Available online at www.sciencedirect.com

ScienceDirect

International Journal of Pavement Research and Technology 9 (2016) 393–402

www.elsevier.com/locate/ijprt

Highway subsurface assessment using pavement surface distress and roughness data

Muhammad Mubaraki

Jazan University, Saudi Arabia

Received 4 May 2016; received in revised form 8 October 2016; accepted 9 October 2016
Available online 15 October 2016

Abstract

In this paper, pavement sections of the highway connecting Jeddah to Jazan were selected and analyzed to investigate the relationship between International Roughness Index (IRI) and pavement damage including cracking, rutting, and raveling. The Ministry of Transport (MOT) of Saudi Arabia has been collecting pavement condition data using the Road Surface Tester (RST) vehicle. The MOT measures roughness (ROU), rutting (RUT), cracking (CRA), and raveling (RAV). Roughness measurements are calculated in terms of the International Roughness Index (IRI). In the present three relationships, including CRA versus IRI, RUT versus IRI, and RAV versus IRI have been developed. The models relating to three types of distresses under study, and model relating IRI to ride quality have been studied in the present work. The results of the analysis indicate that a significant relationship exists between IRI and cracking, and IRI and raveling at 95% confidence level. The results also show that the rutting did not show a significant relationship to IRI values. It can be concluded from the results that cracking and raveling may possibly be described as ride quality distresses, whereas the rutting distress may be described as non-ride quality distress. The results indicate that while statistically significant relationships exist between IRI and both cracking and rutting, these relationships are not strong enough for IRI to be used as a surrogate measure for pavement condition.

Keywords: Pavement; Cracking; Rutting; Raveling; Roughness; Jeddah

1. Introduction

Pavement evaluation is a process by which field surveys and testing are carried out to characterize the condition of an existing pavement structure, both structurally and functionally. The structural condition of a pavement refers to its ability to support the current and future traffic loadings, whereas the functional condition refers to its ability to provide a safe, smooth, and a quiet riding surface for the traveling public [6]. Network-level evaluations are conducted on the pavement sections within the network of pavements for which the agency is responsible, with the aim to document current conditions, to identify projects for maintenance, preservation and rehabilitation, to help prioritize projects and allocate budgets, and to help determine funding needs. In addition, the collection of performance data on a pavement network over time provides a valuable tool for tracking pavement performance as well as a mechanism for developing performance models that can be used to predict future conditions (both with and without the application of treatments) [13].

Visual condition surveys are generally carried out to determine the type of distress, its severity, its extent and location. There are many methods for conducting pavement condition surveys that are adopted by different, agencies involved. Pavement condition index (PCI) ranges from zero to 100, where 100 represents an excellent pavement condition. The PCI values are calculated based

---

E-mail address: mmubaraki@jazanu.edu.sa

Peer review under responsibility of Chinese Society of Pavement Engineering.

http://dx.doi.org/10.1016/j.ijprt.2016.10.001

1996-6814/

on pavement distress type, severity and quantity collected through visual inspection. To collect the appropriate distress data an inspector is sent to a particular pavement section to record the existing distress types, severities and quantities. The information is collected by actually walking through the section. The procedure provides detailed information on the pavement section condition. However, considering the size of the city pavement network the procedure is tedious, time consuming and very costly.

Roughness is primarily a measure of riding quality of the road pavement surface. Pavement roughness is intrinsically related to pavement serviceability, which is a measure of physical characteristics of pavement surface. Roughness measurement systems that are currently used can be grouped into profilometric, vehicle response and subjective evaluation. Profilometric methods are the most accurate and best suited for detailed analysis. Roughness measurements are calculated in terms of the International Roughness Index (IRI). The IRI is calculated over equally spaced intervals along the road profile, the IRI computation method converts the longitudinal and vertical profile data into a vehicle motion response using a mathematical model. The IRI value is expressed as the units of displacement over units of length. Roughness measurements are performed at speeds between 40 and 50 km per hour. Thus, roughness measurements can be collected in a relatively short time without excessive cost [12].

2. Literature review

2.1. Background

Pavement condition data are an essential component of any pavement management system, and is required to determine the existing pavement condition, to set up the pavement maintenance needs, and to plan for future need [20]. Pavement management system (PMS) is increasing being used for efficient management of highways at all levels of government. PMS strategies can offer assistance at two levels: the network level and the project level. Network level information provides management with broad-based data about the entire system. Information about planning purposes and financial analysis is often provided by the network level, whereas the project level information includes details about engineering design, construction and cost accounting. Consequently, the data required for each level differ considerably. Pavement condition evaluation methods include four main practical techniques [6]: (1) distress survey, (2) roughness, (3) structural capacity, and (4) skid resistance.

2.2. Roughness evaluation

In the 1970s the World Bank sponsored several large scale research programs aimed at developing cost effective maintenance alternatives for roadway pavements. Roughness is a measure of variation along the vertical axis through horizontal profile. It gives an idea about the riding quality and represents the user's opinion of the pavement surface. ASTM E867 defines pavement roughness as "the deviation of the pavement surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality dynamic load and drainage [16].

The IRI (International Roughness Index) was initiated by the international roughness experiments. IRI is a standard roughness index adopted as a reference scale for all roughness devices and equipment. The IRI is based on simulation of roughness response of standard quarter car at speed of about 80 km/h. IRI model comprises of a series of differential equations which relate the motions of a simulated quarter-car to the road profile. The IRI is the accumulation of the motion between the sprung and the length of the profile. It is measured in meter per kilometer or millimeter per meter [16].

Pavement roughness is one of the most important indicators of pavement performance directly reflecting pavement serviceability to the road users. In recent years, some American states and Canadian provinces have used IRI in their business plan as an objective measure of their pavement network conditions [6,19].

For example, the U.S. Federal Highways Administration (FHWA) uses IRI as a performance measure for describing and monitoring the pavement condition of its National Highway System. The States of Kansas and Washington use IRI to describe the condition of their network in terms of percentages of miles in IRI rating categories. Because IRI is a geographically- transferable, repeatable and time-stable measure, its measurement at network level has become a routine practice for many road agencies in recent years. At the network level, roughness is measured on an annual or biennial basis as a part of pavement evaluation that is critical to formulating maintenance and rehabilitation priorities.

In 1982, IRI was proposed in Brazil by the World Bank as a standard statistic to correlate and to calibrate roughness measurements [16]. The International Roughness Index (IRI) was selected in Riyadh City as a standard procedure to collect roughness data. The Automatic Road Analyzer (ARAN) was used for roughness measurements. A standard speed of 40 ± 5 kmph for all street classes was used. Generally, the critical lane (right or middle) was selected for roughness measurements. The critical lane is defined as the lane in a given street with utility cut patching or high traffic [18].

An attempt was made to relate the pavement condition of an asphalt pavement to its roughness [4]. The study involved varied roadway pavement sections from the North Atlantic region in the United States and Canada. The study introduces a new method for estimating roadway condition, as conveyed by the Pavement Condition Index (PCI), using the International Roughness Index (IRI) which is strictly a direct assessment of pavement condition. The study assessed the applicability of IRI as a predictor variable of PCI. Furthermore, the study developed parametric models of pavement condition in terms of roughness using sample IRI and associated PCI data using readily available pavement rating software. A transformed linear regression model predicts pavement condition for the given roughness. The results from this study confirms the acceptability of the International Roughness Index as a predictor variable of the PCI.

Further; an analysis of variance confirms the existence of strong relationships between both the variables. The correlation between pavement distress and IRI was examined for the data from several sites in the San Francisco Bay area [10]. The goal of the research was to develop a surface roughness model that in turn could be used to estimate vehicle operating costs for the streets in the San Francisco Bay area. A correlation between IRI and pavement distress was developed based on 39 observations measured at 15 m intervals on a 152.4 m test section. A linear relationship was developed between IRI and a composite Pavement Condition Index (PCI) using the type and severity of distress observed for each segment of the roadway. The model had an adjusted R^2 of 0.52 suggesting that just over half of the variance in IRI could be predicted with the aggregate pavement condition index. Al-Mansour et al. [1] studied the effect of crack sealing, chip seal, and sand seal on roughness in flexible pavements used in interstate and state highways. They reported low benefits in roughness reduction due to 19 maintenance activities in the case of new pavements and increased benefit in the roughness reduction of maintenance applied to aged pavements.

In 1999, the Taiwan Highway Bureau imported ARAN (Automated Road Analyzer), a specially equipped car that measured pavement roughness as IRI (International Roughness Index). Since then, the traditional visual inspection performed at network level had the tendency to be replaced by automatic inspection devices. A study aimed to investigate and analyze the relationship between IRI and pavement distress was conducted by Karim and Lee [9]. The authors evaluated the applicability of IRI to be treated as representations of pavement performance to overcome the need for visual data collection. The visual inspection consumes a substantial amount of time and money. It also avoids the effects of unreliable and inconsistence results that creep in due to personal factors in determining index value. A total of 125 road sections with a length of 1 km were used in the collection of data. Moreover the study aims to reinforce the concept that IRI may completely reflect pavement distress conditions, and there is a relationship between IRI and certain pavement distress types. The analytic process was based on back propagation neural network methodology. The results of the analysis prove that rapid measurement of IRI can be used, and simplifies the woks of traditional visual inspection by a road inspector. The effects of distinct distress types and their extent on IRI have been analyzed during this study. The correlation coefficient between IRI and the distress variables reached 0.944, which shows that IRI reflect pavement distress conditions to a large extent. Obviously, different distress types differently impact IRI. It was found that severe potholes, patching, and rutting have the highest correlation to IRI, while the stripping and corrugation have less correlation. Also, cracking, alligator cracking, and bleeding are least related to IRI. Thus, the study shows that pavement distress and pavement roughness have commonly causal relationship affecting one another in both directions.

Effect of asphalt concrete raveling on pavement roughness has been studied by Hozayen [8]. The author presented an approach to investigate the relationship between aggregate raveling of asphalt pavements and surface roughness as a means for assessing pavement riding quality. Pavement distresses have been surveyed on various highway classes (primary, feeder and secondary) of the rural network together with the corresponding pavement condition index. Results indicated that regression relationships (including power, exponential, and polynomial models) could be established between aggregate raveling and pavement roughness with a correlation factor ranging between 0.8 and 0.92 depending on highway class and location. Hall et al. [7] studied the effect of various maintenance activities, including slurry seal, chip seal, crack seal, and thin overlays on pavement roughness. Based upon a statistical analysis, they reported that the effect of chip seals, crack seals, and slurry seals were not significant compared to a control section which did not receive a maintenance treatment. However, thin overlays were found to reduce pavement roughness significantly. In this study, no improvement in IRI was considered for pavements undergoing chip seals, slurry seals, and crack seals, while a roughness reduction resulting in a restored IRI level of 63 inch/mile was assumed following the application of an overlay. Although the rate of change of IRI for overlays is higher than the new pavement IRI deterioration, the same rate was considered for simplicity of calculation in this study.

A study in the United States investigated the interaction between pavement surface roughness and distress types [15]. The study involved 462 pavement sections from thirty-seven projects in the state of Michigan. The pavement sections were analyzed to investigate the interaction between pavement surface roughness and distress. The Michigan Department of Transportation (MDOT) used two measures of pavement performance in managing its pavement network: the Distress Index (DI), and the Ride Quality Index (RQI). The DI equals the sum of the distress points along the project over the section length. The DI scale starts at zero for a perfect pavement and it increases without a limit. MDOT categorizes DI into three levels: Low; <20, Medium; 20–40, and High; >40. A study was conducted to investigate a relationship between some pavement distresses and ride quality by Aultman and Jackson [2]. The Pavement Maintenance Management System used in the United States Army Corp of Engineers (PAVER) sorts five distresses as ride quality related types. PAVER describes the ride quality by riding in a standard size automobile over the pavement section at the posted speed which is similar to the description of the roughness definition. According to the PAVER visual inspection procedure, the inspector should take into account the vehicle vibration and reduction in comfort in order to evaluate the severity levels for these types of distresses. The list of the five roughness related distresses in PAVER system includes:

- Bumps and sags.
- Corrugation.
- Railroad Crossing.
- Swells.
- Shoving.

There are other distress types not related to roughness such as alligator, slippage, edge and block cracking, polished aggregate, bleeding and rutting. Ningyuan et al. [15] used a large field- measured IRI dataset collected in the summer and fall of 2001 on a total of 650 km highway to investigate the relationships between IRI, rutting and pavement cracking The study objective was to determine if these relationships were consistent enough to allow IRI, the more easily measured quantity, to be used as a surrogate for the others or it is necessary to collect all three measures in pavement management programs. The results indicated that while statistically significant relationships exist between IRI and both cracking and rutting, these relationships are not strong enough for IRI to be used as a surrogate measure for pavement condition. It was concluded that IRI, while appropriate for measuring ride ability, is not an appropriate for measuring cracking or rutting.

Perera and Kohn [17] reported that, for pavement sections with IRI greater than 97 inch/mile before applying an overlay, the IRI after placing the overlay was reduced to between 52 and 76 inch/mile. The authors reported that IRI values would be less than 64 inch/mile after the application of an overlay when pre-overlay IRI values of less than 97 inch/mile were present. Thus, for roughness prediction of pavement following rehabilitation, an IRI level of 63 inch/mile was assumed in this study. Maintenance represents pavement improvement activities which are performed when the pavement is in a structurally sound condition. Chandra et al. [3] studied the relationships between pavement roughness and distress parameters like potholes, raveling, rut depth, cracked areas, and patchwork. The pavement distress data collected on four national highways in India using a network survey vehicle (NSV) are used to develop linear and nonlinear regression models between roughness and distress parameters. Analysis of variance of these models indicated that nonlinear relation is better than a linear model. R^2 value, root mean square error (RMSE), and mean absolute relative error (MARE) also supported nonlinear models. An artificial neural network (ANN), which is an advanced technique of modeling, was also used in the study to model pavement roughness with distress parameters. A network with five input nodes, 15 hidden nodes, and one output node was considered. The network was trained with 90% of the data and tested with remaining 10% data. Results of R^2 and MSE showed that the neural network performed highly significantly in both training and testing phases. Finally, the performance of the ANN model was compared with that of linear and nonlinear regression models. The mean absolute error (MAE) for the ANN model is around 18% less than that for the linear model and 11% less than that for the nonlinear model. MARE values are also 12.5% lower in the case of ANN modeling, indicating that the ANN model yields a better forecast of road roughness for a given set of distress parameters.

Meegoda et al. [11] defined IRI as an average rectified slope (ARS) which summarizes the ratio of the accumulated suspension motion to the distance traveled. This value is obtained from a mathematical model of a standard quarter car traversing a measured profile at a speed of 50 mph or 80 km/h. The LTPP database provides the necessary pavement performance data, which contains detailed information about average IRI. A typical test section, was used to collect information on seven modules: Inventory, Maintenance, Monitoring (Deflection, Distresses, and Profile), Rehabilitation, Materials Testing, Traffic, and Climatic. The compatibility of existing data sets must be considered since sections with different ages and treatment methods were included in the study. The data were adapted to fit a regression model between the number of years elapsed since the last overlay and the corresponding changes in IRI values. It was concluded that the pavement near the end of service life starts to deteriorate quickly.

Elghriany et al. [5] found pavement roughness may have a significant impact on traffic safety, but its effect on the overall safety problem needs to be studied and quantified. The study investigated the relationship between International Roughness Index (IRI) and rates of crashes by looking into the traffic safety performance over time under changing pavement conditions (change of IRI). Specifically, the proposed model provides insight into the effect of roadway (rigid pavement) surface conditions on traffic safety in order to develop a better understanding of the problem. Data on a geographic information system (GIS) platform from different sources in the state of Ohio were compiled and analyzed using a statistical analysis approach. Different model formulations were examined, and a quadratic relationship was found to be the most effective in linking the crash rates with pavement roughness. The findings of this study by Elghriany et al. [5] may serve as a good reference that can assist the state and local transportation agencies in roadway maintenance decision making. From the review of available literature, it is clear that the IRI is an acceptable predictor variable of pavement conditions. Some studies suggest that the International Roughness Index can be used to set maintenance needs and priorities without visual inspections, others considered an IRI measurement at the network level as a part of pavement evaluation that is critical to formulating maintenance and rehabilitation priorities. The studies reviewed, however, did not agree on type of distresses that mostly affect pavement roughness.

3. Objectives

The main objective of this study is to study the relationship between pavement condition evaluation and roughness measurements and examine the effect of pavement distress types on pavement roughness for the entire Jazan road network.

4. Methodology

4.1. Study methodology

The methodology used in the present study consisted of four main steps. The first step was to collect the required data for a selected sample of pavement sections from Highway No. 5 which connects Jeddah with Jazan. The data include information on three types of distress, including cracking, rutting and raveling, and the International Roughness Index for each included pavement section. The second step of the methodology was to investigate the correlation between IRI and three collected types of distress data. The third step was to examine the effect of the aggregation of all distress types on the International Roughness Index measurements and the effect of each distress individually. The fourth step was to draw a conclusion of the analysis and results obtained from the collected data with respect of significance of the three distress types on IRI, and ride quality related distresses. The idea of the study methodology can be expressed in Fig. 1.

4.2. Correlation of IRI and types of distress

The Pearson correlation analysis was conducted to estimate the correlation factor and correlation hypothesis and to find out whether a significant statistical relation between IRI and types of distress exists. The statistical hypothesis test displays a *p*-value to determine the significant effect of a distress on IRI values [16].

4.3. IRI and distress model

The modeling procedure used in the present analysis is based on statistical regression. The basic form of the regression equation is as follows:

$y = \mathrm{b}0 + \mathrm{b}1X;$

where Y: dependent variable (response), X: independent variable, and b0, b1: regression coefficients.

To conduct the analysis, a spreadsheet program was used to examine and tabulate the data, draw charts (graphs) that describe the trend of the collected data, build models and to find out correlations and the relationship between pavement roughness (IRI) and types of distress. The IRI and distress model is constructed in order to predict types of distress in terms of a distress behavior as a function of pavement roughness (IRI). The procedure involved the use of regression techniques to construct models linking IRI and distress values. The most suitable model was then selected based on the results of statistical tests. The process of constructing the regression model was based on three types of regression functions: linear, logarithm nonlinear, and quadratic nonlinear. The nonlinear relation is transformed to linear regression by calculating new parameter called IRIa, where a is a constant. The regression equation is in the form: Distress = b0 + b1 IRIa. In this equation the regression coefficients are b0 and b1.

4.4. Adequacy of IRI and distress model

After the regression equations are constructed, a process of testing was used. The aim of the testing process was to find out the best model that represents the given data. The analysis procedure was based on three main statistical regression tests, which are:

1. Test of hypothesis (T-test).
2. Coefficient of multiple determination (R^2).
3. Analysisof Variance Test (ANOVA – Test).

The T-test of a hypothesis is incorporated to study the relationship between each of the regression coefficients

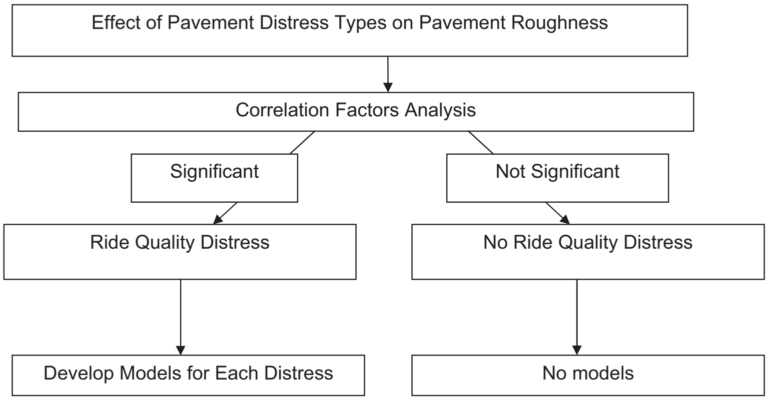

Fig. 1. Flowchart for Pavement roughness and pavement distress types.

(b0, b1) and the response variable at a certain degree of confidence (assumed 95% in our study). Hence the test was conducted for all of the regression coefficients in the regression model. The coefficient of multiple determinations (R^2) was used to illustrate the adequacy of a fitted regression model. The R^2 indicates the proportion of the response variable variance explained by the regression model. The coefficient takes values from 0 (no correlation exists between variables) to 1.0 (perfect correlation between variables). The Analysis Of Variance test (ANOVA) is a powerful tool used to investigate the relationship between the response variable (distress in this study) and the independent variables (IRI). The ANOVA test extends the *t*-test for a more general null hypothesis to estimate the quality of the regression line. That is, to determine whether the variation in distress readings is dependent on the IRI readings. This provides the significant evidence to accept or reject the regression model [14].

4.5. Ride quality related distresses

Pavement roughness measurements are primarily a measure of the riding quality of roadway pavement surface. Usually pavement roughness is related to pavement serviceability. Pavement serviceability is a measure of the physical characteristics of the pavement surface. Therefore, roughness is related to the opinion of the roadway users. It has a significant effect on vehicle operating cost, safety, comfort and speed of travel. In this section, an attempt was made to investigate pavement distresses to determine the riding quality related to different type of distresses. The effect of all pavement distresses on the IRI reading was investigated in the present study. The density of each distress type was plotted against the respected IRI values. The plot was then utilized to check the trend of the relationship. The correlation test was applied to find the correlation coefficient between IRI and the distress density. The Pearson correlation coefficient was used to measure the degree of linearity between distress density and IRI. The correlation coefficient assumes a value of 1 for maximum correlation. Positive correlation coefficient means that the distress density tends to increase with increasing IRI. The hypothesis test displays *p*-value that determines the significant effect of IRI on each distress type. The statistical analysis is then carried out at a confidence level of 95%. Therefore, if the value is below the 5% significance level, then there is a sufficient evidence that there is a statistically significant relationship between IRI and distress density. The statistical regression techniques have been utilized to achieve an appropriate model relating to the International Roughness Index and ride quality distress types. The ANOVA test was also used to investigate the relationship. The ANOVA test was extended to estimate the quality of the regression coefficients in the regression model. The *p*-values indicate at 95% confidence the significant evidence to accept or reject the regression coefficient of each distress density in the regression model [2].

4.6. IRI and distress density model

In this part, the regression technique was used to construct models linking IRI and all three distresses under study, including cracking (CRA), rutting (RUT), and raveling (RAV).

The linear regression model would be in the form:

$$\mathrm{IRI} = \mathrm{b0} + \mathrm{b1CRA} + \mathrm{b2RUT} + \mathrm{b3RAV}$$

where b0, b1..., bn are regression coefficients.

CRA = Cracking Distress Density.

RUT = Rutting Distress Density.

RAV = Raveling Distress Density.

This model studied the effect of three distresses on pavement roughness (IRI). This model was then used to confirm the earlier results in determining the ride quality types of distress. However, this model was modified to generate the most fitting relationship between IRI and the ride quality distress types. The effect of the pavement roughness on three distress types was studied and analyzed. Two regression models were developed and investigated; first model was to relate the IRI index to all the three types of distress. The second regression model was to relate the IRI index to types of distresses that are considered as ride quality distresses. This model was investigated and interpreted through many statistical tests. The *T*-test of hypothesis was utilized to study the relationship between each of the regression coefficients (b0, b1) and the response variable at 95% degree of confidence. The ANOVA was used to estimate the quality of the regression line, that is, whether the variation in IRI is dependent on the distress data. Finally, the coefficient of multiple determinations (R^2) was used to illustrate the sufficiency of a fitted regression model [10].

4.7. Site selection and data collection

The highway considered in the present study connects North West of Saudi Arabia with South West of Saudi Arabia, and is more than 2000 km in length. The study involves the analysis of roughness and distress data only from pavement sections between Jeddah city and Jazan city. The distance between Jeddah and Jazan is 800 km. The selected sections have been determined to be having same factors affecting the performance of the pavement including maintenance and evaluation team. All pavement information collection is performed by ARAN which has been recommended by the World Bank. ARAN system obtains the roughness index value and rutting depth of each pavement section by using a laser roughness measuring device and supersonic rutting measuring device which are mounted in ARAN. The pavement distress data are obtained based on the pavement image obtained from the image retrieval system. All the data are integrated with the software package for each kilometer and stored in the Pavement Management System (PMS) database. All the data including pavement distress and roughness were collected by the Ministry of Transport (MOT) in years of

2009, 2011, and 2013. The study uses the MOT data and deploys them to conduct the methodology of the study. The pavement distress and roughness data were available for 400 km for each km interval. Detailed distress data were available in the form of distress type, distress density, and as well as measurement of roughness.

5. Data analysis

5.1. Cracking vs.IRI

Fig. 2 presents the graph showing the relationship between IRI and cracking density. It can be seen from Fig. 2 that the IRI never exceeded 5 for most data points. This may be attributed to the fact that data collecting van drivers are instructed to avoid driving through heavily deformed segments of the road. Also, for a cracking distress between 4% and 6%, the IRI values were clustered around "1". This irregularity most likely represents the segments of the road with a very good IRI but had longitudinal cracks between the road and its paved shoulders. The plot shown in Fig. 2 verifies the positive relationship between the cracks and the IRI values. However, the graph does not indicate a definite linearity of the relation. The correlation coefficient of IRI and patching density is 0.5 and the p-value is equal to 0.019. The positive sign of the coefficient indicates a positive relation between cracking density and IRI. The value of correlation factor indicates that about 50% of the IRI and crack density observations were distinguished by the linear relation. The best representation for the cracking data was given by logarithmic formula:

$$\text{Cracking} = 8.6 + 2.7 \log \text{IRI}$$

In the hypothesis test, the p-value was found to be 0.019 thus indicating that the relationship between IRI and patching density was statistically significant at 5% significance level. The result of the statistical test does not conform to the previous results that suggest that cracks distress is a ride quality type of distress at all severity levels.

5.2. Rutting vs IRI

The relationship between IRI and rutting density is presented in Fig. 3. The graph indicates a positive relationship between the rutting and IRI values. There is no definite trend in the linearity of the relation. The correlation coefficient of IRI and rutting density is 0.464 and p-value is 0.151. The value of correlation coefficient of 0.464 indicates that the relationship between the percent of rutting and IRI cannot be expressed adequately by a linear equation. For this reason, a logarithm nonlinear relationship was developed. The fitted regression model was as follows; Rutting = 8.2 + 2.5 log IRI. The p-value is 0.15 which indicates that the relationship between IRI and rutting density is statistically significant at 5% significance level.

5.3. Raveling vs IRI

Fig. 4 presents a relationship between IRI and raveling distress density. The raveling data were obtained from 50 different pavement sections. The graph shown in Fig. 4 indicates a positive relationship between raveling and IRI. The value of correlation factor indicates that about 45% of the IRI and raveling density observation were described by the linear relation. The best model formula is as follows: Raveling = 28.2 + 9.00 log IRI. In the hypothesis test, the p-value was found to be 0.006, which indicates that there is a sufficient evidence at 95% confidence level of the relationship between IRI and raveling density.

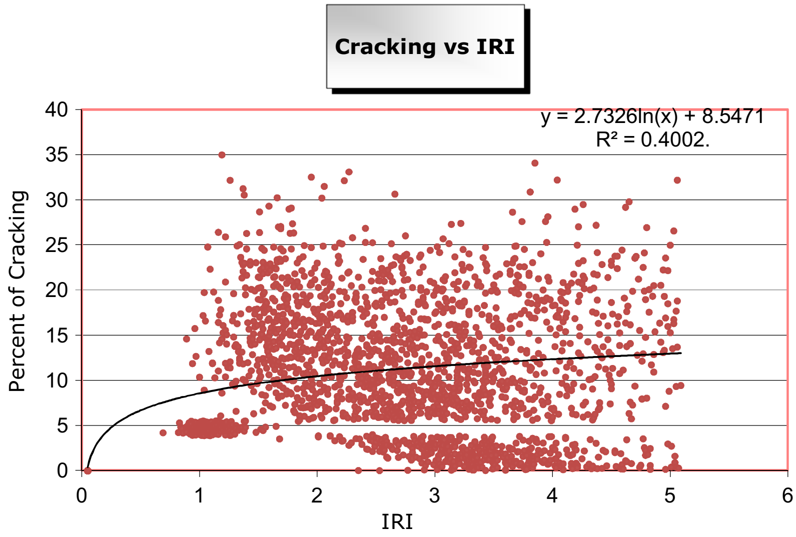

Fig. 2. IRI and Cracking Distress Density relationship.

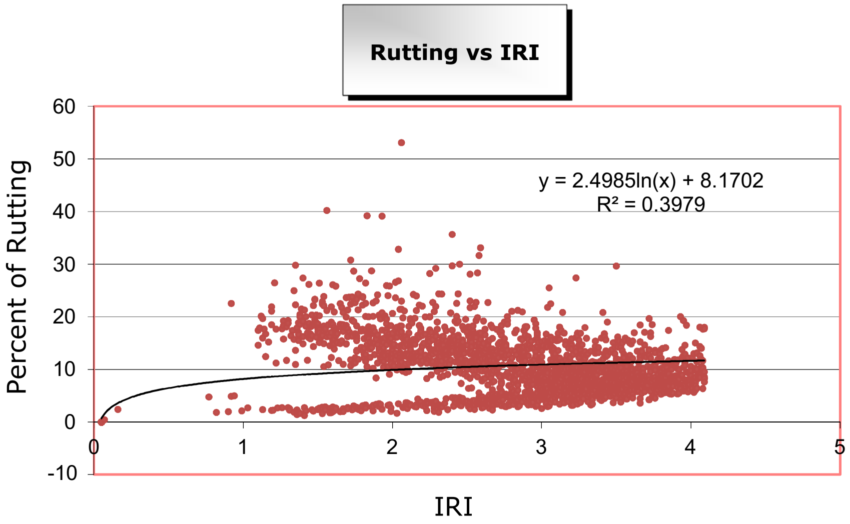

Fig. 3. IRI and Rutting Density relationship.

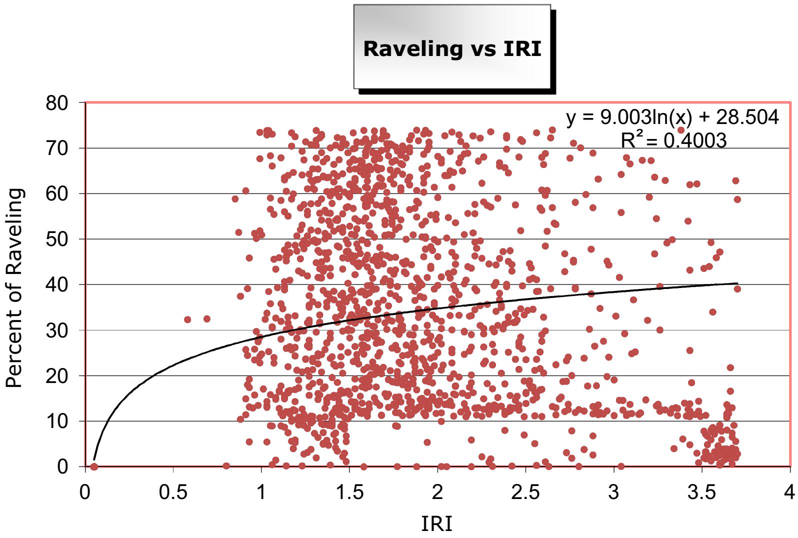

Fig. 4. IRI and Raveling Density relationship.

5.4. *Model-1: relates IRI to all apparent distress*

$$\mathrm{IRI} = 4.498 + 0.0096\mathrm{CRA} + 0.0083\mathrm{RUT} + 0.0067\mathrm{RAV}$$

Statistics of *T*-test of the regression coefficients.

Predictor	coefficient	*T*	*P*
Constant	4.498	161.73	0.000
CRA	0.0096	21.11	0.000
RUT	0.0083	5.01	0.07863
RAV	0.0067	14.13	0.000

The *p*-values for most regression coefficients are either equal or close to zero, indicating significant relationship between the distress types and the predicted values of IRI. However, the *p*-value of the rutting (RUT) coefficient is greater than the 0.05 level of significance. Therefore, there is a significant evidence to exclude the pothole and rutting in predicting the roughness index. The *p*-values for the ANOVA test for the model are equal to zero, indicating no significant amount of variation in the IRI response variables by the regression model. The data reflect sufficient evidence of dependency-between-IRI-and-types of distress. The coefficient of multiple determinations (R^2) equals 28%, which means that 28 percent of the IRI value are represented and explained by the regression model. It also indicates that while-statistically-significant-relationships exist between IRI and some distress types, the relationship is not strong enough for distressed type stone used as a predictable measure for roughness condition.

5.5. Model-2: relates IRI to ride quality distresses

The distresses that showed a significant relationship to the IRI index were chosen to be ride quality types distresses. These distresses include cracks distress (CRA), and raveling distress (RAV). The regression model developed is as follows:

$$\text{IRI} = 3.58 + 0.0077\text{CRA} + 0.0054\text{RAV}$$

Statistics of *T*-test of the regression coefficients.

Predictor	coefficient	*T*	*P*
Constant	4.498	161.73	0.000
CRA	0.0096	21.11	0.000
RAV	0.0067	14.13	0.000

The *p*-values for most regression coefficients are equal to zero, indicating a significant relationship between the distress types and the predicted values of IRI. The *p*-values for ANOVA-test is equal to zero, indicating no significant amount of variation in the IRI response variables by the regression model. The data reflect sufficient evidence of dependency relationship between IRI and distress values. It is clear that the F-value for the second model is greater than that of the previous model indicating improvement of the second model over the first one. The coefficient of multiple determinations (R^2) is equal to 30.5%, which means that 30.5 percent of the IRI values are represented and explained by the regression model. However, the-relationships are not strong enough for distress types to be used to predict pavement roughness condition.

6. Discussion

The effect of all the distress types that appears in the study segment on the IRI reading was investigated. The results of the present research indicated the riding quality related types of distress. A statistical summary of the results obtained in the analysis conducted herein is shown in Table 1. The-correlation-hypothesis test results shown in Table 1 indicate that the *p*-value is either zero or close to zero for cracking, rutting and raveling. This is, however, not true for rutting. Therefore, it can be concluded with 95% confidence that a significant relationship exists between IRI and cracking and IRI and raveling. Furthermore, the low correlation factors for all the three types of distress showed that no definite conclusion could be drawn about the linearity of the relationships. The best representation of the relationship was obtained using a nonlinear regression equation. In this study, it was found that the logarithmic equation shows reasonable fitting for the data. The regression coefficient test computes *p*-values for each regression coefficient. The regression coefficients for cracking and raveling are equal to zero. This indicates a significant linear relationship between IRI and different regression coefficients. The result of both correlation and regression coefficient tests indicates at 95% confidence that cracking, and raveling are ride quality type distress. However, it is not realistic to conclude that IRI may completely reflect pavement distress conditions. It is clear from Table 1 that the rutting pointed toward no significant relationship to IRI values.

7. Conclusion

Pavement sections from highway connecting Jeddah with Jazan was selected in this study to evaluate the relationships of three types of distresses including cracking, rutting, and raveling to IRI values. Based on the results, the statistical models that relate IRI values to the distress density values were established. The results indicate that while statistically significant relationships exist between

Table 1
IRI vs. distress density statistical summary.

Distress type	Correlation factor	Correlation hypothesis test	Best presentation
Cracking	$r = 0.500$	$P = 0.019$	$\text{Cracking} = 8.6 + 2.7 \log \text{IRI}$
Rutting	$r = 0.464$	$P = 0.151$	$\text{Rutting} = 8.2 + 2.5 \log \text{IRI}$
Raveling	$r = 0.450$	$P = 0.006$	$\text{Raveling} = 28.2 + 9.00 \log \text{IRI}$
Regression model equations			
Model 1: $\text{IRI} = 4.498 + 0.0096\text{CRA} + 0.0083\text{RU}T + 0.0067\text{RAV}$			
Model 2:$\text{IRI} = 3.58 + 0.0077\text{CRA} + 0.0054\text{RAV}$			
Regression coefficients test (*T*-test)			
Distress type	Hypothesis test (Model 1)		Hypothesis test (Model 2)
Cracking	$P = 0.000$		$P = 0.000$
Rutting	$P = 0.078$		–
Raveling	$P = 0.000$		$P = 0.000$
ANOVA			
$P = 0$ Model 1			
$P = 0$ Model 2			
Regression model adequacy			
$R2 = 28\%$ Model 1			
$R2 = 30.5\%$ Model 2			

IRI and the distresses under the study, these relationships are not strong enough for IRI to be used as a surrogate measure for pavement condition. It is concluded that IRI, while appropriate for measuring ride ability, is not appropriate for measuring cracking, rutting, and raveling. This result is in conformity with the previous studies detailed in the earlier sections of this paper.

The results of the present study clearly suggest that the pavement roughness is not strongly enough to be used as an appropriate measure of the pavement deformation, and any increase in the pavement roughness accelerates the pavement deterioration. Similarly, any pavement distresses will also result in deterioration of the pavement roughness index value. An increase in roughness leads to higher dynamic axle loads, which in turn can lead to a tangible acceleration in pavement distress. Therefore, a distinct practical advantage of the present research is that it will greatly assist in determining maintenance needs by defining the types of distress that are most likely to be encountered. The results of the present research can provide valuable aid in determining the effective timing of applying the maintenance needs by defining the time after which the rate of deterioration will increase drastically. The results of the present research can be beneficially utilized by the municipalities in setting up priority index for the budget and for devising strategies for efficient maintenance programs. The present research has the potential to provide impetus for modeling in the field of pavement maintenance.

References

[1] A. Al-Mansour, K.C. Sinha, T. Kuczek, Effects of routine maintenance on flexible pavement condition, J. Transport. Eng. ASCE 120 (1) (1994).

[2] L. Aultman, E. Jackson, Model relating pavement quality measures, J. Transport. Res. Board (2004), The 83rd Transportation Research Board Annual Meeting, Washington, D.C..

[3] S. Chandra, C. Sekhar, A. Bharti, B. Kangadurai, Relationship between Pavement Roughness and Distress Parameters for Indian Highways, J. Transport. Eng. 139 (2013).

[4] S.A. Dewan, R.E. Smith, Estimating IRI from Pavement Distresses to Calculate Vehicle Operating Costs for the Cities and Counties of San Francisco Bay Area Transportation Research Record 1816, Transportation Research Board, Washington, DC, 2002.

[5] A. Elghriany, Ping. Yi, Peng. Liu, Yu. Quan, Investigation of the effect of pavement roughness on crash rates for rigid pavement, J. Transport. Safety Security 8 (2) (2016).

[6] R. Hass, W. Hudson, J. Zaniewnski, Modern Pavement Management, Krieger Publishing, 1994.

[7] K.T. Hall, C.E. Correa, A.L. Simpson, LTPP data analysis: effectiveness of maintenance and rehabilitation options, NCHRP Project (2002) 20–50.

[8] A. Hozayen, Effect of asphalt concrete raveling on pavement roughness, Annual Conference of the Canadian Society for Civil Engineering, Montréal, Québec, Canada, 2002.

[9] Chatti Karim, D. Lee, Development of a preventive maintenance strategy for minimizing roughness-related pavement damage, J. Transport. Res. Board, 2001, The 80th Transportation Research Board Annual Meeting, Washington, D.C..

[10] J. Lin, J. Yau, L. Hsiao, Correlation analysis Between International Roughness Index (IRI) and pavement Distress by Neural Network, J. Transport. Res. Board (2003), The 82nd Transportation Research Board Annual Meeting, Washington, D.C..

[11] J. Meegoda, S. Gao, Roughness progression model for asphalt pavements using long-term pavement performance data, J. Transp. Eng. (2014) 04014037, http://dxdoi.org/10.1061/(ASCE)TE.1943-5436.0000682.

[12] M. Mubaraki, Identification of pavement distress types and pavement condition evaluation based on network level inspection for Jazan City road network, J. Eng. Res. (TJER) 11 (1) (2014) 44–54.

[13] M. Mubaraki, A methodology for project-level maintenance for urban road, J. Transport-ICE 168 (3) (2015) 239–255.

[14] Myers, Keying E. Ye, Probability and Statistics for Engineers and Scientists, 2011.

[15] Ningyuan Li, T. Kazmierowski, B. Sharma, Verification of network level pavement roughness measurements, J. Transport. Res. Board (2001), The 80th Transportation Research Board Annual Meeting, Washington, D.C..

[16] K. Park, K. Lee, T. Natacha, Applicability of the international roughness index as a predictor of asphalt pavement condition, J. Transport. Res. Board (2004), The 83rd Transportation Research Board Annual Meeting, Washington, D.C..

[17] R.W. Perera, S.D. Kohn, Ride quality performance of asphalt concrete pavements subjected to different rehabilitation strategies, in: ASCE Proceedings of 2006 Airfield and Highway Pavements Specialty Conference, Atlanta, Georgia, April 30–May 3, 2006.

[18] RPMMS, Riyadh Pavement Maintenance Management System, Riyadh Municipality, 2005.

[19] M.Y. Shahin, S.D. Kohn, Pavement Maintenance Management for Road And Parking Lots, 2002.

[20] Tahar El-Korchi, Norman Wittels, Visual Appearance of surface Distress in Pavement, TRB No. 1260 Washington, D.C., 2004.