Distress-based PSI Models for Asphalt Pavements of Rural Highways

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ABSTRACT

Pavement serviceability index (PSI) is one of the pavement performance measures that have been originally used in the AASHO (currently AASHTO) road test to evaluate the pavement condition. The PSI is highly correlated with roughness index which is currently used in the Mechanistic-Empirical Pavement Design method to predict pavement performance. Therefore, PSI is still considered an important index used for pavement performance evaluation. Experimental PSI models based on regression analysis were developed in this research study. The study involved thirty-five asphalt pavement sections with a 366-m (1200 ft) length representing thirty-five rural highways. Pavement distresses, including linear and fatigue cracking, rut depth, raveling, patching, debonding and potholes were measured. In addition, the present serviceability rating (PSR) and the roughness (measured by the slope variance (SV)) were obtained. The ride quality on a scale from 0 to 5 was used to provide the PSR, where 5 is the highest rating and 0 is the lowest rating. Two PSI regression models were developed that can be used for rough pavements (SV ≥ 500) and smooth pavements (SV < 500), respectively. The most significant variables affecting the PSI were found to be rut depth, debonding and potholes (merged in one variable). Linear cracking and rut depth were found to be the second significant variable affecting PSI for rough pavements and smooth pavements, respectively. On the other hand, the slope variance had a relatively higher effect on the PSR of smooth pavements than that of rough pavements.

KEYWORDS: Asphalt pavements, Rural highways, Serviceability, PSR, PSI, Performance, Distress, Slope variance, Roughness.

INTRODUCTION

The majority of pavement networks in the world are composed of asphalt pavements. Asphalt pavements of major roadways generally perceive a quite high percentage of trucks having different axle types and wheel configurations, particularly those pavements of highways serving as arterials between major cities, international expressways or collectors from industrial areas.

Pavement performance evaluation and measures are considered a critical part in pavement management system that can significantly affect pavement maintenance and rehabilitation (M&R) priorities and long-term strategies. Asphalt pavement performance measures can be done using different methods, including (1) pavement condition index (PCI), international roughness index (IRI), (3) present serviceability rating (PSR), (4) deflection measurement and (5) skid resistance safety rating (functional behavior).

It is known that roughness provides the major correlation variable for computing PSI. For this reason, many agencies use only roughness to determine PSI or to measure pavement rating. However, roughness of asphalt pavements is also affected by pavement structural and functional distresses. For this reason, the overall pavement condition is a major factor for estimating the present serviceability index (PSI) of asphalt pavements. Recently, research efforts have been devoted to study the PSR, PSI and the relationship between PSR and pavement condition index, which considers all pavement distresses.

Received on 10/3/2020.
Accepted for Publication on 4/4/2020.

Al-Khateeb and Al-Smadi (2013) developed PSI models for flexible pavements of urban highways. A multiple regression experimental model was presented for PSI of urban highway pavements. The study showed that potholes represented the most significant variable affecting the PSI predictions, whereas rut depth was the least variable impacting PSI predictions.

Hall and Munoz (1999) estimated the present serviceability index (PSI) from international roughness index (IRI) in a study aimed at developing models for PSI as a function of IRI for asphalt and concrete pavements. Their methodology was based on analyzing the correlation between slope variance and PSI values obtained from the analyses conducted by the AASHO and then analyzing the correlation between slope variance and IRI representing a wide range of road roughness levels. According to their study, the road test data demonstrated a difference in serviceability between concrete pavement and asphalt pavement for a given level of roughness.

Terzi (2006) used data mining in a study to model the pavement serviceability index of flexible highway pavements. A regression tree (RT) model was presented for determining flexible pavement surface layer thickness. Findings of the study showed that the RT model values for the wearing course thickness of flexible pavements were better than those of the AASHTO model.

Terzi (2007) used artificial neural networks (ANNs) in another study to model the pavement serviceability index of flexible highway pavements. Experimental data obtained from the AASHTO including rut depth, patches, cracking, longitudinal cracking and slope variance was used in the study. Findings of the study showed that the developed ANN model had a higher regression value than the AASHO model. This approach can be easily and realistically performed to solve the problems which do not have a formulation or function about the solution.

Sun (2001) developed theoretical models for international roughness index (IRI) and present serviceability index (PSI). The models used power spectral density (PSD) roughness. The stochastic process theory was used to obtain frequency response functions of quarter-car model and CHOLE-type profilometer. The study also provided a correlation between typical PSI and IRI of flexible and rigid pavements whose PSD roughness is given in the form of power law at specified levels.

Bryce et al. (2019) conducted a study to relate the pavement condition index (PCI) and the present serviceability rating (PSR) for asphalt-surfaced pavements and presented a model to estimate the PSR using data collected during a PCI survey. The study was initiated in light of the measurement of IRI on pavements with a speed limit below 40 mph not expected to provide a reliable estimation of ride quality. Although reporting the present serviceability rating (PSR) on these routes is allowed, many agencies do not measure the PSR or collect the slope variance data required to estimate the PSR. In their study, the model presented is capable to estimate the PSR from the PCI data. Furthermore, the study explored the reasons why pavements can have a good PCI and a poor PSR and *vice versa*.

Gulen et al. (1994) in their study for Indiana Department of Transportation (INDOT) searched realistic models for the correlation between the present serviceability index (PSI) and the international roughness index (IRI). Ten 1-mi-long sections were selected at three roughness levels for both concrete and bituminous pavements. Two nearly identical cars were used, and each rated the 20 test sections as a driver and as a front seat passenger. The IRI of each test section was measured by a van equipped with noncontact laser sensors. The statistical analyses indicated that the PSI rating observations were normally distributed, the variances were homogeneous and the position of the rater in the car was not significant. Simple linear and exponential models were obtained to fit the PSI and IRI data with r^2 values ranging from 0.80 to 0.95.

Titi and Rasoulian (2008) evaluated the smoothness of Louisiana pavements based on the international roughness index (IRI) and ride number (RN). A high-speed road profiler was used to measure the longitudinal profiles along approximately 100 km of asphalt pavements. Several relationships were established between the smoothness indices considered in the study, including the profile index, IRI and RN. The models developed were used to establish IRI-based specifications for construction control of pavements in Louisiana.

Obaidat et al. (2018) investigated the potential integration of Geographic Information System (GIS) and PAVER system for efficient pavement maintenance management. The developed system helped in pavement distress classification and decision making for maintenance priorities. Statistical models were developed in their study to predict pavement distress quantities using traffic, climatic and socio-economical characteristics and pavement age.

Velaga and Dhingra (2011) developed a road maintenance and rehabilitation (M&R) system to determine cost-effective strategies for maintaining road networks based on both GIS and GPS platforms. After implementing the developed M&R system for a small part of road network in Mumbai metropolitan area in India, it was found to be effective in day-to-day road maintenance and helpful in decision making for road M&R work planning and scheduling.

In this paper, distress-based models are developed for the PSI of asphalt pavements of rural highways. The slope variance of the pavement surface and all pavement distresses expected to affect the present serviceability rating of the pavement are considered in the study. Statistical regression analysis using stepwise regression techniques is performed to select the most significant variables that affect the PSI in the final developed models.

Objectives

The main objective of this study is to develop distress-based models for the present serviceability index (PSI) for asphalt pavements of rural highways considering distress and roughness measurements. Multiple non-linear regression techniques were used following the mathematical form shown below:

$$PSI = k_0 + k_1 f(D_1) + k_2 f(D_2) + k_3 f(D_3) + k_4 f(D_4) + \ldots\ldots + k_n f(D_n) \quad (1)$$

where:

$k_0, k_1, k_2, k_3, k_4, \ldots$ and k_n are regression coefficients and $D_1, D_2, D_3, D_4, \ldots$ and D_n are measurements of slope variance and distress types, respectively.

Methodology and Field Procedures

Selection of Highway Sections

In this study, thirty-five pavement sections of 366 m (1200 ft) length and 3.1 m (10 ft) width representing thirty-five rural highways in Jordan were selected, which cover a variety of existing loading and climatic conditions. The selected rural highways also covered different geographical locations and two major classes, primary and secondary highways. The thirty-five asphalt pavement sections were surveyed for distresses and roughness. In the following parts of the paper, field procedures followed in this study are detailed.

PSR and Ride Quality

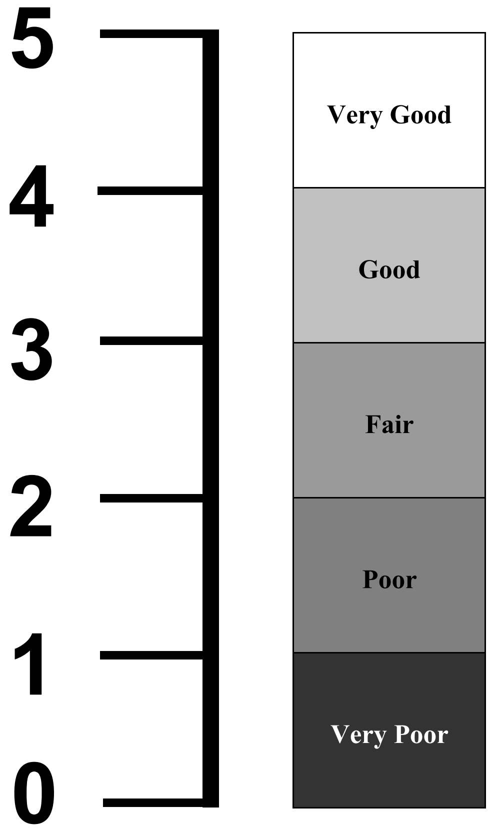
The concept of ride quality was used to determine the present serviceability rating (PSR) for pavement sections. A panel of engineers measured the ride quality (rating) over the pavement section using a common pavement rating form (Fig. 1). The rating was performed by engineers / experienced technicians riding in a standard passenger car with very good mechanical and dynamic conditions.

The rating was provided by each engineer independently without the effect of the others, in order to minimize the bias in pavement rating. Additionally, a group of road users (seven drivers) of passenger cars, buses, large trucks, semi-trailers and single-unit trucks provided ratings for the pavement sections. The ratings done by the road users helped in validating the ratings performed by the engineers, especially since this kind of pavement rating is subjective. The relationship between the two sets of ratings was developed to check the goodness-of-fit of the correlation between the two sets. It was found that a linear model with a coefficient of determination (r^2) of 0.70 best fitted the data (Fig. 2).

Roughness

The slope variance (SV) along the wheel paths over each pavement section was used to measure roughness of the pavement section. The slope variance was measured using a surveying level device with a high level of accuracy. The measurement of slope was taken every 1.5-m interval along the pavement section. The slope was computed over 25.4-cm (10-in) length using two measurements at the two ends. The measurement of slope was taken every 1.5-m interval along the pavement section. The slope was computed over 25.4-cm (10-in) length using two level readings at the two ends. The difference between the two readings divided by the 25.4-cm distance is simply the slope at that point. The number of slope data points for each pavement section was 240, providing a total number of 8400 data points for the study. To estimate the slope variance, Equation (2) (Huang, 2004) was used:

Rating Form for Pavement Section			
Name of Roadway		Rater Name	
Class of Roadway		Vehicle	
Section ID		Time	
Type of Pavement		Date	
Length of Section		Rating	
Width of Section			



	Yes	**No**	**Not Sure**
Is this pavement section acceptable?			
Does it need routine maintenance?			
Does the pavement need major maintenance?			

Figure (1): Pavement rating form

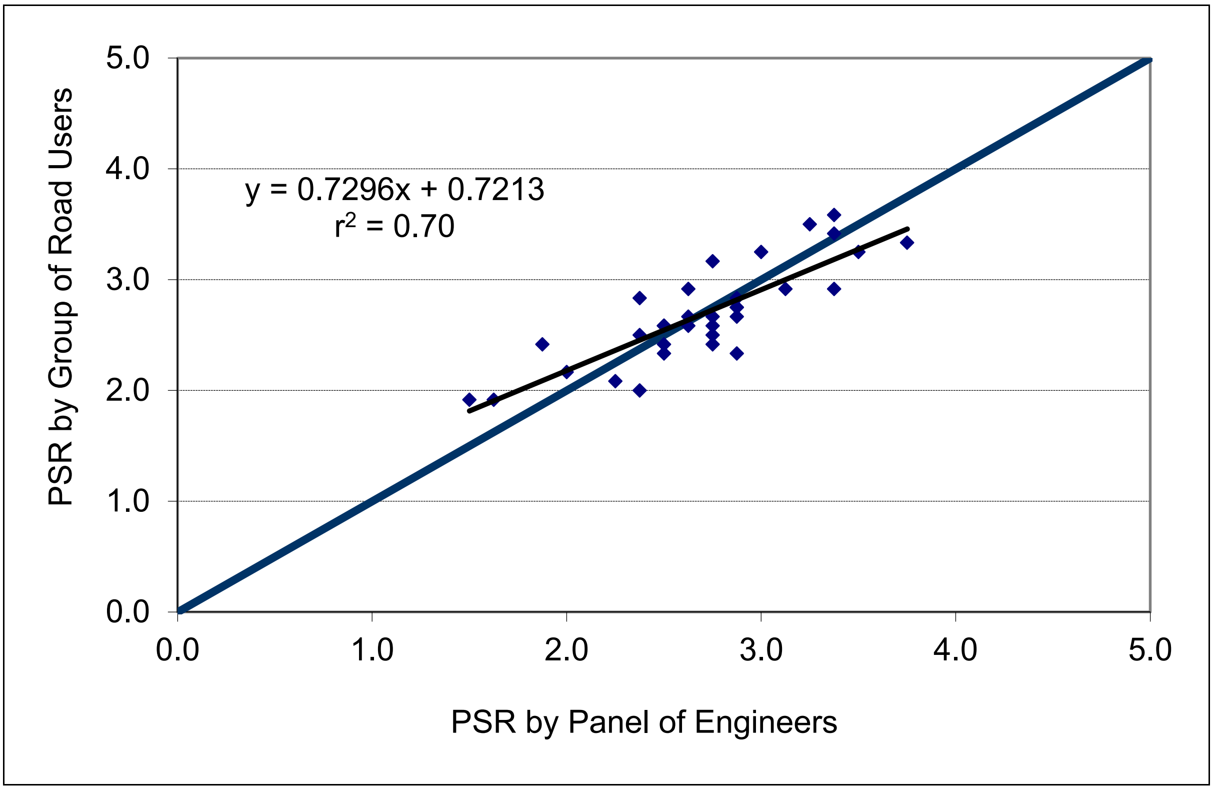


Figure (2): PSR by panel of engineers *vs.* PSR by group of road users

$$SV = \frac{\sum_{i=1}^{n}(S_i - \bar{S})^2}{n-1} \qquad (2)$$

where:
SV = slope variance;
S_i = slope I;
$\bar{S}$ = mean of slopes;
n = number of observations (data points).

Pavement Distresses

The following major flexible pavement distresses that are expected to affect the pavement rating are considered and measured over each pavement section: rut depth, linear cracking, fatigue cracking, patching, raveling, potholes and debonding. Other distresses that were less possibly to affect the pavement rating and existed at a minimum rate in the pavement sections were avoided in the study. The distresses considered in the study are given the symbols shown below:
Rut Depth = RD;
Linear Cracking = LC;
Fatigue Cracking = FC;
Patching and Raveling = PR;
Potholes = H;
Debonding = DB

Rut depth (RD) was measured in the wheel path across the rutting area using a straightedge. The average of ten RD measurements taken across the straightedge was estimated to represent the RD at that point. The RD measurements were taken at 5-m intervals in the wheel paths along the rutting area. The mean rut depth for the pavement section was estimated by taking the mean of the rut depth averages for the entire rutting area. Linear cracking (LC) was measured by length (m). Fatigue cracking (FC), patching and raveling (PR) and debonding (DB) were measured by surface area (m^2) and potholes were measured by number. The distresses considered in the study are shown in Fig. 3.

The severity levels for all distresses in the thirty-five highway sections ranged from low-to medium-severity levels. For linear cracking, the width of the cracks ranged from 5 mm to 15 mm. For fatigue (alligator) cracking, the severity was determined based on whether the cracks are lightly or heavily well-defined and spalled at the edges. In all fatigue cracking areas, the severity levels were between low and medium. Debonding was treated as potholes in terms of severity level, since it does not have a common severity level definition in pavement maintenance. The maximum depth of potholes ranged from 1.5 to 5 cm and the average diameter ranged from 10 to 30 cm. Since debonding occurs in the asphalt surface layer due to a weak bond between the surface and binder layers and the surface layer has a standard 5-cm thickness, the depth of debonding would be 5 cm. For raveling, the severity level is based on the condition of the surface and the wearing between the asphalt and the aggregate. On the other hand, the severity level of patching is based on the condition of the patch and the degree of deterioration. The rut depth was considered in the modeling; therefore, the severity level for rutting was by default considered in the analysis.

Distress-based statistical regression models for the PSI are developed. The seven independent variables (RD, LC, FC, PR, H, DB and SV) representing distresses and roughness are taken into consideration in the multiple regression analysis that is performed using the least squares' method. The PSI general model takes the following form:

$$PSI = k_0 + k_1 f(SV) + k_2 f(RD) + k_3 f(LC) + k_4 f(FC) + k_5 f(PR) + k_6 f(H) + k_7 f(DB) \quad (3)$$

where: k_0, k_1, k_2, k_3, k_4, ... and k_n are regression constants.

Modeling of PSI

Selection of Appropriate Correlation Functions

The relationship between each independent variable and PSR was carefully investigated prior to regression analysis to select the most appropriate function (*f*) that describes the relationship. In some cases, two independent variables are combined to represent one variable for better results. For example, the relationship between log (RD) and PSR is plotted using a scatter plot, as shown in Fig. 4. Additionally, the relationships between $(PR+AC)^{0.5}$ and PSR and between $(DB+PH)^{0.5}$ and PSR are also plotted in Fig. 5 and Fig. 6, respectively. The coefficient of determination (r^2) values for these three relationships are 0.4, 0.3 and 0.6, respectively. It has to be noticed herein that the equation for each relationship of the above generally has a relatively low r^2 value due to the fact that each independent variable is plotted individually against the PSR value in isolation of the other variables.

The final mathematical expression of the PSI model using the afore-mentioned correlation functions is shown in the following equation:

$$PSI = k_0 + k_1(SV) + k_2\,log(RD) + k_3\,log(LC)^2 + k_4(PR + FC)^{0.5} + k_5 f(DB + PH)^{0.5} \quad (4)$$

Development of Distress-based PSI Models

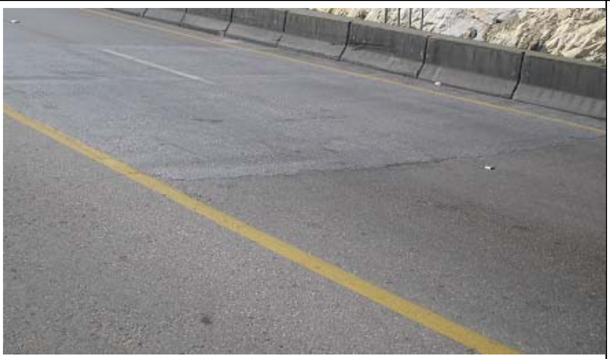
The STATISTICA package (2012) was used to perform the multiple non-linear regression analysis. The regression constants *k1, k2, k3, k4 and k5* for the final PSI model were determined from the regression analysis. It was found that PSI could be best modeled with a higher coefficient of determination (r^2) when two ranges for the slope variance (SV) were used. Consequently, PSI models were developed for two cases: the first case is when the SV ≥ 500 and the second case is when the SV < 500. The PSR was plotted against the slope variance to see the effect of roughness on PSR variations. It was found that the relationship between the slope variance and the PSR was logarithmic, as shown in Fig. 7. This result indicates that the PSR decreases logarithmically at a higher rate for smaller SV values (smooth pavements) and afterwards the PSR values become no longer affected by the SV variations in higher SV values (rough pavements). This finding is supported by a similar finding found in Khedaywi and Elkhatib (1991), in which they stated that the PSR is influenced by slope variance to a certain level, after which increasing slope variance does not reduce the PSR value.

(a) Fatigue Cracking

(b) Potholes

(c) Debonding

(d) Linear Cracking



(e) Patching

(f) Rutting and Raveling

Figure (3): Major pavement distresses

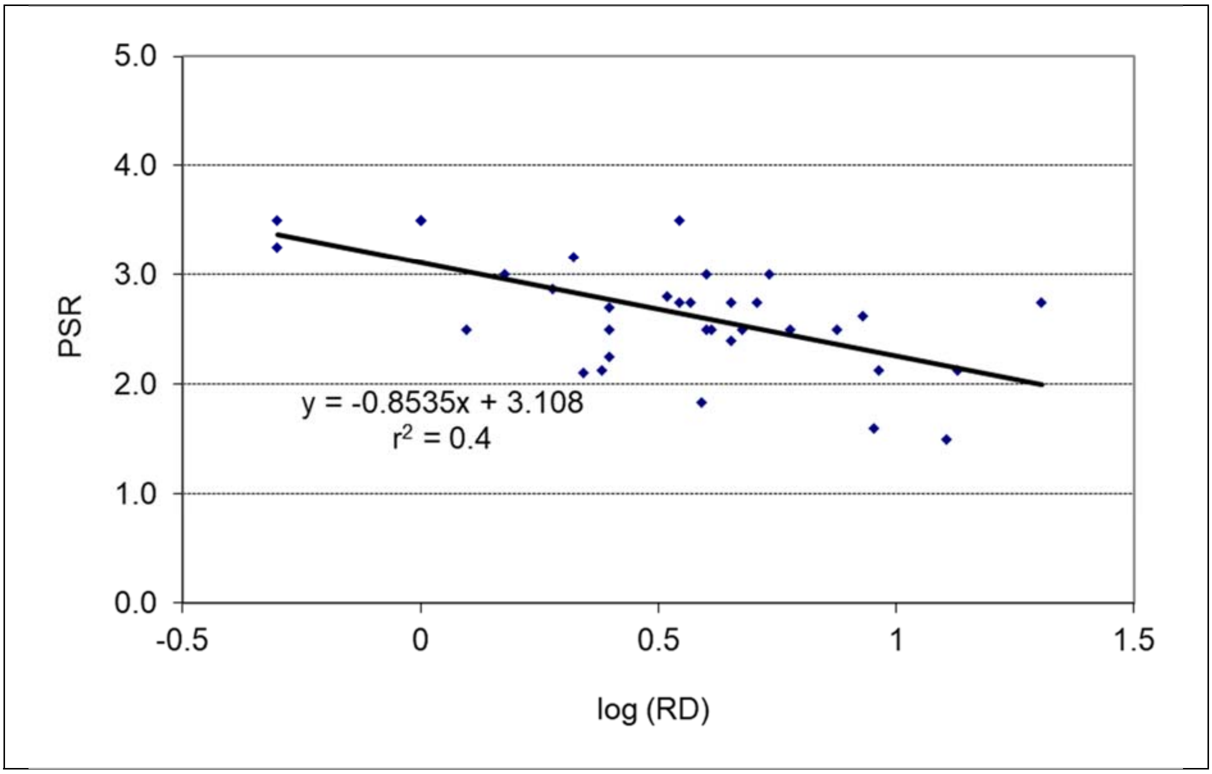


Figure (4): RD *versus* PSR relationship

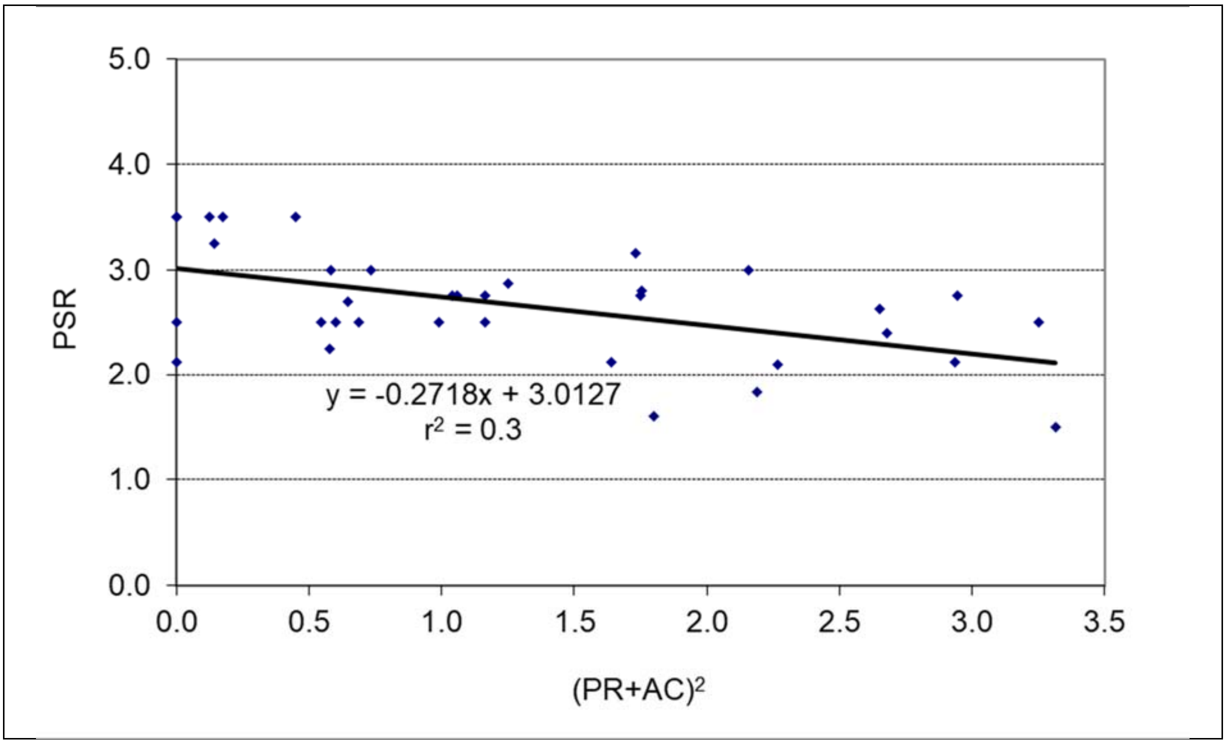


Figure (5): $(PR+AC)^2$ *versus* PSR relationship

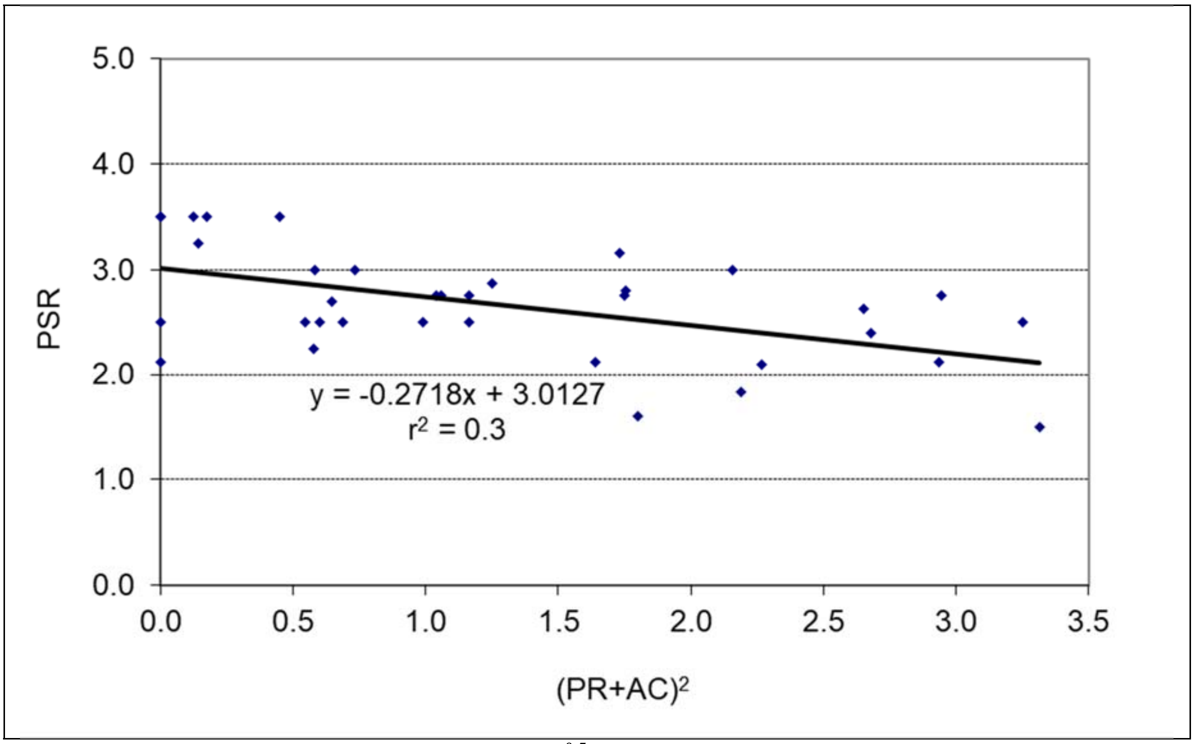


Figure (6): (DB+PH)$^{0.5}$ versus PSR relationship

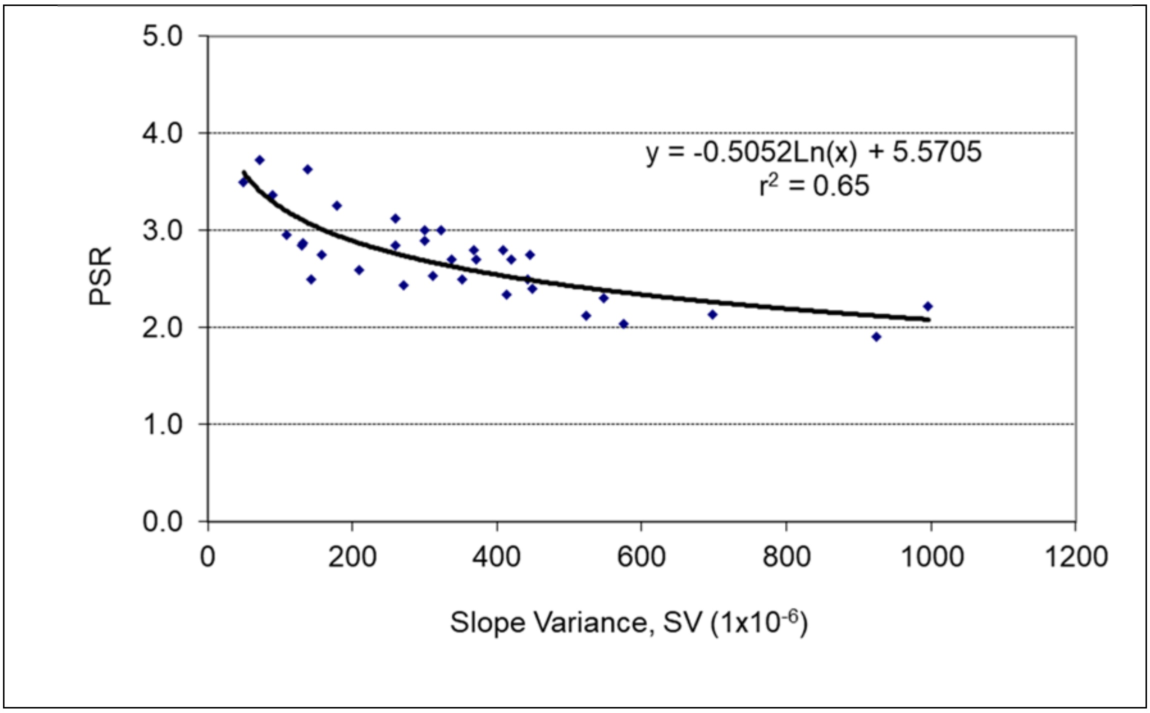


Figure (7): Slope variance *versus* PSR

For SV ≥ 500, the following expression is used for the PSI model:

$$PSI = 3.974 - 0.000106(SV) - 0.11971\,log(RD) - 0.308\,log(LC)^2 - 0.0309(PR + FC)^{0.5} - 0.227(DB + H)^{0.5} \quad (5)$$

The above model has a coefficient of determination (r^2) of 0.80. Tables 1 and 2 show the analysis of variance (ANOVA).

On the other hand, the PSI model for SV < 500 was developed and is shown in the equation below:

$$PSI = 2.676 + 0.000417\left(\frac{1\times10^6}{SV^2}\right) - 0.4971\,log(RD) - 0.0914\,log(LC)^2 - 0.0780(PR+FC)^{0.5} - 0.200(DB+H)^{0.5} \quad (6)$$

The above model has an r^2 value of 0.75. Tables 3 and 4 show the ANOVA and the inter-correlation matrix for this model, respectively.

It can be concluded from these tables that for SV ≥ 500; i.e., rough pavements, (DB+H) provided the most significant variable for estimating PSI. The LC, RD, (PR+FC) and SV came next in order. Similarly, for SV < 500; i.e., smooth pavements, (DB+H) was the most significant variable affecting the PSI predictions. However, the next significant variables after (DB+H) were RD, (PR+FC), SV and LC, respectively. The common outcome between rough and smooth pavements is that both were affected mostly by (DB+H), which means that these pavements reached stages of highly deteriorated fatigue cracking before maintenance or rehabilitation took place. Moreover, as debonding was found to be a significant factor in the prediction of PSI value, these pavements were likely to suffer from improper or poor compaction, poor tack coat application and/ or insufficient asphalt layer design thickness.

Fig. 8 and Fig. 9 show the PSI predicted values *versus* measured values for SV ≥ 500 and for SV < 500, respectively. It is concluded from these two figures that there is a relatively good match between the model-predicted values and the measured values at the 95 percent confidence interval, which means that the two developed models provided a relatively sound correlation between the PSR and the pavement distresses and slope variance.

Table 1. ANOVA for PSI model (SV ≥ 500)

ANOVA					
Source of Variance	**Degrees of Freedom**	**Sum of Squares (SS)**	**Mean of Squares (MS)**	**F-Value**	**Significance F**
Regression	5	1.635	0.327	2.683	0.094
Residual	9	1.0969	0.122		
Total	14	2.7319			

Table 2. Inter-correlation matrix between variables for PSI model (SV ≥ 500)

Variable	PSR	$(PR+FC)^{0.5}$	$\log(LC)^2$	$(DB+H)^{0.5}$	log (RD)	SV
PSR	1					
$(PR+FC)^{0.5}$	-0.3264	1				
$\log(LC)^2$	-0.5222	0.1868	1			
$(DB+H)^{0.5}$	-0.6726	0.1599	0.3123	1		
log (RD)	-0.3512	0.0674	0.1939	0.3832	1	
SV	-0.0347	0.0095	0.3723	-0.0426	-0.3312	1

Table 3. ANOVA for PSI model (SV < 500)

ANOVA					
Source of Variance	**Degrees of Freedom (DF)**	**Sum of Squares (SS)**	**Mean of Squares (MS)**	**F-Value**	**Significance F**
Regression	5	4.449	0.890	5.806	0.00416
Residual	14	2.145	0.153		
Total	19	6.594			

Table 4. Inter-correlation matrix between variables for PSI model (SV < 500)

Variable	PSR	$(PR+FC)^{0.5}$	log (LC) ^{2}	$(DB+H)^{0.5}$	log (RD)	SV
PSR	1					
$(PR+FC)^{0.5}$	-0.6397	1				
log $(LC)^2$	-0.4747	0.1476	1			
$(DB+H)^{0.5}$	-0.8016	0.7122	0.4935	1		
log (RD)	-0.7057	0.4962	0.2909	0.6515	1	
SV	0.5372	-0.5827	-0.2653	-0.6593	-0.7064	1

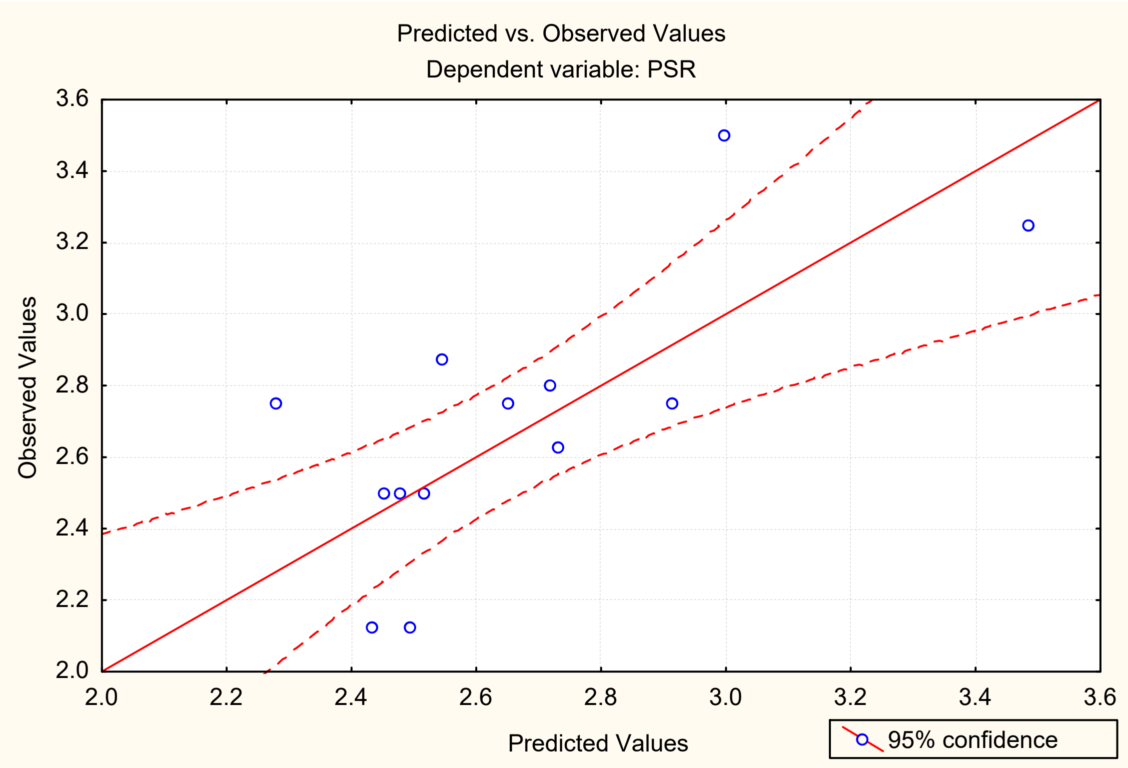


Figure (8): Predicted against measured values of PSI for SV ≥ 500

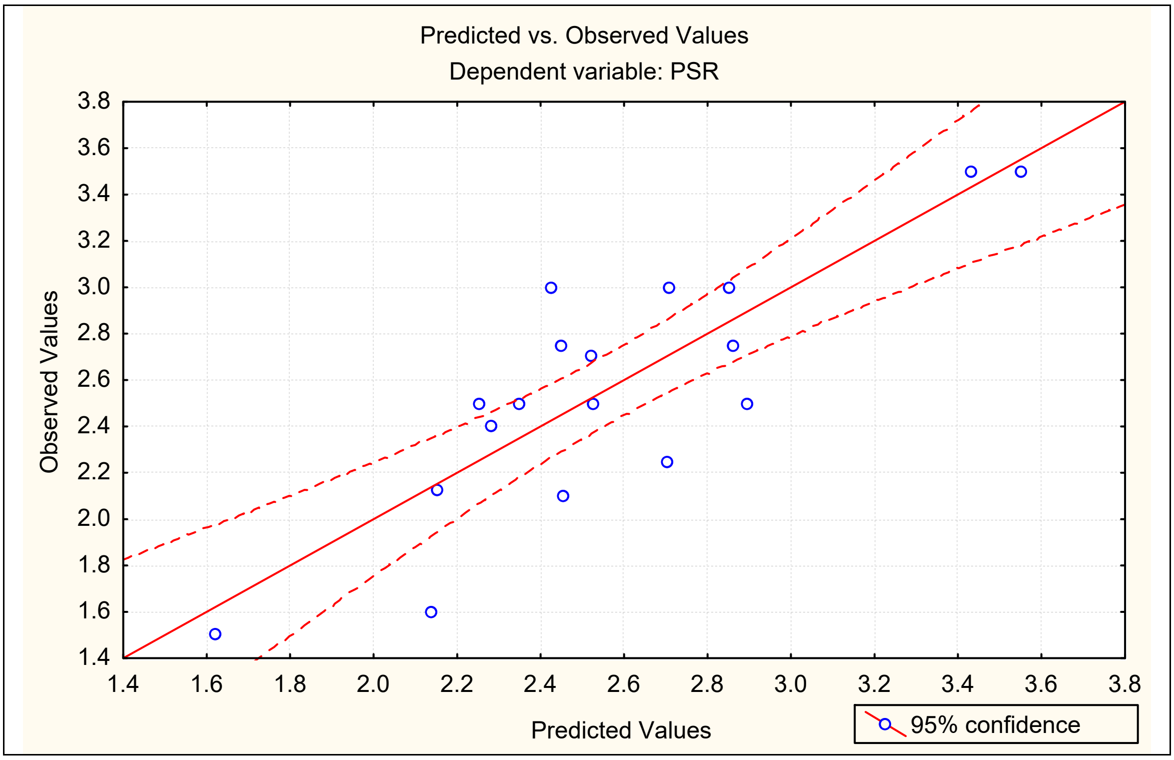


Figure (9): Predicted against measured values for SV < 500

CONCLUSIONS

Based on the analysis and results of this study, the following conclusions are drawn:

1. Distress-based PSI models were developed for asphalt pavements of rural highways using multiple non-linear regression techniques.
2. Using two ranges for the PSI value in modeling (SV ≥ 500 and SV < 500) provided the best results for the two models developed in the study.
3. The r^2 values for the developed models are 0.8 and 0.75 for SV ≥ 500 and for SV < 500, respectively.
4. The variation in the SV after a specific period will no longer impact the pavement rating due to the logarithmic reduction of PSR with the increase in SV.
5. The predicted values of PSI compared well with the measured values of PSR at 95 percent confidence interval.
6. For rough pavements (SV ≥ 500), (DB+H) provided the most significant variable for estimating PSI, while LC, RD, (PR+FC) and SV came next in order.
7. For smooth pavements (SV < 500), (DB+H) was the most significant factor for estimating PSI, while RD, (PR+FC), SV and LC came next in order.
8. It was found that SV provided a relatively higher significant effect on the PSI values for smooth pavements (SV < 500) than that for rough pavements (SV ≥ 500).

Recommendations

1. Maintenance agencies can use these models to determine the PSI for decision making towards M&R needs and strategies for the pavement network.
2. Pavement and maintenance engineers can monitor pavements over several years of service life to determine the PSI *versus* time, which provides the performance index for these pavements.
3. Traffic safety engineers can provide a safety measure for rural highways based on the PSI predicted from the developed models, which reflects the pavement surface condition and ride quality.

Compliance with Ethical Standards

The authors declare that they have no conflict of interest.

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