. IRI-PCI Data Acquisition

Recent PCI and IRI data for years 2009 and 2012 were provided by the District Department of Transportation for this study. The IRI-PCI data sets for pavement types and roadway classifications for each year were sufficiently large (>30) and were classified by pavement type and functional classification for each year.

The data was screened based on the expectation that a high IRI value should correspond to a low PCI value and vice versa. In all, 895 data points were used to develop the models. The following data were used by functional classification: Freeways = 20, Arterials = 149, Collectors = 140 and Locals = 157. By pavement type, the following data points were used: Concrete = 91, Asphalt = 171 and Composite = 167.

4.2. Statistical Analysis

The Ordinary Least Squares (OLS) regression method was employed in the development of the PCI-IRI models. The statistical significance of the regression coefficients of the resulting model were tested at 5% level of significance. In addition, the overall statistical significance of each regression model for each roadway classification was tested using the F-test (ANOVA) at 5% level of significance.

4.3. Regression Model Validation Methods

The following were employed to confirm the validity of the models developed for each category.

R^2: R^2 indicates the goodness of fit of the model and provides the proportion of total variance that is explained by the model.

F-test: The F-test evaluates the null hypothesis that all regression coefficients are equal to zero versus the alternative that at least one does not. An equivalent null hypothesis is that R^2 equals zero. A significant F-test indicates that the observed R^2 is reliable, and is not a spurious result of oddities in the data set. Thus, the F-test determines whether the proposed relationship between the response variable and the set of predictors is statistically reliable.

Residual Plots: The regression model was checked for homoscedasticity (constant variance) using residual plots. The residuals from a fitted model are the differences between the observed variables and the corresponding predicted values using the regression function developed. Mathematically, the definition of the residual for the i^{th} observation in the data set is defined as:

$$e_i = y_i - f(x_i, \hat{\beta}) \quad (3)$$

with y_i denoting the i^{th} response in the data set and x_i the vector of explanatory variables, each set at the corresponding values found in the i^{th} observation in the data set. If the model fits the data, the residuals would approximate the random errors that make the relationship between the explanatory variables and the response variable a statistical relationship. Therefore, if the residuals appear to behave randomly, it suggests that the model fits the data well. On the other hand, if non-random structure is evident in the residual plots, it is a clear sign that the model fits the data poorly.

Normal Probability Plots: The normal probability plots were also used to assess whether or not the data sets are approximately normally distributed. In a normal probability plot, if all the data points fall near the line, an assumption of normality is reasonable. Otherwise, the points will curve away from the line, and an assumption of normality is not justified.

Kolmogorov-Smirnov Test: The two-sample Kolmogorov-Smirnov test (KS test) was used to test whether the predicted dependent variables from the models are similar to the observed dependent variables given the same set of independent variables. The null hypothesis is that the two data sets are similar or have the same continuous distribution while the alternative hypothesis is that they are not similar or have different continuous distributions. The KS test has the advantage of making no assumption about the distribution of data and computes a D-statistic with an associated p-value. If the p-value is greater than the level of significance, then the null hypothesis that the predicted (from the regression model) and observed dependent datasets are statistically the same cannot be rejected.

The KS test is used to evaluate the hypothesis that the differences between the cumulative distribution functions (CDFS) of the distributions of the two sample data vectors (predicted and actual dependent variables) are similar. The two-sided test uses the maximum absolute difference between the CDFS of the distributions of the two sample sets. The test statistic is

$$D^* = \max_X(|F_1(x) - F_2(x)|),$$

where $F_1(x)$ is the proportion of x_1 values less than or equal to x and $F_2(x)$ is the proportion of x_2 values less than or equal to x.

Model Development

After a series of data transformations, the best generalized regression model was determined to assume the following form:

$$PCI = A\ (IRI) + k + \varepsilon \quad (5)$$

where IRI is the independent variable and PCI is the dependent variable with A and k being constants. The models were assumed to have an associated error of ε [$\varepsilon \sim N(0, \sigma^2)$].

5. Results

5.1. Descriptive Statistics

The summaries of the mean IRI and PCI are presented by functional classification and pavement type for 2009 and 2012.

5.1.1. By Functional Classification

The summary of the mean IRI values for both years by functional classification is presented in Figure 2. From the figure, the highest mean IRI was 332 in/mi for local roads in 2012. It can be observed that freeway functional class was the only roadway type that improved in smoothness from 2009 to 2012. The remaining functional classes showed a decline in smoothness, based on the increases in the IRI values. Local roads experienced the most reduction in smoothness based on the average IRI value of 300 in/mi in 2009 to 332 in/mi in 2012. The local roadways were closely followed by collectors with an average IRI score of 268 in/miin 2009 to 291 in/mi in 2012, and arterials with a mean IRI score of 247 in/mi in 2009 to 274 in/mi in 2012.

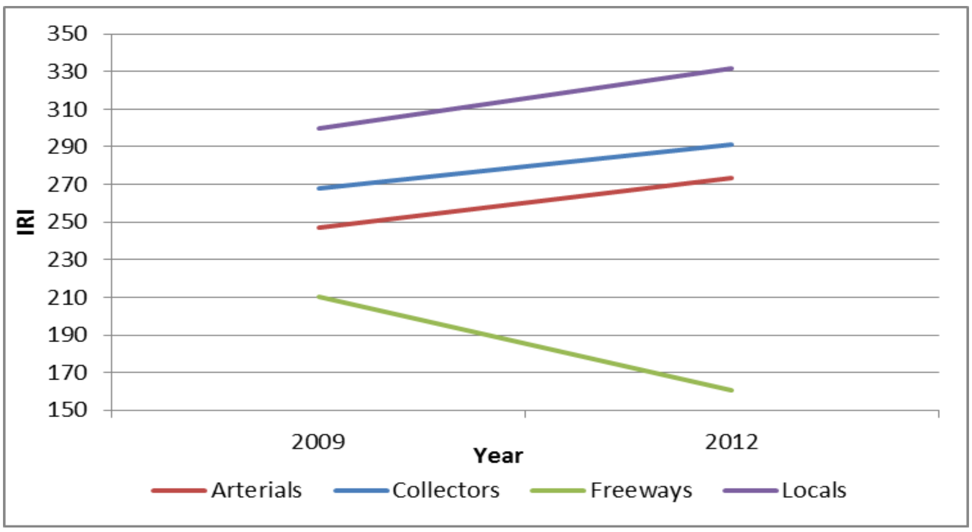

Figure 2. Overall Mean IRI Values (in/mi) by Functional Classification

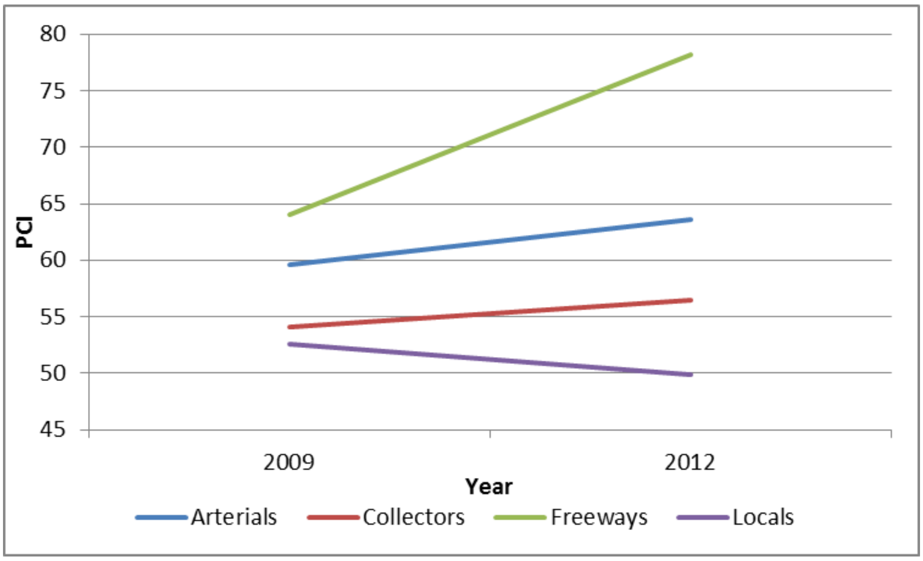

Figure 3. Overall Mean PCI Values by Functional Classification

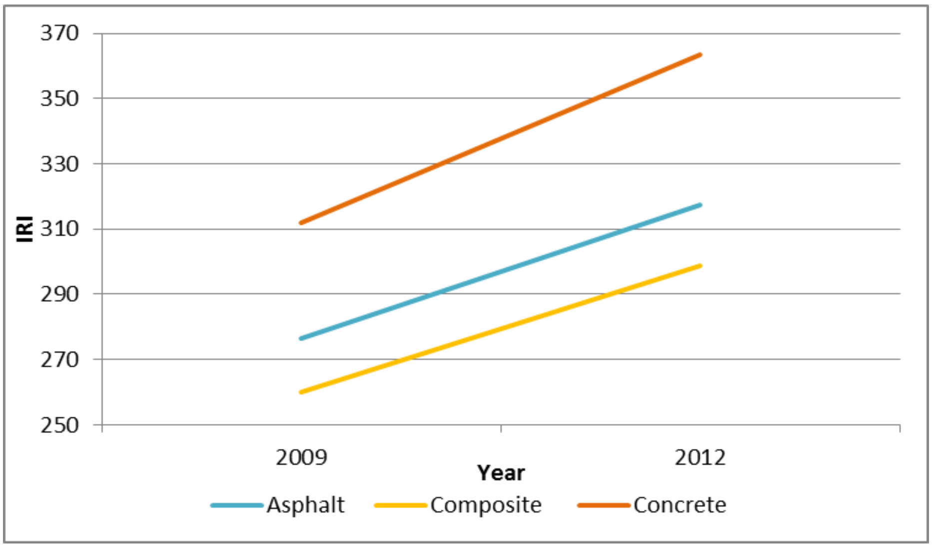

Figure 4. Overall Mean IRI Values (in/mi) by Pavement Type

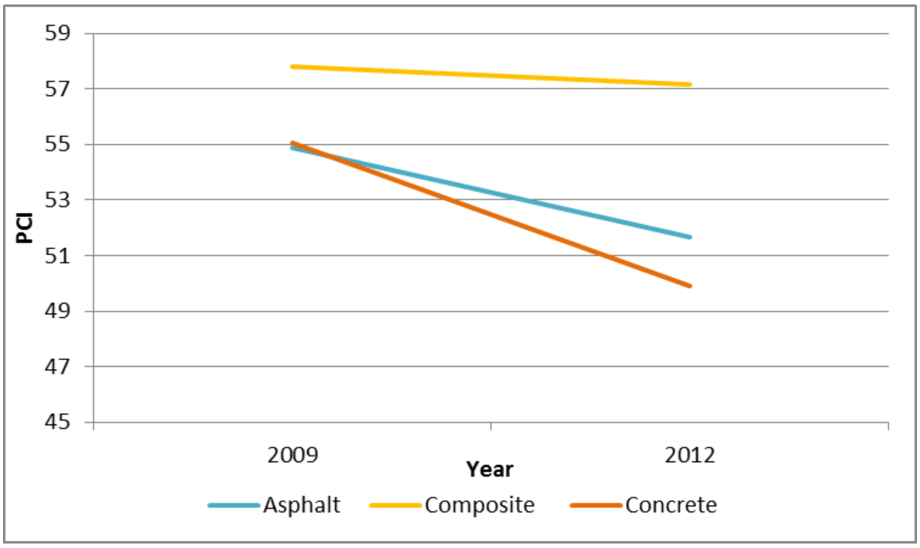

Figure 5. Overall Mean PCI Values by Pavement Type

Figure 3 shows the mean PCI values by functional classification for the years considered. From the figure, the lowest mean PCI value was 50 for local roads, while the highest mean PCI (78) was recorded for freeways. This confirms that freeways had a smoother ride compared to the other roadway classes. Also, it can be observed that local roads have the most distresses compared to arterials and collectors.

5.1.2. By Pavement Type

The summary of the means of the IRI values for the years 2009 and 2012 by pavement type is presented in Figure 4. The results showed that the highest mean IRI was 363 in/mi for concrete pavement in 2012, and the lowest was 260 in/mi for composite pavement in 2009. From the figure it can be observed that all pavement types experienced a decline in smoothness from 2009 to 2012.

In Figure 5, the summary of the mean PCI values by pavement type from 2009 to 2012 are presented. The figure shows that the lowest mean PCI value was 50 for concrete pavement in 2012, while the highest mean PCI was recorded for composite pavement was 58 in 2009. It was observed that all pavement types experienced an increase in distresses; however, on average, composite pavement had lower irregularities than asphalt and concrete pavement for the two years considered.

Table 2. Summary of Regression Analysis by Functional Classification

Functional Classification	Model Equation	R^2	ANOVA	
			F - value	*p*-value
Freeways	PCI_{FWY}=-0.215(IRI_{FWY}) + 110.73	0.56	21.37	0.00
Arterials	PCI_{ART}=-0.206 (IRI_{ART}) + 114.15	0.71	190.80	0.00
Collectors	PCI_{COL}= -0.217(IRI_{COL}) + 115.32	0.73	209.15	0.00
Locals	PCI_{LOC}=-0.186(IRI_{LOC}) + 110.31	0.74	253.70	0.00

Table 3. Summary of Regression Analysis by Pavement Type

Pavement Type	Model Equation	R^2	ANOVA	
			F - value	*p*-value
Asphalt	PCI_{ASP}=-0.224(IRI_{ASP}) + 120.02	0.82	391.98	0.00
Composite	PCI_{COM}=-0.203 (IRI_{COM}] + 113.73	0.75	258.50	0.00
Concrete	PCI_{CON}=-0.172(IRI_{CON})] + 110.01	0.72	140.75	0.00

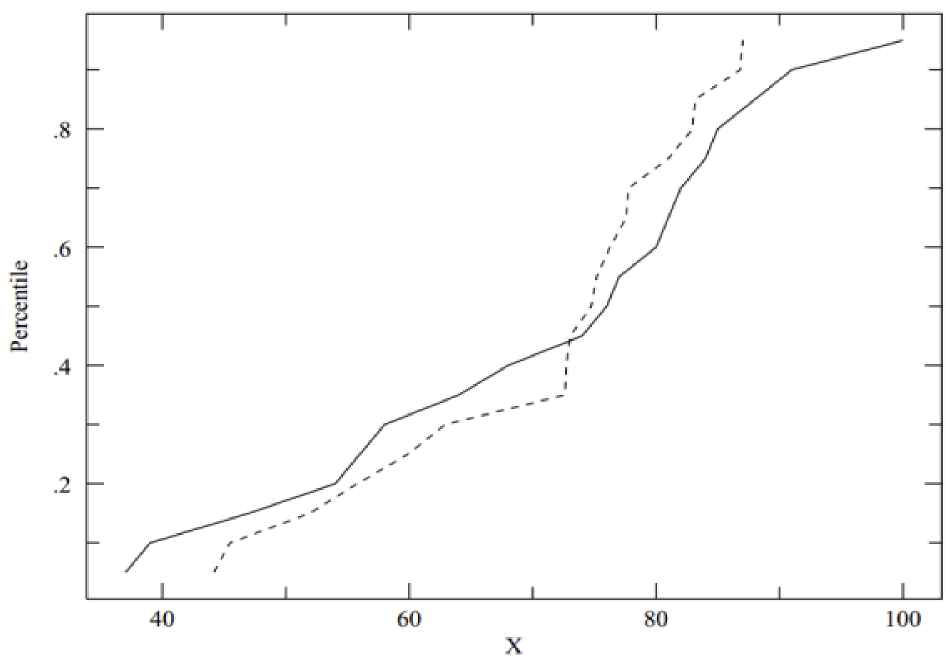

Figure 6. KS-test Comparison Percentile Plot for Freeways

5.2. Regression Analysis

Regression models were developed by functional classification and by pavement type using the combined data for 2009 and 2012. The regression models for four functional classifications were developed: freeways, arterials, collectors and locals. Those developed by pavement type were asphalt, concrete and composite. The adequacy and significance of the regression models were all tested at 5% level of significance. The summary of the regression models and their indicators by functional classification and pavement type are respectively presented in Tables 2 and 3.The results shown in the tables indicate that the regression models could explain relatively high percentages of the total variations in the data, based on the R^2 values (56% or more). Also, the p-value for the F-statistic for each regression model by functional classification and pavement type was determined to be less than 0.05, indicating that the regression model is adequate.

5.3. Kolmogorov Smirnov Test

The D-statistic and corresponding p-values for the proposed regression models show that they adequately predict the observed values. Figure 6 presents the output of the KS tests for the regression model for freeways.

5.4. Residual and Normal Probability Plots

For each functional classification and pavement type, the residual plots show a similar number of points above and below the zero line showing that the model fits the data well. Also, the normal probability plots show a line along the points, demonstrating that an assumption of normality is reasonable for the data sets.

Thus, from the results, it can be concluded that the models are adequate since the residual plots show the randomness while the normal probability plots show the points near a straight line. From the results, it can be concluded that the models could adequately predict PCI using IRI, at a 5% level of significance.

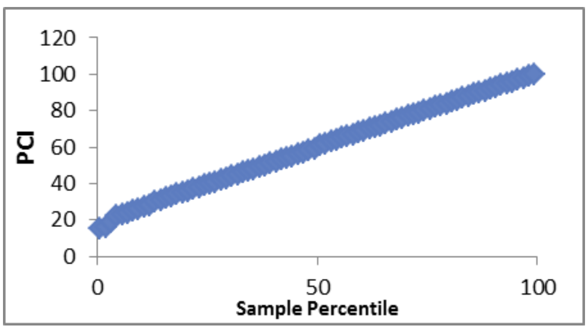

Figure 7. Normal Probability Plot for Arterials

6. Discussion

From the literature review, a variety of statistically significant models or relationships between the IRI and PCI (and other pavement indices) were identified for various jurisdictions. The studies also reveal the notion that it is acceptable to use the IRI as a predictor variable of PCI. The IRI, which is a profile-based statistic, is shown to be an ideal predictor (or independent variable) since it has the advantage of being repeatable, reproducible, and stable with time. The vast variations of models developed between IRI and PCI is a strong indication that models can only be developed exclusively for each jurisdiction. The statistically significant relationships or models developed for these variables also suggest that one variable can be predicted or estimated from the other.

From the results, it can be suggested from the mean IRI and PCI values that freeways have a smoother ride than arterials, followed by collectors and local roads in D.C. The lowest mean IRI value was 160 in/mi for freeways in 2012 combined with a corresponding mean PCI value of 78. Similarly, when the data was analyzed by pavement type, the results show that Composite Pavements were smoother than Asphalt Pavements followed by Concrete Pavement. Composite Pavements recorded the least average IRI value (260 in/mi) with a corresponding mean PCI value of approximately 57.

For the data considered, the mean IRI values appear to be decreasing for freeways from 2009 to 2012 (210 to 160 in/mi respectively), indicating an improved smoothness of the roadway type. For arterials and collector streets, however, an increase was identified in 2012 compared with 2009. The average IRI values for arterials, collectors and local roads showed an increase from 2009 to 2012, indicating a decline in the smoothness of the roadway types. The increases in IRI values could be attributed to the increased number of work zone and roadway rehabilitation projects which commenced in the 2010-2011 timeframe. The average PCI values showed a similar trend as the mean IRI values.

A review of the results of the analysis by pavement type revealed that, overall, composite pavement had the lowest mean IRI values over the period considered. The mean IRI values ranged from 260 to 299 in/mi. This was followed by asphalt pavement (averages range between 277 and 317 in/mi) and then concrete pavement (average ranges between 312 and 363 in/mi). These results were supported by the corresponding PCI values.

The regression models between the IRI and PCI values for the years considered yielded statistically significant regression models within the margin of error (5% level of significance), with relatively high R^2 values (between 0.56 and 0.82). The results of the ANOVA tests also showed statistically significant F - statistics ($p < 0.05$) in addition to statistically significant regression coefficients (from the t-tests, with $p< 0.05$). The residual plots for all the models also showed randomness about the zero line indicating their viability, in addition to the normal probability plots showing points near a straight line.

It is important to note that the pavement indices displayed by year are not necessarily to show progress of IRI/PCI over time, but simply as aggregate indicators of the road conditions in those years. This is due to the fact that information regarding pavement maintenance or rehabilitation work on the selected road segments for this research was not readily available.

7. Conclusions

The OLS method used in predicting PCI from IRI yielded statistically significant regression models. Within the margin of error, the regression models can be adequately used for roadway functional classifications and pavement types in the District of Columbia. Since the District of Columbia is committed to moving in the direction of predicting PCI values from IRI, the models developed in this study could be used to predict PCI for pavement management assessments. This would also reduce the need for the subjective determination of the PCI values and thereby the need for allocating funds and several man-hours for its determination. Additional data sets for other years will be needed to further validate these models. Although, potential modern 3D-scanning technologies are purported to predict PCI values more accurately, the technology is still evolving and very costly. As a result, such prediction models could be used in the meantime in order to eliminate the subjectivity of calculating PCI values.

ACKNOWLEDGEMENTS

The authors extend their appreciation to the District Department of Transportation for funding and contributing to this study. Any opinions, findings, and conclusions or recommendations in this material are those of the authors and do not necessarily reflect the views of the District Department of Transportation.

REFERENCES

[1] Gillespie, T.D. (1980) "Calibration of response Type Road Roughness Measuring Systems."National Cooperative Highway Research Program Report. No. 228.

[2] Sayers, M.W., T.D. Gillespie, and W.D. Paterson. (1996) "Guidelines for Conducting and Calibrating Road Roughness Measurements." World Bank Technical Paper Number 46.

[3] Shafizadeh, K., F. Mannering, and L. Pierce.(2002) A Statistical Analysis Of Factors Associated With Driver-Perceived Road Roughness On Urban Highways. Washington: Washington State Department of Transportation (WSDOT).

[4] Dewan, S.A. Transforming LTTP Distress Information for Use in MTC-PMS, "Improving Pavements with Long-Term Pavement Performance: Products for Today and Tomorrow." http://www.fhwa.dot.gov/publications/research/infrastructure /pavements/ltpp/03049/paper2.cfm. Accessed September 2/2013.

[5] Park K., Thomas, N., and Lee K. (2007)"Applicability of the International Roughness Index as a Predictor of Asphalt Pavement Condition." Journal of Transportation Engineering-asce:doi:10.1061/(ASCE)0733-947X(2007)133: 12(706).

[6] Shahnazri, Habib, Nohammad A. Tutunchain, Mehdi Mashayekhi, and Amir A. Amini. (2012)"Application of Soft Computing for Prediction of Pavement Condition Index." http://ascelibrary.org/doi/abs/10.1061/(ASCE)TE.19435436. 0000454?journalCode=jtpedi. Accessed September 2/2013.

[7] Dewan, S.A., and R.E. Smith.(2002) "Estimating IRI from Pavement Distresses to Calculate Vehicle Operating Costs for the Cities and Counties of San Francisco Bay Area." Transportation Research Record No. 1816.

[8] Vidya, R., Moses S. Santhankumar, and Samson Mathew. (2013)" Estimation of IRI from PCI in Construction Work Zones". ACEE International Journal on Civil and Environmental Engineering. Vol. 2, No. 1.