Evaluation of Urban Road Stability Through the Integration of the Surface Distress Index and International Roughness Index

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ABSTRACT

In an effort to improve the quality of transportation infrastructure, road maintenance requires an evaluation of road conditions. The Surface Distress Index (SDI) and the International Roughness Index (IRI) are two primary classical indicators used to assess road conditions. Although both are utilized independently, the relationship between them has not been widely studied. This research aims to analyze the correlation between the Surface Distress Index (SDI) and the International Roughness Index (IRI), particularly in the context of road maintenance, and to evaluate the effectiveness of integrating both indices in urban road maintenance planning. This study was conducted using a correlation method and approach, involving field data collection along urban road segments. The SDI and IRI were measured using standard measurement devices provided by Bina Marga, and the correlation patterns between the two were analyzed statistically. The findings reveal that SDI is significantly correlated with IRI, indicating that as surface distress (SDI) increases, it directly leads to an increase in road surface roughness (IRI). The results also indicate that combining the two indices can improve the accuracy of road condition assessments. The quadratic model was identified as the most optimal for describing the relationship between SDI and IRI, with a model performance explaining 79% of the variation in IRI.

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1. INTRODUCTION

The Surface Distress Index (SDI) is one of the key indices for evaluating pavement conditions, particularly for asphalt pavements. More commonly, it is used to measure surface damage such as cracks, potholes, and rutting, providing critical information on how roads should be rehabilitated and maintained. Several parameters in the calculation of SDI include the length and width of cracks, the number of potholes, and rutting or grooves on the road surface [1], [2], [3]. This approach plays a significant role, especially in periodic assessments of road performance in terms of functionality and road safety [4], [5]. The Indonesian Ministry of Public Works (Bina Marga) has standardized the methodology for calculating the Surface Distress Index (SDI) by developing a systematic approach to assess road surface conditions [6], [7]. The SDI is a single index measurement that evaluates general surface damage, similar to the Pavement Condition Index (PCI) and the International Roughness Index (IRI) [8], [9]. While the PCI determines the severity and density of damage, the SDI provides a direct measure of surface conditions through visual inspection and quantitative measurements [10], [11], [12]. Recent studies have emphasized the role of SDI in various contexts, with examples ranging from assessments of urban to rural roads. For instance, the SDI and IRI methods were utilized to evaluate provincial roads in the city of Tarakan, highlighting the importance of visual surveys alongside quantitative data collection [2], [13]. Additionally, comparisons between SDI and PCI in previous studies have shown that the results from both indices are comparable, thereby proving the consistency of SDI as a reliable tool for road surface assessment[14].

The International Roughness Index (IRI) is a common measure used to determine road surface roughness or irregularity, which significantly affects vehicle operation, passenger comfort, and is a critical factor in road safety [15], [16]. IRI values are directly related to vehicle operating costs and user satisfaction levels [17]. IRI is highly useful as it serves as an indicator value that facilitates the identification of road damage conditions and assists planners in prioritizing rehabilitation and maintenance efforts [18], [19]. Factors influencing IRI values include road surface age, environmental conditions, and traffic loads [20], [21]. For instance, studies have shown that surface roughness increases over time, highlighting the need for monitoring [22]. Moreover, IRI is often combined with additional indices, such as the Pavement Condition Index (PCI), to provide a more detailed evaluation of road surface conditions [9], [23], [24]. This integrated model provides valuable insights into the structural and surface performance of roadways. These innovations enhance the efficiency of IRI data collection while also reducing the costs associated with traditional data collection techniques [25], [26]. As a result, these technologies are increasingly being adopted by transportation agencies to improve pavement management systems, ensuring optimal road conditions for end users. In road condition assessments using the SDI, decision-making is seamlessly integrated with IRI values serving as the foundation for informed decision-making.

The Surface Distress Index (SDI) and the International Roughness Index (IRI) are key guidelines in the evaluation and management of road stability, particularly in urban road maintenance. SDI focuses on quantifying visible surface damage such as cracks, potholes, and rutting. A combined index is derived through visual inspection and measurements of various types of damage, providing a single value that reflects the overall condition of the road surface [4], [27]. As a model based on data, SDI proves to be a practical tool for assessing road conditions and enabling quick evaluations that can aid maintenance strategies [28]. On the other hand, IRI is a measure of road surface roughness, making it a more comprehensive indicator of road instability. It quantifies vertical variations experienced by a standard vehicle traveling on the road, measured in units of m/km. The International Roughness Index (IRI) is important for evaluating ride quality, vehicle operating costs, and user service quality, as rougher surfaces tend to cause faster vehicle wear or discomfort for occupants [2]. Using SDI and IRI simultaneously and incorporating them into pavement management systems enhances pavement condition analysis. These indices provide transportation agencies with tools to prioritize repairs based on visible damage and ride quality, ensuring sustainable investment in road networks to maintain stability [24]. The Surface Distress Index (SDI) and the International Roughness Index (IRI) are key components of an efficient pavement management system. Combining their results offers a comprehensive assessment of road stability, supporting the optimization of maintenance and rehabilitation processes while enhancing road safety and performance. This study aims to build upon previous research by focusing on urban road stability assessment through the integration of the Surface Distress Index (SDI) and International Roughness Index (IRI).

2. METHODS

In this study, the research design was systematically structured to achieve the stated research objectives. The methodological approach consisted of several interconnected stages, including research design, data collection, data analysis, and result interpretation. Each stage was carefully designed to ensure the validity of the data collected and to support a comprehensive and objective conclusion-drawing process. Below is a detailed description of each step carried out in this study.

2.1 Research Design

This study used a quantitative approach using correlation analysis and statistical modeling. The data consisted of SDI and IRI values as the primary indicators representing the physical condition and comfort level of roads. Statistical modeling was conducted to identify the correlation or relationship between these two indicators and to measure the level of urban road stability.

2.2 Research Location and Object

The research was conducted on 10 urban road segments with a total length of 8.51 km, divided into 187 stationings. Samples were taken at secondary collector roads based on varying levels of road damage. The locations and road segments selected for this research are as follows:

Table 1. Research Road Segment Locations

No	Road Segment Code	Road Name	Road Length (Km)	Road Width (m)	Road Class
1	220	Perintis Kemerdekaan	1.684	8.50	Secondary Collector Road
2	15	Arjuna	0.896	6.50	Secondary Collector Road
3	16	Sumbodro	0.754	7.50	Secondary Collector Road
4	3	Werkudoro	1.254	6.00	Secondary Collector Road
5	26	R. A. Kartini	0.495	10.00	Secondary Collector Road
6	156	Smeru	0.655	6.00	Secondary Collector Road
7	38	Tentara Pelajar	0.605	7.50	Secondary Collector Road
8	29	Kol. Sudiarto	0.874	6.00	Secondary Collector Road
9	12	Panggung Timur	0.524	8.00	Secondary Collector Road
10	1	Jend. A. Yani	0.767	5.50	Secondary Collector Road

Source: Public Works Office of Tegal City, 2024

2.3 Surface Distress Index (SDI) Data Collection

SDI data collection was conducted through visual surveys at existing locations to assess road surface damage. Road damage measurements using the SDI method included the dimensions of crack area, crack gap, the number of potholes, and rutting or wheel track marks. The methods and steps for assessing road conditions using the SDI approach are as follows:

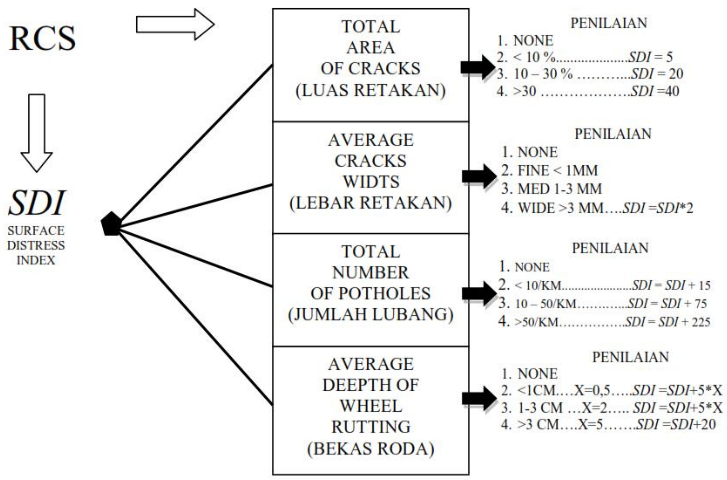


Figure 1. SDI Analysis Scheme (Bina Marga, 2011)

2.4 International Roughness Index (IRI) Data Collection

IRI data collection was conducted using the Hawkeye Vehicle. The Hawkeye Vehicle is a specially designed survey vehicle used to capture geometric data and road assets. In this study, it was utilized to obtain IRI (International Roughness Index) values. The survey results for IRI values were segmented by stationing along the reviewed road sections.

2.5 Analisis Data

a) Evaluation of Road Stability Using SDI and IRI

Table 2. SDI Stability Levels

SDI Value	Road Condition	SDI Stability Level
<50	Good	Stable Road
50-100	Fair	
100-150	Minor Damage	Unstable Road
>150	Severe Damage	

Source: Bina Marga, 2011

b) Assessment of Road Stability Based on SDI and IRI

Table 3. IRI Stability Levels

IRI Value	Road Condition	IRI Stability Level
≤4	Good	Stable Road
4.1 ≤ Average IRI ≤ 8.0	Fair	
8.1 ≤ Average IRI ≤ 12.0	Minor Damage	Unstable Road
Average IRI > 12	Severe Damage	

Source: Bina Marga, 2011

c) Correlation Analysis Between SDI and IRI
The relationship between the Surface Distress Index (SDI) and the International Roughness Index (IRI) was analyzed using five regression models: Linear, Logarithmic, Quadratic, Exponential, and Logistic regression models. These models aim to determine the best-fit pattern in describing the relationship between SDI and IRI. The model performance was evaluated using the coefficient of determination (R^2).

3. RESULTS AND DISCUSSION

3.1 Descriptive Statistics of Road Damage

The Descriptive Statistics of Road Damage aims to provide a general overview of road damage data used for analyzing the Surface Distress Index (SDI). This data assists in understanding the distribution of road damage across the variables analyzed for the Surface Distress Index (SDI).

Table 4. Descriptive Statistics of Road Damage

Variable	N	Range	Minimum	Maximum	Mean	Std. Deviation
Length of Cracks (m)	187	58.20	5.50	63.70	18.90	10.30
Width of Cracks (m)	187	17.25	1.55	18.80	5.90	3.94
Crack Area (m²)	187	186.24	11.32	197.56	92.93	41.75
Road Area per STA (m²)	187	225.00	275.00	500.00	348.93	64.80
Crack Area (%)	187	37.77	4.11	41.88	26.87	11.24
Crack Gap (mm)	187	14.05	0.50	14.55	4.85	4.18
Number of Potholes	187	5.00	-	5.00	0.64	1.41
Rut Depth (cm)	187	3.00	-	3.00	0.11	0.44
Valid N (listwise)	187					

Table 4 presents descriptive statistics providing an in-depth analysis of road damage conditions across 187 segments measured using various parameters. The crack length ranges up to 58.2 meters, with an average crack length of 18.90 meters and a standard deviation of 10.30, indicating significant variation in crack lengths among the road segments. The average crack gap is 5.90 mm with a standard deviation of 3.94, suggesting that most sections of the road are evenly affected, although some segments have a maximum crack gap of 18.8 mm. The average crack area is 92.93 m² with a standard deviation of 41.75, showing variability in the extent of damage, with the maximum crack area reaching 197.56 m². Per segment, the road area has an average of 348.93 m² but has high variability, with an interquartile range difference of 225 m² and a standard deviation of 64.80. On average, 28.87% of the road area is affected by cracks, with some segments reaching up to 41.88%. Therefore, road segments with significant damage require prioritized attention.

The crack gap has an average of 4.85 mm with a standard deviation of 4.17, indicating that this parameter has a more uniform distribution compared to others. The average number of potholes is 0.64, with a maximum of 5 potholes, suggesting that some locations still experience damage. Rutting or wheel track marks along the road average 0.114 cm with a very low standard deviation of 0.44, indicating that most road segments are affected by light traffic loads. This analysis reveals substantial variability in road damage conditions, with some segments urgently requiring repair. The data plays an important role in supporting decision-making processes for road maintenance based on data, leading to more efficient and effective planning. Furthermore, the data is essential for identifying the root causes of damage and developing comprehensive, strategies for mitigating road damage based on data.

3.2 Descriptive Statistics of SDI and IRI

The descriptive analysis of SDI and IRI data provides a general overview of the extent of surface damage and irregularities across 187 road stationings. The SDI data shows a large range of 120, with a minimum value of 5 and a maximum value of 125. The average SDI value is 59.503, with a standard deviation of 39.63, indicating a high variation in road damage levels across the segments. On the other hand, the range of IRI values is smaller, at 10.96, with a minimum value of 1.00 and a maximum value of 11.96. The average IRI value is 4.96, with a standard deviation of 2.53. This indicates that surface irregularities exhibit much less variation compared to the SDI variable. The IRI variance of 6.424 further suggests that the IRI variable is less dispersed compared to the SDI variable.

Table 5. Descriptive Statistics of SDI and IRI

	N	Range	Minimum	Maximum	Mean	Std. Deviation
SDI	187.00	120.00	5.00	125.00	59.50	39.63
IRI	187.00	10.96	1.00	11.96	4.96	2.53
Valid N (listwise)	187.00					

The analysis of Table 5 shows that road damage is categorized as highly varied, which may be caused by factors such as traffic volume, weather conditions, and the frequency of road maintenance. On the other hand, surface roughness is relatively more controlled, although some segments have high values that could negatively affect the comfort and safety of road users. Therefore, this study was conducted to better understand the relationship between these two variables and their causal factors to facilitate more targeted and data-driven road maintenance planning. The following is a visualization of the SDI and IRI values for the observed road segments. Each SDI value was divided by 10 to produce a more realistic visual representation.

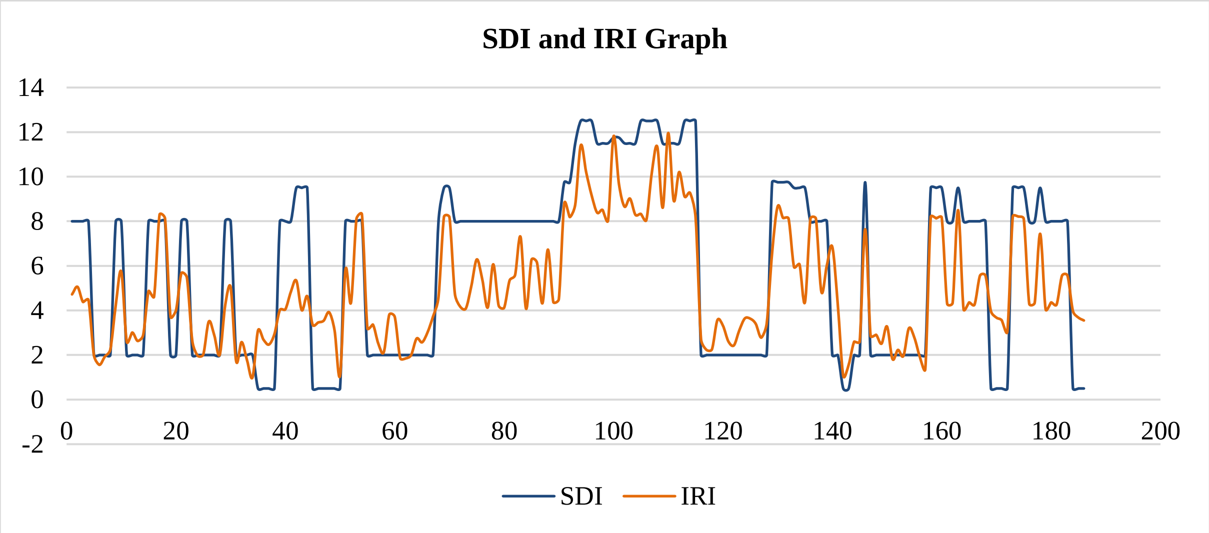
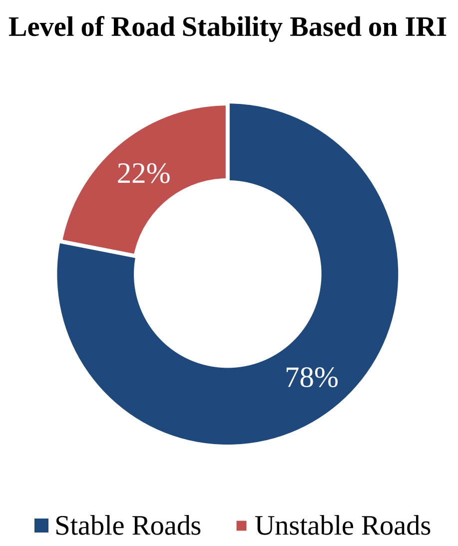


Figure 2. Visualization of SDI and IRI Values

3.3 Road Stability Assessment Based on SDI and IRI



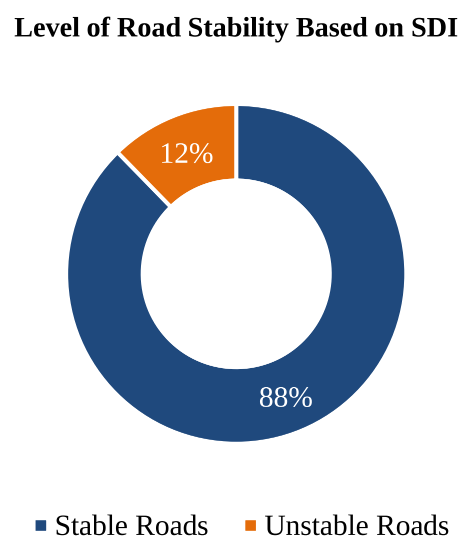


Figure 3. Road Stability Based on SDI and IRI

According to the analysis results, road stability levels show significant differences when measured using the Surface Distress Index (SDI) and the International Roughness Index (IRI). Based on SDI measurements, 88% of roads are categorized as stable, while 12% are classified as unstable. Conversely, in IRI measurements, the percentage of stable roads decreases to 78%, while 22% of roads are identified as unstable. This difference indicates that SDI provides a relatively optimal characterization of road stability compared to IRI, as SDI considers physical road characteristics such as cracks or potholes, while IRI captures vehicle dynamics, focusing only on road unevenness. Combining these two methods can offer decision-makers a more comprehensive understanding of road conditions, which is beneficial for planning road maintenance and rehabilitation, as well as for developing sustainable road infrastructure.

3.4 Correlation Analysis Between SDI and IRI

The quality of road infrastructure impacts both the quality of travel and the safety of road users. Two common indicators used in evaluating road conditions are the Surface Distress Index (SDI) and the International Roughness Index (IRI). SDI measures the extent of visible damage on the road surface, such as cracks, rutting, and potholes. IRI, on the other hand, measures road surface roughness, which affects driving comfort and vehicle operating costs. The correlation between SDI and IRI is crucial to study because an increase in road damage (SDI) typically leads to an increase in road roughness (IRI), thereby affecting the quality of road service. The following section outlines the correlation modeling approach between SDI and IRI.

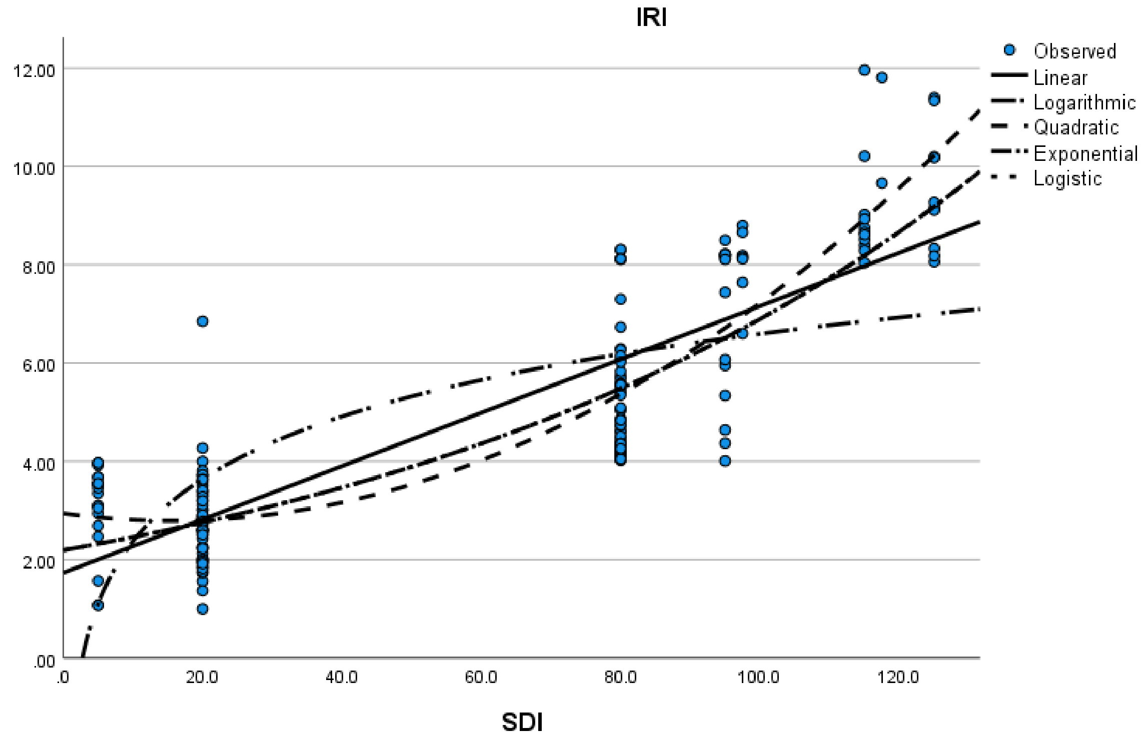


Figure 4. Correlation Graph Between SDI and IRI

Figure 4 illustrates the relationship between the Surface Distress Index (SDI) and the International Roughness Index (IRI) represented by five regression models: Linear, Logarithmic, Quadratic, Exponential, and Logistic. The relationship between SDI and IRI generally appears positive, where road damage (SDI) increases along with road roughness (IRI). However, this is not a simple linear correlation but rather a non-linear relationship, making more complex models like quadratic and logistic better predictors. The linear model provides reasonably accurate predictions in the early stages of road damage but fails to adequately model the increase in IRI at high SDI values. The logarithmic model is more suitable for describing the initial effects of damage at low SDI values but becomes less accurate in advanced stages. The exponential model represents the increasing trend fairly well but is slightly less accurate in predicting IRI values at low SDI levels. Given the evident non-linear relationship between IRI and SDI, the quadratic model effectively captures the increasing pattern of IRI at high SDI values. However, the logistic model may be useful as it accounts for saturation at high SDI values, where further increases in road damage do not always result in unlimited increases in IRI.

Based on the analysis of the five modeling approaches, the quadratic model is the most suitable for predicting the relationship between SDI and IRI due to its ability to capture the increase in IRI at high SDI values, reflecting the effects of severe road damage on the longitudinal roughness of the road surface. The logistic model is also noteworthy for representing saturation at high levels of road damage. This graph has significant implications for road maintenance planning, particularly for maintaining roads with low to moderate SDI values to prevent significant increases in roughness. The quadratic or logistic model can serve as a valuable predictive tool for road managers to prioritize repairs more efficiently and optimize budget allocation for urban road maintenance. This non-linear relationship aligns with previous studies, which indicate that increasing road damage has an exponential impact on pavement performance [9], [12], [18]. From a practical perspective, these findings contribute to supporting more accurate and efficient road infrastructure management based on data.

Table 6. Comparison of Regression Models

Model	Regression Equation	R^2
Linear	$IRI = 0.054 \cdot SDI + 1.733$	0.720
Logarithmic	$IRI = 1.834 \cdot \ln(SDI) - 1.853$	0.524
Quadratic	$IRI = 0.001 \cdot SDI^2 - 0.019 \cdot SDI + 2.942$	0.793
Exponential	$IRI = e^{(0.011 . SDI + 2.195)}$	0.721
Logistic	$IRI = \frac{1}{e^{(0.989 \cdot SDI + 0.456)}}$	0.721

The Surface Distress Index (SDI) and the International Roughness Index (IRI) have become key topics in publications frequently addressing pavement condition assessments. SDI indicates the overall level of physical damage on the road surface, while IRI estimates the longitudinal roughness of the road, which contributes to driving discomfort. The results of this study show that the quadratic model is an effective method for describing the relationship between the two variables, SDI and IRI. The quadratic model is well-suited for illustrating the relationship between SDI and IRI. The increase in SDI values has a significant impact on the rise in IRI values [29], [30]. This data demonstrates the direct effect of road surface damage on road roughness, particularly at moderate to severe levels of damage.

The results of this study align with previous research, which stated that cracks, rutting, and potholes contribute to the increase in IRI values. Furthermore, non-linear models, as illustrated by the quadratic model, provide a more comprehensive understanding compared to linear models, which only illustrate damage patterns in the early stages. These findings have highly practical applications in implementing predictive road maintenance schemes based on data. Road maintenance management can adopt the quadratic model as the most effective approach to prioritize preventive maintenance. Focusing on roads with low to moderate SDI values can prevent significant increases in IRI values.

This strategy will not only reduce maintenance costs but also enhance the comfort and safety of road users. Additionally, these models can be integrated into road management systems to optimize resource allocation for maintenance and rehabilitation projects on urban roads. This study reinforces the importance of adopting predictive approaches based on mathematical models in urban road management. However, the findings of this study may not be fully replicable due to certain limitations. The research does not consider stratification factors, including traffic, other pavement types, and climate. Furthermore, model validation requires further studies and evaluations across various regional strata and road surfaces. Therefore, broader and more multifaceted data should be studied to improve the accuracy and validity of the model.

4. CONCLUSION

This study reveals a significant relationship between the Surface Distress Index (SDI) and the International Roughness Index (IRI) in evaluating urban road conditions. Based on data from 10 road segments with 187 stationings reviewed, the analysis proves that SDI and IRI provide significant information about the overall condition of road surfaces, where SDI assesses functional damage and IRI evaluates road surface roughness. The road stability levels show significant differences when measured using the Surface Distress Index (SDI) and the International Roughness Index (IRI). According to SDI measurements, 88% of roads are categorized as stable, while 12% are classified as unstable. On the other hand, IRI measurements show a decrease in stable roads to 78%, with 22% of roads identified as unstable. These two methods not only correlate but also effectively illustrate road stability correlations associated with broader implications for road performance metrics.

The quadratic regression model is the best model to describe the relationship between SDI and IRI, indicating that as road damage (SDI) increases, road roughness (IRI) also increases, although it reaches a point where changes in IRI values become more limited under severe road damage conditions. The quadratic model is the most optimal model for explaining the relationship between SDI and IRI, with a model performance of 79% of the IRI variation explained. This study emphasizes that SDI and IRI should be processed simultaneously through pavement management systems to capture a detailed picture of road conditions and develop more effective and efficient maintenance plans. Further integration of these two indices in the future will optimize the planning, maintenance, and rehabilitation of urban road transportation infrastructure.

The integration of Surface Distress Index (SDI) and International Roughness Index (IRI) data in road monitoring and maintenance will enhance the evaluation and assessment of road stability. A maintenance management system based on data can effectively process SDI and IRI values to expedite decision-making and optimize road maintenance. Additionally, through routine and periodic maintenance, other factors such as traffic loads and weather conditions can be examined in the context of current climate changes. This will support the development of models to optimize road maintenance and improve the efficiency of urban road maintenance practices.

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