Article

Correlation of Pavement Distress and Roughness Measurement

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Abstract: Riyadh City established and implemented a Pavement Maintenance Management System (PMMS) through the General Directorate of Maintenance and operation. The system was created to address the difficulties that come with maintaining and reserving the pavement network. To evaluate pavement conditions, Riyadh (PMMS) uses visual checks, structural capacity roughness, and skid resistance. An Urban Distress Index (UDI) is calculated during the visual assessment process. Distressed pavement types, severity, and quantity are taken into account when calculating UDI values. As a result, the procedure gathers extensive data on the pavement's condition. However, the procedure is time-consuming and very costly. The Automatic Road Analyzer car provides data on road roughness in accordance with the International Roughness Index (IRI). The IRI data are often generated quite quickly and at a cheap cost as compared to the distress survey. This study's aim is to examine whether a sample of Riyadh city pavement sections can be connected to the IRI depending on the distress type. The research develops statistical models that correlate IRI values with several distress-types associated with roadway classes. Correlating the International Roughness Index values to distress type will eliminate the necessity to implement the manual inspection at a network- level. This saves money and time for PMMS employees when preparing annual maintenance requirements and setting priorities. The finding of the study, of the relationship between the pavement distresses and the International Roughness Index showed a statistically significant relationship between pavement roughness and some ride-quality distresses, like depression and patching, as well as some non-ride quality distresses like potholes and rutting. In addition, for both main and secondary streets, an analysis of variance shows the existence of a correlation between the two variables.

Keywords: International Roughness Index; pavement condition evaluation; correlation; Saudi Arabia

1. Introduction

Evaluation of pavement condition is one of the major elements of any pavement maintenance management system (PMMS). Through pavement condition, maintenance needs, budget, and priority are determined. Pavement condition usually involves distress surveys, roughness and structural capacities, and skid resistance. Most, if not all highway agencies incorporate at least one of these components [1].

There are two levels of pavement evaluation: network level and project level. Network level evaluation gives us a comprehensive overview of the network's condition. In project level evaluation, detailed information on pavement conditions are determined.

Riyadh city and through Riyadh Municipality, and the General Directorate for Maintenance and Operation, have been implementing PMMS utilizing visual condition surveys, roughness measurements, structural capacities, and skid resistance to evaluate pavement condition. Visual checks and pavement roughness are usually performed annually on the street network. Pavement skid resistance is conducted annually on only main streets. Evaluation of structure is only performed at a project-level and is based on manual and roughness evaluation results [2].

In general, visual condition surveys include analyzing the distress type, as well as its severity level, extent, and site. As there are various authorities involved, there are many

techniques for conducting pavement condition surveys. The city of Riyadh has its pavement inspection procedure. As part of the procedure, a local pavement condition evaluation called the Urban Distress Index (UDI) should be established. The index is scaled from 0 to 100, with 100 representing excellent pavement condition. The UDI values are determined by visual assessment of the type, severity, and extent of pavement distress. Typically, an investigator is sent to a specific section of pavement in order to gather the necessary distress data to report the current types, severity levels, and quantities of distress. The data is gathered by physically walking through the segment. The process delivers specific information regarding the state of each segment of pavement. Furthermore, due to the large size of the city's pavement network, the process is both time-consuming and expensive.

Road pavement surface roughness is generally used to assess the riding condition of a road pavement surface. It is closely linked to the serviceability of pavement, which is a measurement of the pavement's physical characteristics. Profilometric, vehicle response, and subjective evaluation are the three types of roughness measurement techniques currently in use. The most accurate and well-suited for detailed analysis are profilometric techniques.

Riyadh PMMS uses the profilometric method to measure pavement roughness. The International Roughness Index (IRI) is used to calculate roughness measures. The IRI and the road profile are computed at regular intervals and are both shown on the computer. The horizontal and vertical profile data obtained from the profilometric method are converted into a response of the vehicle's motion by utilizing the technique of IRI calculation, which is predicated by a mathematical model. The IRI value is calculated by dividing the displacement units by the length units. At speeds of (40–50) kilometers per hour, roughness measurements are taken. Due to this, roughness measurements were acquired in a reasonably short period of time and at a cheap cost.

The major goal of this study is to determine the relationship between pavement distress assessment and roughness measures in the Riyadh roadway network. The pavement distresses were ride quality-related distresses such as cracking, patching, potholes, depression, rutting, and raveling.

Roughness measurements are indicated by the International Roughness Index (IRI). The analysis included establishing correlation factors between the distress types of riding quality and IRI and developing models to forecast the pavement distress type values based on IRI and highway class.

2. Literature Review

2.1. Background

Any pavement management system (PMS) is required to contain data of the pavement condition. The main goal of collecting and evaluating the condition of the pavement is to evaluate the current state of pavement condition at the time of inspection in order to determine urgent pavement maintenance requirements and plan for future objectives [2].

Pavement management systems (PMS) are increasingly being employed at all levels of government for effective highway management. Most PMS techniques may provide support at two levels: the network-level and the project-level. The data collected at the network level gives management comprehensive information on the whole system. The network-level level frequently provides information for planning reasons and financial analyses. Project-level information, on the other hand, contains construction, engineering design, and cost accounting details. The amount of data necessary for each level varies greatly. The general goals of network-level pavement condition evaluation are to analyze current pavement conditions, determine immediate pavement repair needs, and make a strategy for future requirements. Distress survey, roughness, structural capacity, and skid resistance are four common approaches for evaluating pavement conditions.

2.2. The Visual Inspection and Roughness Relationship

Research by Mubaraki was performed to find out the relationship between IRI and specific types of distress. Raveling, rutting, and cracking were among the distresses that

occurred. Three relationships linking IRI and raveling, rutting, and cracking have been observed. According to the findings of this investigation, raveling and cracking are related to IRI and it might be categorized as "ride quality distress." Furthermore, IRI was shown to have no statistically significant correlation with rutting [3].

Abdelaziz and his team built an artificial neural network (ANNs) and regression models to predict IRI as a function of pavement distresses. The LTPP database was used to create these models. The models that were constructed included prediction of IRI as an age function, IRI initial, alligator fatigue cracking (all severities), transverse cracking (all severities), and rut depth standard deviation (RUTSD). The correlation coefficient (R^2) of the regression analysis was 0.57, but the correlation coefficient (R^2) of the ANNs model was 0.75 [4,5].

In the same way [6], examined data from California's locations in the Bay area of San Francisco city to see if there was a correlation between IRI and pavement distress. To do this, the researchers set out with the objective of developing a surface roughness model that could be used to predict car operating expenses on highways in the Bay region of San Francisco city. In this study, 39 measurements were taken at 15 m intervals over a 152.4 m test section, the researchers developed a link between IRI and pavement distress. The outcome was the development of a linear link between IRI and a composite Pavement Condition Index (PCI. It was computed by taking into account the type and level of distress observed for each segment of the roadway. The PCI scale ranges from zero to one hundred, with one hundred representing ideal road conditions. The model obtained an adjusted R^2 of 0.52, In other words, the aggregate pavement quality index could predict slightly more than half of the variation in IRI.

In the United States, researchers investigated the association between pavement surface roughness and various types of distresses on the pavement [7]. The research included 462 pavement portions from 37 projects throughout Michigan. The sections of road pavement were studied to explore the connection between pavement surface roughness and distress. Assumption number one in this research was that an excess roughness results in increased dynamic loads on axles, which can then result in a tangible acceleration of pavement degradation. If this relationship is established, then it will be possible to plan preventive maintenance (PM) action to smooth the pavement surface.

The transportation department in the State of Connecticut utilized data in order to determine a relationship between the pavement distresses and IRI. Rutting and total quantity of cracking were the only distress types used. They called the associations they discovered "relatively weak." R^2 values for various lengths of pavement sections were 0.177 for 10 m, 0.242 for 30 m, and 0.299 for 90 m. They also found that utilizing neural networks did not enhance the findings, thus, they concluded that the IRI could not be utilized to forecast the general condition of pavements. Their study concentrated on pavement segments less than 90 m in length, and a simple summation was used to aggregate the value of cracks [8].

Other researchers have discovered that when the IRI is compared to other performance measures, the R^2 value is greater. For example [9], investigated the correlation between IRI and cracks, depth of rutting, potholes, patchwork, and raveling, and discovered that a R^2 value of 0.77 was the best they could come up with. They checked asphalt roads in India for guidance. Another study [10] investigated the relationship between the IRI and the PSI in Dubai by using a nonlinear regression model. They discovered that the R^2 for differing types of asphalt roads was 0.67 and 0.44, respectively.

Pavement roughness is a key indicator of pavement performance since it directly reflects pavement serviceability to road users. Recently, certain governments and provinces in Canada and the US are utilizing IRI in terms of an objective indicator of their pavement network conditions in their business plans [11]. For example, The Federal Highway Administration (FHWA) in the United State utilizes IRI as a performance metric to describe and monitor its National Highway System's pavement performance. There are two states in America, Kansas and Washington, that utilize IRI rating percentages to represent the

status of their highway network. In recent years, it has been a widespread practice among several highway organizations to measure IRI at the network level. Many road agencies now collect roughness on a routine basis since the IRI is a scale that may be transferred, is repeatable, and stable. Roughness is measured at the network level once a year or twice a year as a component of the evaluation of pavements, which is critical in setting maintenance and rehabilitation priorities.

3. Methodology and Data Collection

3.1. Study Methodology

There are two primary phases in the study's methodology. Collecting the information required for a sample group of streets in Riyadh City is the first phase in the process. The data includes information on the type, size, verity, and density for each distress and the IRI for each section of pavement that is included. The collected data of main streets and secondary streets were treated separately to avoid the possible effect of highway class and traffic categories. The second phase in the methodology is to investigate the relationship between IRI and all other types of distress.

3.2. Data Collection

The city of Riyadh is divided into smaller components for management and maintenance purposes. The city is divided into branch municipalities, districts, and regions. The region is a subdivision of the district and it's surrounded by four main streets and contains no main street within its entire area. The two main categories of the Riyadh street network are main streets and secondary streets. The main street is defined as the street that connects two main streets and is more than twenty-five meters wide or has an island. Main streets account for about 27 percent of the overall network area in Riyadh City. Secondary streets are all the categories of streets outside the definition of main streets. Secondary streets represent about 73 percent of the overall network area. Main and secondary streets are divided into sections. The segment of the main street is defined as distance between two intersections in the main street. The segment for the secondary street is defined as a region within a district. The segments for main and secondary streets are divided into several sample units; a representative unit of sample for the main streets was 100 m in length per lane. The sample unit of the secondary street is a street in a region.

The mean source of data was the General Directorate for Maintenance and Operation, Riyadh Municipality. A representative sample of pavement sections from both main and secondary streets was randomly selected. A section may have two to three lanes. In secondary streets, each data point represents the section. A total of 1619 main street sections were included in the study, with a total distance of more than 898.258 km. For secondary street sections a total of 140 were sections covered in the study. These represent an area of about 1814 square km.

The data for both main and secondary streets include distress data, pavement, condition, and International Roughness Index for each observation period. Time between the pavement condition survey and roughness measurements were less than 6 and 3 months for main and secondary streets, respectively. Table 1 presents the types and codes for distress that appear in both main and secondary streets according to the Riyadh Pavement Maintenance Management System (PMMS).

Table 1. Distress Types and Codes in Riyadh PMMS.

Main Streets		Secondary Streets	
Type of Distress	**Distress Code**	**Type of Distress**	**Distress Code**
Fatigue Cracking	D1	Block Cracking	D2
Block Cracking	D2	Long. and Trans. Cracking	D3
Long. and Trans. Cracking	D3	Patching	D4
Patching	D4	Potholes	D5
Potholes	D5	Depressing	D6
Depressing	D6	Raveling	D11
Rutting	D7		
Shoving	D8		
Bleeding	D9		
Polished Aggregate	D10		
Raveling	D11		
Patching Cracks	D12		
Patching Depression	D13		

3.3. Relationship between Types of Pavement Distress and IRI

Statistical correlation analysis was carried out to analyze the interaction between IRI and pavement distresses. Riding quality distresses are expected to show a considerable effect on IRI values. That means that distress is characterized as riding quality distress if a high degree of linkage exists between the value of IRI and the distress density for a pavement section. In contrast, distress is characterized not affecting riding quality if the correlation between distress density and IRI is not significant.

The analysis of IRI and distress types involved investigating the linkage between the value of IRI and each distress type. It is expected that a section of pavement will have more than one distress. Therefore, pavement sections are grouped based on the distress that is dominating in each section. The IRI can then be related to riding quality distresses through statistical models. Figure 1 describes the suggested procedure of analysis.
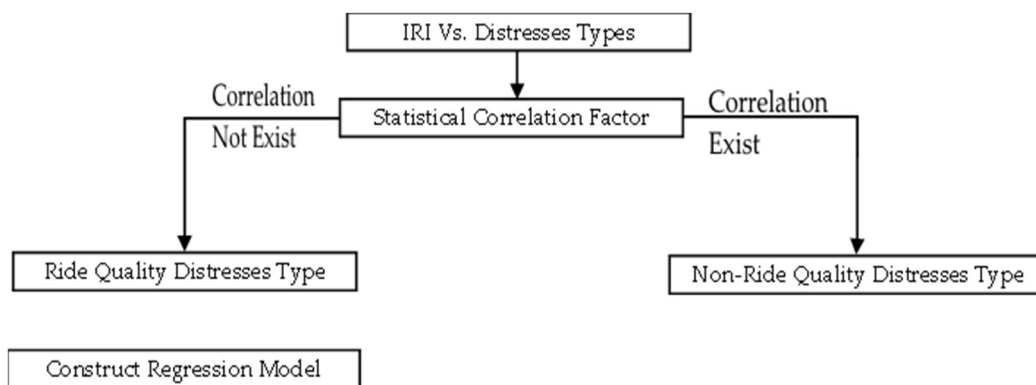

Figure 1. Analysis of IRI and type of distress.

4. Data Analysis and Results

4.1. Statistical Information

The modeling approach applied in the analysis is based on statistical regression. The fundamental form of a regression equation is as follows [12]:

$$Y = b_0 + b_1 X \tag{1}$$

The regression equation can be solved to estimate the predicted values of the regression coefficients (b_0 and b_1).

To perform the analysis procedure, two types of computer software were used to examine and study the data. This software was a spreadsheet program and a statistical

program. The data was entered into an Excel spreadsheet, which then generated the graphs (charts) that show the overall trend of the data. The "Minitab" statistical software was used for the following analysis [13]:

- Conduct descriptive and general statistics for the IRI and various distress types.
- Perform correlation tests between IRI and various distress types.
- Model the correlation between IRI and distress types.

In the preliminary analysis, the statistical program (Minitab) was used to select the general statistics of the IRI and various distress type data for both main and secondary streets.

4.2. Distresses Related to Ride Quality

Pavement roughness measures are generally used to determine the riding quality surface of a roadway's pavement. Pavement roughness is usually connected to pavement serviceability. The qualities of the pavement's physical characteristics are measured by pavement serviceability. So, roughness is connected to the opinions of persons who drive on the road. It has a major influence on comfort, safety, vehicle operating costs, and travel speed.

This section attempts to research pavement distresses to generate the types of distresses that are related to riding quality for both main and secondary streets. All pavement distresses in the study region were studied for their impact on the IRI measurement.

- Main Street sections

For main street sections, ten types of distress appear in the study sample. The cracking distresses fatigue cracking (code D1), block cracking (code D2), longitudinal and transverse cracking (code D3) and patching cracks (code D12) have been aggregated into one group called cracking distress. In addition, the distress types of depression (code 6) and depression patching have been assembled into one group called depression distress. After grouping, the distress types were reduced to six. The distress groups in the main sections are as follows:

Cracking (codes D1, D2, D3 and D12); Patching (code D4); Potholes (code D5); Depression (codes D6 and D13); Rutting (code D7); Raveling (code D11).

The relation between IRI and each of the distress types in main street samples is investigated and discussed in the subsequent paragraphs.

1. Cracking vs. IRI

Figure 2a presents crack distress as dominant in the total sample units. It is clear from the graph that a visible scattering exists in the roughness and density of distress data. The chart doesn't show a strong link between the IRI value and cracking density. Furthermore, the IRI and the crack density correlation coefficient is 0.167. The low correlation factor means that the two variables have a poor linear relationship. The *p*-value is equal to zero. This means that there is enough relation between IRI and distress density. The statistical test result does not correspond to previous experiences indicating that cracking distress is a non-ride quality form of distress at all levels of severity.

2. Patching vs. IRI

Figure 2b shows that the patching and IRI values have a positive relationship. The graph, on the other hand, does not demonstrate any clear-cut conclusions regarding the relationship's linearity. IRI and patching density have a correlation coefficient of 0.471 and a *p*-value of zero. The coefficient has a positive sign which mean that patching density and IRI have a positive relationship. The linear relationship distinguished around 47 percent of the IRI and patching density observations, according to the correlation factor value. The hypothesis test obtained a *p*-value of 0, indicating that there is sufficient evidence of a link between IRI and patching density at a 95% confidence level.
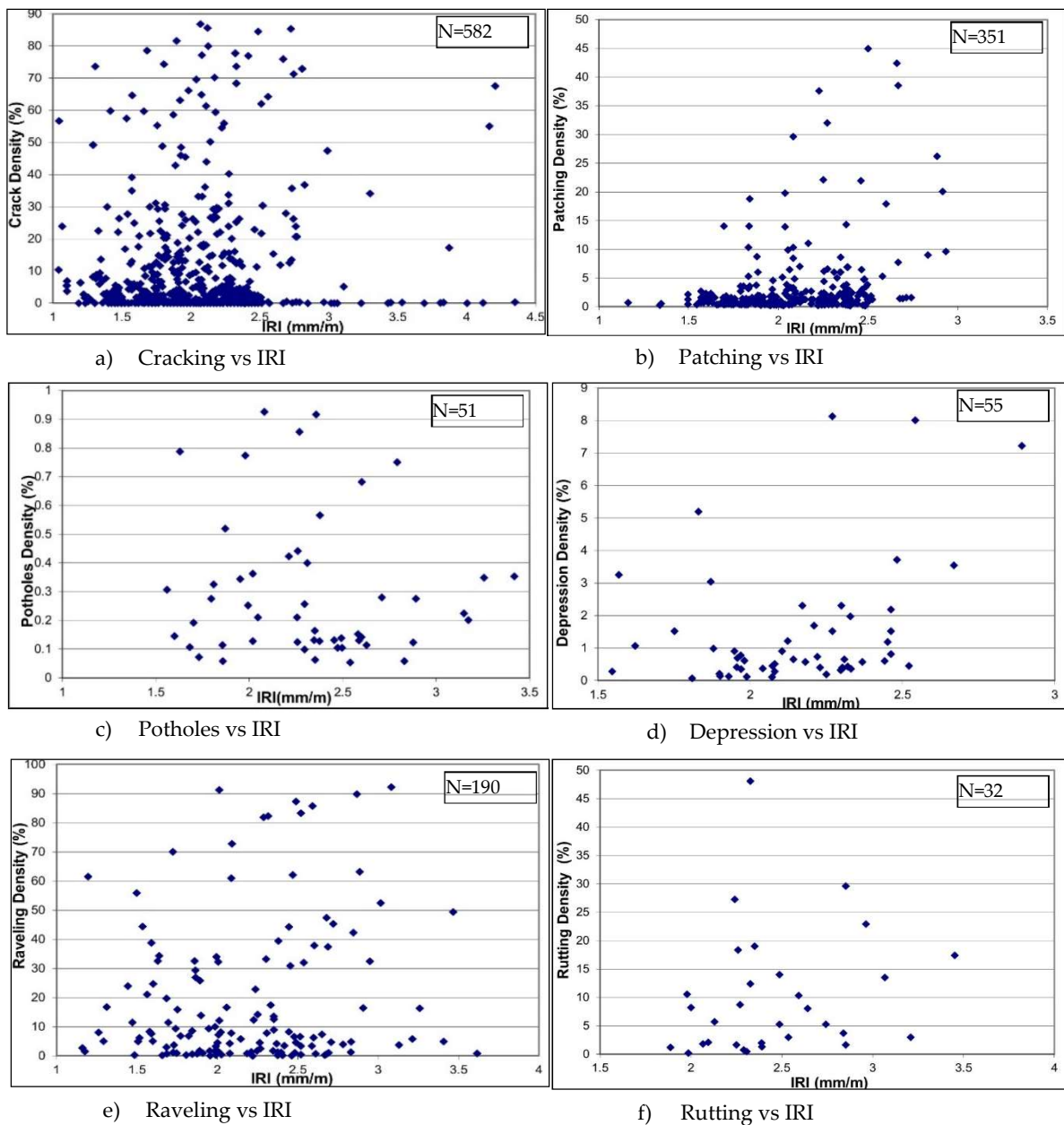
Figure 2. Distress types vs. IRI for Main Road, N = number of sections included.

3.　Potholes vs. IRI

Figure 2c represents the relation between pothole density and IRI. The pothole distress was the dominant distress. The graph shows that the relationship's linearity is not well defined. The coefficient of correlation is 0.123. The *p*-value is 0.390, which is larger than the level of significance of 0.05. As a result, there is not enough evidence of a link between IRI and the number of potholes.

4.　Depression vs. IRI

The graph in Figure 2d shows the relationship between IRI and depression density. The graph shows that depression and IRI values have a positive relationship. IRI and depression density have a correlation coefficient of 0.342 and a *p*-value of 0.011. The positive sign indicates that depression density and IRI have a positive relation. When the correlation coefficient equals 0.34, there is no clear choice about the relationship's linearity. The *p*-value for the hypothesis test is 0.011, which is less than the 0.05 level of significance.

The result is that we have sufficient evidence to understand that there is a statistically significant correlation between IRI and depression density with 95 percent confidence.

5. Raveling vs. IRI

Figure 2e shows the relationship between IRI and distress of raveling density. The correlation coefficient is 0.399 and the *p*-value is zero. There is no clear-cut decision about the linearity of the relation. The positive sign indicates a positive relation between raveling density and IRI. In the hypothesis test the *p*-value= 0, therefore there is sufficient evidence of the relationship between IRI and raveling density.

6. Rutting vs. IRI

Figure 2f shows the correlation between IRI and rutting density. The graph shows that rutting density and IRI values have a positive relationship. there is no clear choice about the relationship's linearity. The correlation coefficient is 0.357, meaning that the linear relationship only affected 35.7 percent of the IRI and rutting density observations. There is insufficient evidence of a link between IRI and rutting density since the *p*-value is 0.045, which is extremely near to the 0.05 level of significance.

- Secondary Street Sections

There are six distress types included in secondary pavements of the Riyadh street network. The cracking distresses Block Cracking (code D2) and Longitudinal and Transverse Cracking (code D3) have been aggregated to one group called cracking distress. After grouping the distress types were reduced to five. The total distress groups in the second section are Cracking (codes D2 and D3) Patching (code D4); Potholes (code D5); Depressing (code D6) and Raveling (code D11).

The relation between IRI and each group of distress types in secondary Streets is discussed in the subsequent paragraphs.

1. Cracks vs. IRI

The graph in Figure 3a shows the relationship between IRI and crack density. The correlation coefficient is 0.28, which indicates that the linear relationship only affected 28 percent of the IRI and crack density observations. There is insufficient evidence of a link between IRI and crack density since the *p*-Value of the hypothesis test is zero. The positive sign means a positive correlation between IRI and carack density, the low relationship factor indicates insignificant linearity relation between crack density and IRI.

2. Patching vs. IRI

The relation between IRI and patching distress density is seen in Figure 3b. The graphic shows that patching density and IRI have a positive relationship. The coefficient of correlation is 0.514. The positive sign indicates that patching density and IRI have a positive relationship. Furthermore, the correlation factor indicates that the linear relationship distinguished around 51.4 percent of the IRI and patching density data. The p-value for the hypothesis test is zero. As a result, the relation between IRI and patching density has sufficient evidence at a 95 percent confidence level.

3. Potholes vs. IRI

Figure 3c shows the relationship between IRI and pothole distress density. The correlation factor is 0.322 indicating low linearity of the relationship. The *p*-value is 0.208 which is greater than the 0.05 level of significance; so, there is insufficient evidence of the relation between the value of IRI and pothole density. This result could be because potholes are usually avoided during roughness measurements.
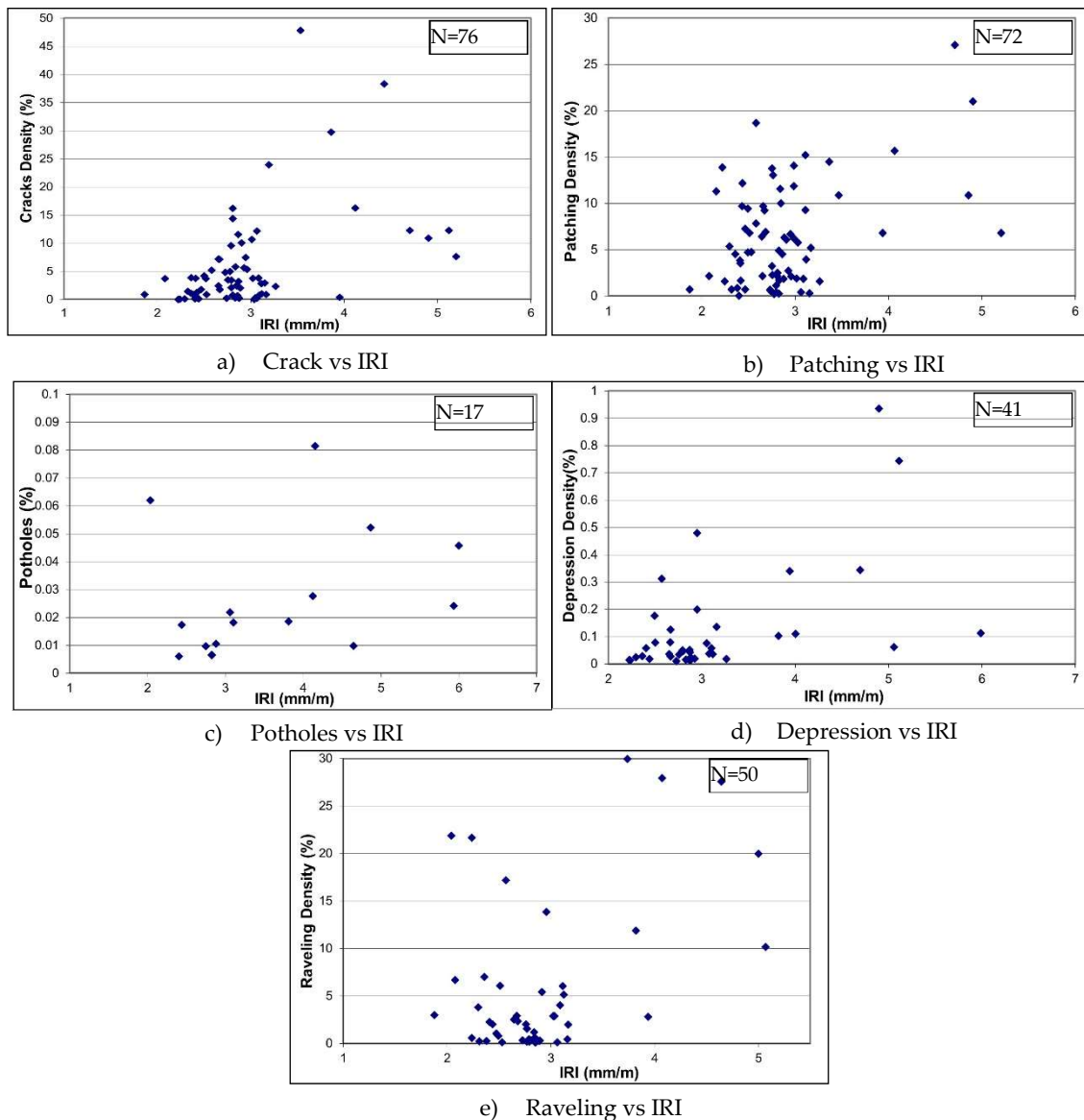
a)   Crack vs IRI

b)   Patching vs IRI

c)   Potholes vs IRI

d)   Depression vs IRI

e)   Raveling vs IRI

Figure 3. Distress types vs. IRI for secondary roads, N = number of sections included.

4.   Depression vs. IRI

The correlation between IRI and depression distress density is presented in Figure 3d. The graph shows that patching density and IRI have a positive relationship. When the density of depressions in the pavement sample is high, the IRI value increases. The linear relationship distinguished about 43.6 percent of the IRI and depression density data, on the basis of the correlation factor value. The hypothesis test gave a *p*-value of 0.004, which is less than the 0.05 level of significance, showing that there is sufficient relation between IRI and depression density at the 95 percent confidence level.

5.   Raveling vs. IRI

The graph in Figure 3e shows the relationship between the value of IRI and the raveling distress density. The graph shows a relationship between raveling and IRI. The linear relationship distinguished about 38.7% of the IRI value and raveling density data, according to the correlation factor value. The *p*-value in the hypothesis test is 0.006. As a result, there is sufficient evidence of the association between the value of IRI and the raveling density at the 95 percent confidence level.

4.3. Distresses Density and the IRI Model

In this section, the regression method was chosen to create models that related IRI with the density of different distresses. The linear regression model would be in the form:

$$IRI = b_0 + b_1 \text{ distress}(1) + b_2 \text{ distress}(2) + b_3 \text{ distress}(3) \ldots + b_n \text{ distress}(n); \qquad (2)$$

where; $b_0, b_1, \ldots, b_n$: regression coefficients

For each street category, two regression models were generated. The first model looked at how different types of distress impacted pavement roughness (IRI). The previous results in detecting ride quality types of distress were then confirmed using this model. The second model was created to find the best match between IRI and the different types of ride quality distress. The two models were checked and analyzed using a variety of statistical tests. The *t*-test was used to evaluate the relationship between the two regression coefficients (b_0, b_1) and the dependent variable at the 95% confidence level. Analysis of variance was used to determine the regression line's quality, or if the variation in IRI is dependent on the distress data. Finally, the correlation coefficient (R2) was used to show how well the regression model was fitted to the data.

- Main Street Sections
- The influence of pavement roughness on six different types of distress in the main street sections in Riyadh city was studied and analyzed. The study developed and tested two regression models; the first model attempted to link the IRI index to all types of distress in main street samples. The second regression model was developed to connect the IRI index to different types of distress that have been identified as ride quality distresses. The linear regression looked like this:

$$IRI = b_0 + b_1 \text{ Cr} + b_2 \text{ Pa} + b_3 \text{ Po} + b_4 \text{ Dr} + b_5 \text{ Ru} + b_6 \text{ Ra}; \qquad (3)$$

where; $b_0, b_1, b_2, b_3, b_4, b_5, b_6$ are regression coefficients; Cr = crack distress density; Pa = patching distress density; Po = potholes distress density; Dr = depression distress density; Ru = rutting distress density; Ra = raveling distress density.

1. Model-1—connects IRI to all observable distresses:

$$IRI = 2.09 + 0.00265 \text{ Cr} + 0.00554 \text{ Pa} + 0.00906 \text{ Po} + 0.0193 \text{ Dr} + 0.00531 \text{ Ru} + 0.00317 \text{ Ra} \qquad (4)$$

Summary of the model parameters is presented in Table 2.

Table 2. Summary of *t*-tests for main streets (Model-1).

Predictor	Coef.	St.Dev.	T	*p*
Constant	2.09494	0.01593	131.54	0
Cr	0.0026529	0.0002124	12.49	0
Pa	0.0055395	0.000327	16.94	0
Po	0.009056	0.00501	1.81	0.071
Dr	0.019317	0.002978	6.49	0
Ru	0.005306	0.00176	3.01	0.063
Ra	0.0031703	0.0003066	10.34	0

The *p*-values for most regression coefficients are zero, meaning that there is a significant correlation between the types of distress and the estimated value of IRI. The *p*-values of the potholes (Po) and rutting (Ra) coefficients, on the other hand, are more than the 0.05 level of significance. As a result, there is sufficient evidence to exclude potholes and rutting in estimating the roughness index.

2.　Analysis of Variance

Source	DF	SS	MS	F	*p*
Regression	6	203.339	33.890	132.26	0.000
Residual Error	1610	412.547	0.256		
Total	616	615.886			

The *p*-values for the ANOVA-tests for the model are zero, meaning that there is no significant variation in the IRI predicted values caused by the regression model. The results show a strong connection between IRI and various types of distress.

3.　Squared multiple correlation coefficient (R2): R-Sq = 32.5% R-Sq(adj) = 32.3%

The squared multiple correlation coefficient (R2) is 32.3 percent. This means that 32.3 percent of the IRI values can be reflected and described by the regression model. It also shows that while there are statistically significant relationships between IRI and some types of distress, the relationship isn't strong enough to use distress types as an accurate measure of roughness conditions.

(a)　Model-2—connects IRI to ride quality distresses:

In this case, the types of distress that had a strong relationship with the IRI index are called ride quality types of distress. This distress includes cracks distress (Cr), patching distress (Pa), depression distress (Dr), and raveling distress (Ra).

1.　The regression model developed is as follows:

$$IRI = 2.10 + 0.00267\ Cr + 0.00553\ Pa + 0.0195\ Dr + 0.00316\ Ra \tag{5}$$

A summary of the regression model is shown in Table 3.

Table 3. Summary of *t*-tests (Model-2).

Predictor	Coef.	St.Dev.	T	*p*
Constant	2.09875	0.01594	131.67	0
Cr	0.0026746	0.0002129	12.56	0
Pa	0.0055299	0.0003278	16.87	0
Dr	0.019547	0.002987	6.55	0
Ra	0.003156	0.0003075	10.26	0

Since all the regression coefficients have *p*-values equal to zero, this indicates that there is a statistically significant link between the different types of ride quality distress and the expected levels of IRI.

2.　Analysis of Variance

Source	DF	SS	MS	F	*p*
Regression	4	200.181	50.045	194.06	0.000
Residual Error	1612	415.705	0.258		
Total	1616	615.886			

The *p*-values for the ANOVA-tests for the model are zero, meaning that there is no significant variation in the IRI predicted values caused by the regression model. The results show a strong connection between IRI and various types of distress. The F-value for model-2 is greater than that in model-1 meaning improvement of model-2 over model-1.

3.　Squared multiple correlation coefficient (R2): R-Sq = 33.0% R-Sq(adj) = 32.8%

The squared multiple correlation coefficient (R2) is 32.8 percent. This means that 32.8 percent of the IRI values can be reflected and described by the regression model. It also shows that while there are statistically significant relationships between IRI and some types of distress, the relationship isn't strong enough to use distress types as an accurate measure of roughness conditions.

- Secondary street sections

The effect of the pavement roughness on five distress types in the section of the secondary streets in the Riyadh city network has been studied and analyzed. The study developed and tested two regression models; the first one was to relate the IRI index to all distresses in the secondary street samples, whereas the second model was to relate IRI index to ride quality distress types. The distresses included in the regression evaluations were, cracks distress (Cr), patching distress (Pa), potholes distress (Po), depression distress (Dr), and raveling distress (Ra). The linear regression model would be in the form:

$$IRI = b_0 + b_1 \, Cr + b_2 \, Pa + b_3 \, Po + b_4 \, Dr + b_5 \, Ra; \tag{6}$$

where the number of regression coefficients equal 6.

The distress in the secondary streets class chosen to be ride quality type distresses that showed a statistically significant association with the IRI were cracks distress (Cr), patching distress (Pa), depression distress (Dr), and raveling distress (Ra). The linear regression model would be in the form:

$$IRI = b_0 + b_1 \, Cr + b_2 \, Pa + b_3 \, Dr + b_4 \, Ra; \tag{7}$$

where the number of regression coefficients equals 5.

(a) Model-1 the linear regression equation for the first model that relates IRI against all apparent distresses:

$$IRI = 2.59 + 0.0422 \, Cr + 0.0411 \, Pa + 5.75 \, Po + 1.32 \, Dr + 0.00996 \, Ra \tag{8}$$

The estimated regression coefficients and the overall model statistics were shown in Table 4.

Table 4. Summary of t-test for secondary streets (Model-1).

Predictor	Coef.	St.Dev.	T	p
Constant	2.594	0.1317	19.7	0
Cr	0.042227	0.00892	4.73	0
Pa	0.04107	0.01259	3.26	0.001
Po	5.752	4.146	1.39	0.168
Dr	1.3185	0.4064	3.24	0.001
Ra	0.009962	0.005005	1.99	0.039

The *p*-values for most of the regression coefficients are zero, clearly showing a significant linear correlation between the estimated values of IRI and the different types of distress. The *p*-value of the potholes (Po) coefficient is equal to 0.168, which is greater than the 0.05 level of significance therefore there is significant evidence to exclude the potholes coefficient which demonstrates no linear relationship between IRI and potholes distress.

1. Analysis of Variance

Source	DF	SS	MS	F	p
Regression	5	70.405	14.081	17.56	0.000
Residual Error	134	107.463	0.802		
Total	139	177.868			

Based on the ANOVA-test results, the *p*-values for the values of IRI response variables are equal to zero, meaning that the regression model does not account for any statistically significant variance in the IRI response variables. Furthermore, the data give sufficient evidence of the presence of a dependence relationship between the value of IRI and distresses.

2. Squared multiple correlation coefficient (R2): R-Sq = 38.7% R-Sq(adj) = 36.9%

The value of the squared multiple correlation coefficient (R2) is 36.9%. This means that 36.9% of the IRI values can be described by the regression model. This shows adequate logic of the regression model relating IRI and distress data.

(b) Model-2 the linear regression equation for the second model that relates IRI vs. ride quality distresses:

$$IRI = 2.5889 + 0.043121\ Cr + 0.04366\ Pa + 1.3193\ Dr + 0.010589\ Ra \qquad (9)$$

The estimated regression coefficients and the overall model statistics were shown in Table 5.

Table 5. Summary of t-tests for main streets (Modal-2).

Predictor	Coef.	St.Dev	T	*p*
Constant	2.5889	0.1321	19.6	0
Cr	0.043121	0.008927	4.83	0
Pa	0.04366	0.01249	3.49	0.001
Dr	1.3193	0.4077	3.24	0.002
Ra	0.010589	0.005002	2.12	0.036

In this case, the *p*-values for all ride quality regression coefficients are equal to zero, meaning that there is strong evidence to accept the regression coefficient of all distress densities in the regression model with 95 percent confidence. This indicates a statistically significant linear association between the different types of ride quality distresses and IRI ratings.

1. Analysis of Variance

Source	DF	SS	MS	F	*p*
Regression	4	68.861	17.215	21.32	0.000
Residual Error	135	109.007	0.807		
Total	139	177.868			

According to the ANOVA-test results, the *p*-values for the response variable is equal to zero, meaning that there is no significant amount of variation within the response variable in the regression model. The data reflect sufficient evidence of a dependent relationship between IRI and distressed values. Note that the F-value for model-2 = 21.32, which is greater than the F-value from model-1 which = 17.56, demonstrating an improvement in model-2 over model-1.

2. Squared multiple correlation coefficient (R2): R-Sq = 39.6% R-Sq(adj) = 37.3%

The value of the squared multiple correlation coefficient (R2) equals 37.3% which means that 37.3 percent of the IRI values are described and evaluated by the regression model showing adequate logic of the regression model relating IRI and distress data. Note that R2 in the second model (37.3) is greater than the first one (36.9) indicating an improvement of model-2 over model-1. It also shows that while there are statistically significant correlations between IRI and some types of distress, these relationships aren't strong enough for distress types to be used as a predictable measure for roughness conditions.

5. Findings

The influence of all of the distress types that are present in the study area, on the IRI measurement was analyzed in order to study the riding quality-related types of distress. From the main street sections, six distress groups exist in the Riyadh network samples. While the secondary streets involve five distresses groups. Tables 6 and 7 conclude the final analysis of the relationship between the roughness evaluation index (IRI) and the pavement

distress density for both main and secondary streets, sequentially. The correlation between the value of IRI and distress types has been investigated by two important statistical tests:

1. Testing the individual correlation hypothesis between the value of IRI and each type of distress.
2. The regression coefficients were used to evaluate the overall regression model that links the IRI value with the different types of distress.

Table 6. Summary of correlation factors and regression models in main street sections.

Distress Type	Correlation Factor	Correlation Hypothesis Test
Cracks	r = 0.167	$p = 0.000$
Patching	r = 0.471	$p = 0.000$
Potholes	r = 0.123	$p = 0.390$
Depression	r = 0.342	$p = 0.011$
Rutting	r = 0.357	$p = 0.045$
Raveling	r = 0.399	$p = 0.000$
Regression Model Equation: IRI = 2.10 + 0.00267 Cr + 0.00553 Pa + 0.0195 Dr + 0.00316 Ra		
Regression Coefficients Test (*t*-test)		

Distress Type	Hypothesis Test
Cracks	$p = 0.000$
Patching	$p = 0.000$
Potholes	$p = 0.071$
Depression	$p = 0.000$
Rutting	$p = 0.003$
Raveling	$p = 0.000$
Analysis Of Variance $p = 0$
Regression Model Adequacy R2 = 32.8%

Table 7. Summary of correlation factors and regression models in secondary street sections.

Distress Type	Correlation Factor	Correlation Hypothesis Test
Cracks	r = 0.280	$p = 0.000$
Patching	r = 0.541	$p = 0.000$
Potholes	r = 0.322	$p = 0.208$
Depression	r = 0.436	$p = 0.004$
Raveling	r = 0.327	$p = 0.006$
Regression Model Equation: IRI = 2.10 + 0.00267 Cr + 0.00553 Pa + 0.0195 Dr + 0.00316 Ra		
Regression Coefficients Test (T-test)		
Cracks	0.280	$p = 0.000$
Patching	0.514	$p = 0.000$
Potholes	0.322	$p = 0.168$
Depression	0.436	$p = 0.001$
Raveling	0.387	$p = 0.036$
Analysis Of Variance $p = 0$		
Regression Model Adequacy R2 = 37.3%		

Tables 6 and 7 show that *p*-values for cracking, depression, patching, and raveling in both main and secondary streets are near zero, indicating a significant relationship between these distress types and IRI. As a result, the findings of the research in both the main and secondary street categories suggests that there is a significant relationship between IRI and cracking, patching, depression, and raveling with a 95% confidence level. Statistical testing on the overall model between IRI and distress types confirmed these findings. The *p*-values for each regression coefficient were obtained in the regression coefficients test. In both the major and subsidiary streets, the regression coefficients for cracking, depression, patching,

and raveling are close to zero (less than 0.05), indicating a substantially linear relationship between IRI and each regression coefficient. IRI is related to different types of distress in different ways. Patching and depression had the highest correlation to IRI, according to the values of the correlation factors. While raveling has a lower relationship with IRI, cracking has the lowest. It was also found that the correlation factors for all the distresses versus IRI did not reach 50%, meaning that the relationship describes less than half of these relationships. The relationship is not strong enough to consider pavement conditions as an indicator of IRI. As a result, the correlation and regression coefficients testing showed that cracking, patching, depression, and raveling are ride quality types of distress with a 95% confidence level. However, it is unrealistic to claim that IRI can completely describe pavement distress conditions.

It's also shown in Tables 6 and 7, that potholes and rutting, point toward a relationship that is not significant with IRI values in both the main and secondary streets. The *p* values (which are larger than 0.05 level of significance) of both potholes and rutting demonstrates that these distress types have no strong evidence of a significant relationship with IRI. These results were proven through the statistical tests on the overall model between IRI and distress types. The *p*-values for each regression coefficient were obtained in the regression coefficients test. Potholes and rutting have regression coefficients larger than 0.05, meaning that there is no significant linear relationship between IRI and each distress type. As a result, the correlation and regression coefficient tests show that potholes and rutting are non-ride quality distress types and that IRI could not describe potholes and rutting distress conditions with 95 percent confidence.

6. Conclusions

The relationship between IRI and pavement distresses was investigated using statistical correlation analysis. The purpose of the research was to measure the level of distress related to riding quality. The relationship between distress density and IRI values was determined using a statistical correlation test. In the pavement portions, the model related IRI and distress types were calculated. The correlation between the value of IRI and distress types has been investigated by two important statistical tests:

1. Testing the individual correlation hypothesis between the value of IRI and each type of distress.
2. The regression coefficients were used to evaluate the overall regression model that links the IRI value with the different types of distress.

The results of the study indicate that there is a significant correlation between IRI and cracking, patching, depression and raveling in both main and secondary street groups, with a 95% confidence level. It has also shown that potholes and rutting distress types did not have a significant relationship to IRI values in both the main and secondary streets. This has led to a conclusion that is based on the statistical investigation of the relationship between IRI and distress types: cracking, patching, depression, and raveling could possibly be characterized as ride-quality type distresses. While potholes and rutting distress, could probably be described as non-ride quality type distresses.

Roughness and the extent of correlation can be helpful in detecting the type of distress. This analysis concludes that IRI can either be used to evaluate pavement quality or to monitor pavement deterioration. Rapid measurements of IRI using the Automatic Road Analyzer (ARAN) can ease the process of traditional pavement visual inspection. Using sample visual inspection ratings from pavement distress images can also be used to determine an approximate IRI value without having a Road Analyzer and allow subsequent planning and evaluation to proceed. However, not all surface distresses can be detected by roughness, especially some types of distress that are of very low severity.

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