



Smart Urban Road Management: Application of Artificial Neural Networks for Predictive Modeling of the International Roughness Index

Yogi Oktopianto^{1*}, Antonius², Abdul Rochim²

¹Politeknik Keselamatan Transportasi Jalan, Jl. Perintis Kemerdekaan No.17 Tegal 52125, Central Java, Indonesia

²Civil Engineering Department, Universitas Islam Sultan Agung, Jl. Kaligawe Raya KM.4 Semarang 50112, Central Java, Indonesia

*yogi.oktopianto@pktj.ac.id

Abstract. Road condition assessment is an important indicator within the infrastructure maintenance management system. The International Roughness Index (IRI) is a standard service instrument used in various countries to evaluate road surface roughness. However, assessing road conditions using IRI faces several challenges, including the need for expensive equipment, long operational time and cost, limited coverage, and the fact that it only represents surface roughness, thereby requiring additional surveys to identify pavement distress types directly. The objective of this study is to develop an IRI prediction model based on the Surface Distress Index (SDI) parameters to optimize the efficiency of road condition assessment by using Artificial Neural Networks (ANN) to enhance road maintenance planning. This model was trained on five years of road-damage data across 42 urban road segments. The coefficient of determination from the study findings indicates excellent prediction accuracy, with an R² value of 0.93, a Mean Absolute Error (MAE) of 0.73, and a Root Mean Square Error (RMSE) of 1.07. This model can serve as a more dynamic strategy for urban road maintenance management in developing countries facing resource limitations. The proposed framework offers an innovative and adaptive solution to issues in road maintenance management and provides support for more sustainable urban infrastructure management.

Keywords: IRI, SDI, ANN, Predictive Modeling, Road Maintenance

(Received 2026-04-16, Revised 2026-06-18, Accepted 2026-07-10, Available Online by 2026-10-31)

1. Introduction

Pavement performance evaluation is essential in infrastructure management, and the International Roughness Index (IRI) serves as a primary metric for assessing road surface roughness. The IRI reflects pavement smoothness and road quality, which affect driving comfort, safety, and become a key indicator in decision-making for road maintenance management [1–3]. The use and limited accessibility of expensive equipment pose significant challenges, particularly in developing countries. In addition, the long processing time, high operational costs, limited equipment coverage, and the fact that the results represent only surface roughness require additional surveys to identify damage characteristics directly. Irregular or infrequent IRI measurements can have serious impacts on road safety and increase the risk of accidents [1,4,5]. Based on the accident data report for the first semester of 2025, there were 21,490 traffic accidents in Indonesia caused by infrastructure and environmental conditions. Delayed maintenance can accelerate pavement deterioration, resulting in higher repair costs [6–9]. Similar issues occur in several developing countries, where extensive road networks often do not receive adequate maintenance due to limited funding and equipment.

Conventional maintenance, which requires substantial human resources and high costs, presents both challenges and opportunities for developing cost-saving alternatives for fast, precise road maintenance operations. This need is becoming increasingly urgent as road networks grow and maintenance demands increase. The integration of technology into road maintenance management systems through Machine Learning (ML) offers a promising solution [10–12]. Artificial Intelligence (AI), particularly Artificial Neural Networks (ANN), has become increasingly important in civil engineering applications [13–15]. This technology has shown effectiveness in predicting the Pavement Condition Index (PCI) with higher accuracy and precision compared to conventional methods [10–12,16]. The integration of ANN with road condition parameters in this predictive model contributes to more sustainable infrastructure management, supporting more accurate decision-making in road maintenance management [7,17].

Previous studies related to the application of IRI prediction using Machine Learning (ML) were limited to small datasets and a narrow range of damage variables, such as relying solely on crack length or rutting [14,18]. Another limitation of previous research is the lack of consideration of the interactions among various types of distress, which have a significant impact on the IRI. As an innovation, this study will develop an IRI prediction model based on local damage variables, including crack length, crack width, crack gap, potholes, and rutting, which are adjusted to the characteristics of road damage in urban areas of Indonesia. Using a set of variables that represent local damage characteristics can provide a more comprehensive illustration of road conditions and improve the accuracy of IRI prediction.

While previous studies primarily focused on conventional ANN applications for pavement condition prediction, this study proposes an ANN based framework with local damage characteristics by integrating several Surface Distress Index (SDI) variables, including crack length, crack width, crack gap, potholes, and rutting, specifically designed for urban road environments in Indonesia. Additionally, this study integrates benchmarking comparisons with conventional machine learning models and applies cross validation techniques to enhance the predictive resilience and generalization of the model. Therefore, the contribution of this study lies not only in the application of ANN but also in the development of a comprehensive, cost effective, and locally adaptive predictive framework for sustainable urban road maintenance management.

Therefore, this study aims to develop an IRI prediction model using Artificial Neural Networks (ANN) with the Surface Distress Index (SDI) as the fundamental variable based on more comprehensive local damage characteristics. By integrating Machine Learning (ML), this model is expected to improve IRI prediction accuracy compared to existing models. In addition, this model is designed to provide solutions for enhancing data-based road maintenance strategies through a planning approach that is more adaptive to local conditions, efficient, and sustainable.

2. Methods

2.1. Research Design

The research design adopted the Artificial Neural Networks (ANN) system, which has the primary capability to identify patterns in previous data to determine the International Roughness Index (IRI) of road surfaces. The ANN framework was designed to identify local pavement distress factors influencing IRI values. The ANN framework is illustrated in Figure 1.

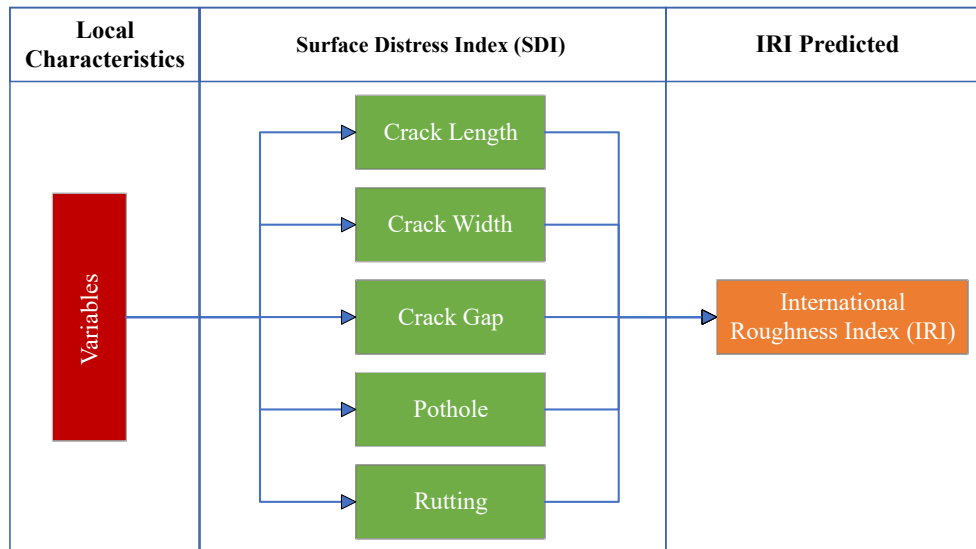


Figure 1. Framework Artificial Neural Network Adoption

The artificial neural network framework in Figure 1 is designed to connect local characteristics of urban road damage in Indonesia, based on the Surface Distress Index (SDI) parameters, to the International Roughness Index (IRI) values. This framework integrates theories of pavement surface distress and related factors that interact to inform data-driven decision-making in road maintenance management.

2.2. Samples and Procedures

The Artificial Neural Network (ANN) model was trained using a dataset consisting of 2,467 road damage observations collected from 42 urban road segments over five years. The variables were selected based on indicators and characteristics of local road damage in Indonesia to predict road surface roughness (IRI), including crack length, crack width, crack gap, pothole, rutting, and IRI as the dependent variable (Y). The predictive model was developed using Machine Learning (ML) techniques implemented in R Studio software.

The dataset was divided into three categories for modeling: 60% for training (1,481 records), 20% for testing (494 records), and 20% for validation (492 records) to ensure model stability and accuracy. The training process aimed to learn the relationship between input features and the output variable, while the testing data were used to evaluate the model's performance in predicting road conditions not included in the training data. Validation procedures were implemented during training to improve model generalization and minimize overfitting risk.

2.3. Data Preprocessing

Previous to the model development, the dataset had been processed with several procedures to improve data quality and model stability. First, the data is examined for missing values and inconsistent observations. Then, outliers are removed using the interquartile range (IQR) analysis to identify abnormal pavement damage values that might affect the model's predictions. Then all numerical

variables are normalised by using the min-max scaling method to convert the input variables into a common numerical scale from 0 to 1. This normalisation process is important for the application of Artificial Neural Networks (ANN) to avoid numerical dominance among variables and to improve the convergence during the training process of the model. Furthermore, random shuffling is used to overcome sampling bias and provide a more representative distribution of observations in the training, testing, and validation datasets. Then, the final dataset is split into training, testing, and validation subsets with a 60:20:20 ratio.

2.4. ANN Architecture and Hyperparameter Tuning

A model of an artificial neural network (ANN) was designed based on the multilayer perceptron architecture, with one input layer, two hidden layers and one output layer. The input layer consisted of five predictor variables for the pavement distress characteristics, and the output layer was for the International Roughness Index (IRI). The tuning of hyperparameters was performed in an iterative manner through a grid-search approach to find the most optimal ANN configuration. Different combinations of neurones and learning parameters were tested to obtain the best predictive performance with the least overfitting.

Network Configurations for Accurate Prediction Results are based on $N_h = N_{\{independent\}} - 1$, where $N_{\{independent\}}$ is the number of independent variables. The ANN model was constructed using the neuralnet package in R with a feedforward backpropagation architecture. The hidden layers used sigmoid activation functions and the output layer used a linear activation function (linear. output = TRUE) to accommodate the continuous IRI prediction. We tested several configurations of hidden layers to find the best network architecture in terms of validation performance.

2.5. Model Evaluation

The validation metrics in the data analysis used to assess model performance include the Coefficient of Determination (R^2), Mean Squared Error (MSE), and Root Mean Squared Error (RMSE). R^2 measures the model's ability to explain data variability, while MSE and RMSE measure the differences between predicted and actual values. The proposed ANN model was evaluated using a training, validation and testing data partition scheme. The dataset was randomly split using the create Data Partition function in R, in which all subsets preserved a representative distribution of the target data. The best ANN architecture was chosen by testing different hidden layer configurations on the validation dataset, taking into account R^2 , MAE and RMSE. These metrics help evaluate the model's accuracy in predicting the International Roughness Index (IRI) values and its reliability in detecting road segment distress for data-based decision-making in road maintenance.

3. Results and Discussion

The methodological framework described above was subsequently implemented to evaluate the predictive capability of the proposed ANN model and compare its performance with baseline prediction approaches.

3.1. Results

The dataset was collected through direct field observation methods to measure road conditions. The data were statistically analyzed to examine the relationship between predictor variables and the output. In the data analysis, understanding the relationship between input variables and the output variable representing road condition values was achieved through correlation analysis. Figure 2 below presents the correlogram of five independent variables (crack length, crack width, crack gap, pothole, and rutting) and one dependent variable (Y). The correlogram is a graphical representation that illustrates the relationships among variables in a dataset, including Pearson correlation (Corr), scatter plots, and distribution graphs.

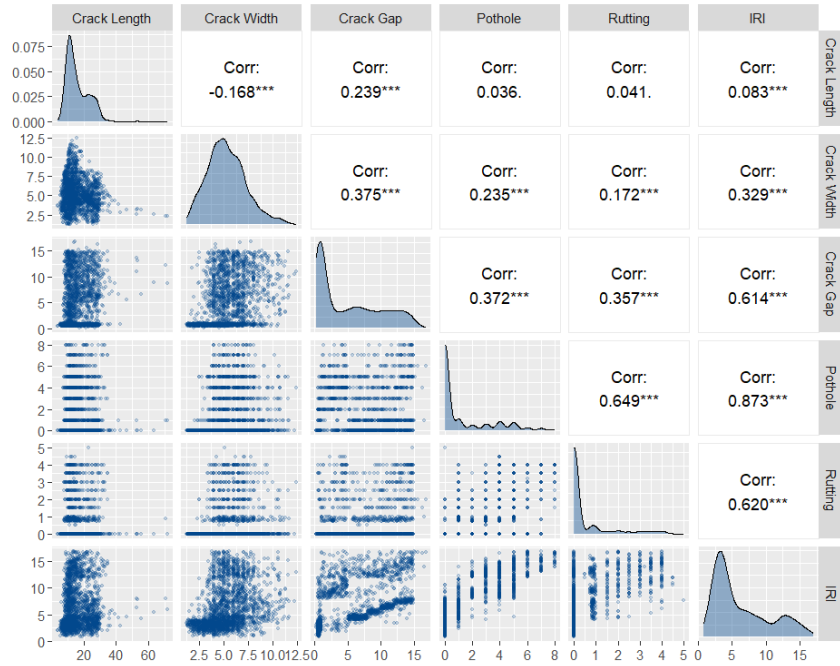


Figure 2. Correlogram of the IRI Prediction Model

The Pearson correlation measures the strength and direction of the linear relationship between two variables, with values ranging from -1 to 1. A value of +1 indicates a perfect positive relationship, -1 signifies a perfect negative relationship, and 0 means there is no linear relationship between the variables. The main relationships between the IRI and the independent variables show varying correlation strengths. The pothole variable has the highest correlation with the IRI at 0.873, which is highly significant, indicating a strong relationship between the two. Meanwhile, the crack gap and rutting show moderate correlations with IRI values of 0.614 and 0.620, respectively, indicating weaker but still significant relationships.

Figure 2 further demonstrates that the correlation between pothole distress and IRI scores is the most robust among all distress measures. The clustered distribution pattern indicates that the escalation in pothole severity substantially enhances pavement roughness. This condition signifies that potholes exert significant vertical dynamic loads on car suspension systems, directly affecting ride quality and elevating IRI values. Conversely, crack-related variables exhibit more pronounced deterioration trends and show moderate associations with pavement roughness. The IRI prediction model was analyzed by testing 19 artificial neural network configurations to achieve accurate prediction results based on the equation $N_h = N_{\{independent\}} - 1$, where $N_{\{independent\}}$ is the number of independent variables [19]. The most optimal model consists of two hidden layers with a 4-4 neuron configuration in the ANN. The first layer contains four neurons, and the second layer also contains four neurons.

This model structure receives five input variables representing road damage conditions obtained from field observations, consisting of crack length, crack width, crack gap, pothole, and rutting, which are implemented as input layers in the ANN. Figure 3 illustrates the architecture of the IRI's predictive model using an ANN. The ANN structure shown is a multilayer network, which allows the model to learn complex nonlinear relationships between multiple pavement distress variables at the same time. The hidden layer configuration improves the model's ability to identify hidden interaction patterns between distress indicators and pavement roughness levels, thus increasing the prediction accuracy over traditional statistical approaches.

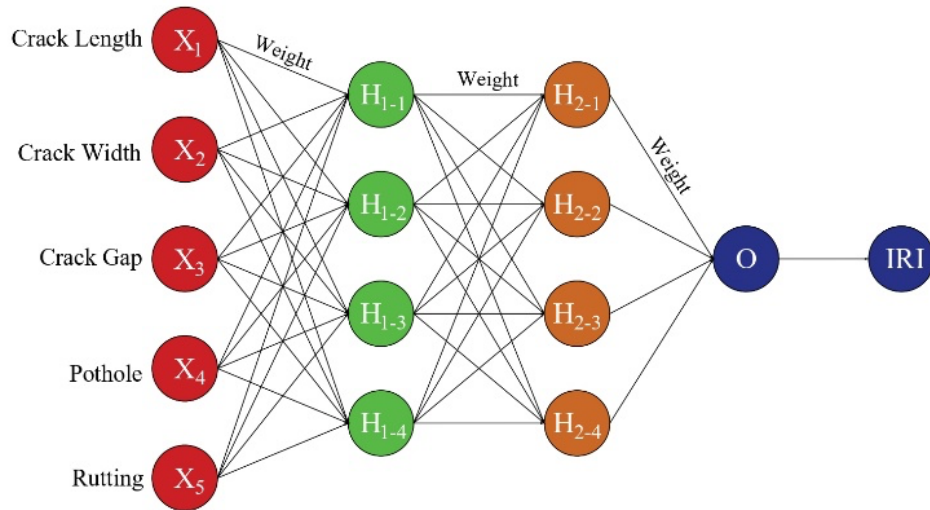


Figure 3. Architecture of the IRI Artificial Neural Network Model

The developed model demonstrates strong generalization capability on unseen data, as indicated by an R-squared value of 0.91 in the validation data. The R-squared values across different data subsets consistently range from 0.93, confirming that no overfitting occurred in this model and that it is valid for data-based prediction. The findings confirm that the proposed ANN framework can accurately predict IRI values for urban pavement assessment in road maintenance planning with a high level of precision and reliability. The model performance metrics in Figure 4 indicate that the model successfully explains most of the variability in the target data, and the prediction accuracy is reflected in the MSE and RMSE values.

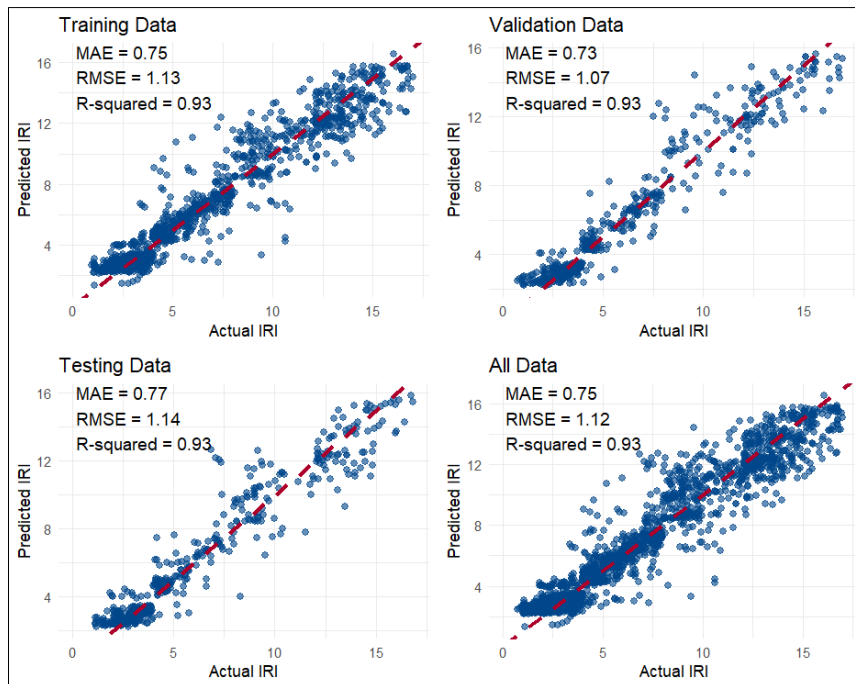


Figure 4. Performance of the Artificial Neural Networks Model

Figure 4 illustrates a robust correlation between anticipated and observed IRI values, evidenced by the concentration of data points adjacent to the regression line. This pattern demonstrates that the ANN

model effectively captures the inherent nonlinear dynamics of pavement deterioration with significant predicted reliability. The minimal prediction deviation further substantiates the robustness of the proposed approach for urban pavement assessment applications.

3.2. Discussion

The findings obtained from the developed ANN model not only demonstrate strong predictive capability but also provide important implications for sustainable pavement management and data-driven infrastructure maintenance strategies in urban environments. The International Roughness Index (IRI) prediction model shows excellent generalization performance on data not seen during training, as indicated by an R-squared value of 0.93 on the validation data. During the validation phase, the model's performance was evaluated using the Mean Absolute Error (MAE), yielding a value of 0.73. This value indicates that the average deviation between predicted and actual values is very small, reflecting the model's high accuracy and precision. In addition, the Root Mean Square Error (RMSE) was 1.07, indicating that the average prediction error is also low.

The developed ANN model demonstrates high predictive accuracy to that of other developing countries, such as the IRI prediction model for national highways in Nepal, which achieved an R^2 value of 0.82 for the entire training model [20]. In addition, the resulting model is comparable to similar models in various countries, which have R^2 values ranging from 0.82 to 0.99 [21–24]. These results also confirm that ANN is effective in modeling non-linear and complex relationships among multiple input variables, with higher accuracy compared to linear regression models [25–28].

The ANN model's performance indicates that pavement roughness is influenced by nonlinear interactions among various pavement distress variables. The ANN model discerns concealed correlations among crack attributes, potholes, rutting, and IRI values through nonlinear learning processes inherent in the neural network framework. This characteristic differentiates the ANN model from conventional regression techniques, which often presuppose linear connections among variables. The prediction outcomes demonstrate that the ANN model attained superior accuracy compared to the baseline statistical models employed in this study. The pothole measure exhibited a stronger association with IRI scores than the other distress variables. This phenomenon is associated with the vertical dynamic effects of pothole degradation on car suspension systems, which amplifies the feeling of pavement irregularity [29–31].

Variables associated with cracking exerted a more mild influence, as surface degradation resulting from cracking transpires gradually over time. The inclusion of local adaptive SDI variables enhanced the model's ability to represent pavement deterioration characteristics of urban roads in developing countries. The urban pavement distress patterns are different from the highway pavement conditions used in previous studies. Such differences include traffic variability, stop and go vehicle movements, drainage conditions, and the activities of urban utilities that influence the progression of pavement surface deterioration [32,33].

Comparative benchmarking against baseline prediction models remains challenging, as the Surface Distress Index (SDI) variables utilised in this study are locally developed parameters for assessing pavement condition specifically implemented in Indonesia, adhering to the standards established by the Bina Marga, Ministry of Public Works regulation No. SMD-03/RCS. Consequently, international research incorporating variables for predicting pavement performance based on Surface Distress Index (SDI) remains scarce.

Significant studies comprise a Multiple Linear Regression (MLR) model that attained a R^2 value of 0.735 [34] and a Radial Basis Function Neural Network (RBFNN) model with a R^2 value of 0.82 [35]. The comparative analysis indicates that the ANN model built in this study attained an R^2 value of 0.93, demonstrating superior predictive ability relative to prior models. The findings indicated that the suggested ANN model exhibited a superior coefficient of determination and reduced prediction error values, signifying its enhanced capacity to elucidate the nonlinear correlations among pavement distress indicators and to deliver more precise and reliable prediction.

The proposed ANN framework provides an efficient approach for estimating IRI values, a smarter approach to assessing road surface conditions can be achieved. The proposed framework offers a practical and cost efficient solution that reduces the need for extensive surveys to detect road surface roughness. By adopting and utilizing this predictive modeling approach, road maintenance management systems can quickly and accurately identify surface roughness conditions and optimize resource allocation for sustainable road maintenance.

4. Conclusion

Based on the experimental evaluation and comparative analysis conducted in this study, several important conclusions can be drawn regarding the applicability of the proposed ANN framework for urban pavement roughness prediction. The International Roughness Index (IRI) prediction model, developed using Artificial Neural Networks (ANN), consists of two hidden layers with four neurons in the first and four in the second. The proposed ANN framework with a 4-4 neuron configuration demonstrates excellent predictive capability and precision in data generalization, achieving an R-squared value of 0.93. The Mean Absolute Error (MAE) of 0.73 indicates that the average deviation between the predicted and actual values is minimal, reflecting the model's high accuracy and precision, while the Root Mean Square Error (RMSE) of 1.07 signifies that the average prediction error is very low.

The developed framework can serve as an efficient alternative for assessing road conditions with high precision and reliability, supporting road maintenance strategies through a more adaptive, comprehensive planning approach to promote a safer, more sustainable transportation system. This study is limited to urban roads and can be further explored across other road classes and expanded to include external factors such as environmental conditions and traffic volume composition to improve the accuracy of the International Roughness Index (IRI) prediction model.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT (OpenAI) to support English editing and improve the clarity of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Acknowledgments

This work was supported by the Politeknik Keselamatan Transportasi Jalan and the Department of Civil Engineering at Universitas Islam Sultan Agung.

References

- [1] Sandamal K, Madushani JPSS, Muttill N, Rathnayake U. Pavement Roughness Prediction Using Explainable and Supervised Machine Learning Technique for Long-Term Performance. *Sustainability* 2023;15:9617. <https://doi.org/10.3390/su15129617>.
- [2] Gharieb M, Nishikawa T. Development of Roughness Prediction Models for Laos National Road Network. *Civileng* 2021;2:158–73. <https://doi.org/10.3390/civileng2010009>.
- [3] Wang G, Burrow M, Ghataora G. Study of the Factors Affecting Road Roughness Measurement Using Smartphones. *Journal of Infrastructure Systems* 2020;26. [https://doi.org/10.1061/\(asce\)is.1943-555x.0000558](https://doi.org/10.1061/(asce)is.1943-555x.0000558).

- [4] Al-Samahi S, Zeiada W, Al-Khateeb GG, Hamad K, Alnaqbi A. A Comparative Study of Pavement Roughness Prediction Models Under Different Climatic Conditions. *Infrastructures (Basel)* 2024;9:167. <https://doi.org/10.3390/infrastructures9100167>.
- [5] Makhmudov F, Turimov D, Xamidov M, Nazarov F, Cho YI. Real-Time Fatigue Detection Algorithms Using Machine Learning for Yawning and Eye State. *Sensors* 2024;24. <https://doi.org/10.3390/s24237810>.
- [6] Moreno MAR, Marín-Urbe CR, Restrepo-Tamayo LM. Probabilistic Model for Prediction of International Roughness Index Based on Monte Carlo. *Ric* 2022;37. <https://doi.org/10.7764/ric.00021.21>.
- [7] Tamagusko T, Ferreira A. Machine Learning for Prediction of the International Roughness Index on Flexible Pavements: A Review, Challenges, and Future Directions. *Infrastructures (Basel)* 2023;8:170. <https://doi.org/10.3390/infrastructures8120170>.
- [8] Allen E, Costello SB, Henning TFP. Quantifying road criticality through the impact of disruptions on pavement deterioration and agency maintenance costs. *International Journal of Disaster Risk Reduction* 2025;126:105592. <https://doi.org/https://doi.org/10.1016/j.ijdr.2025.105592>.
- [9] Al-Mansour A, Lee KWW, Al-Qaili AH. Prediction of Pavement Maintenance Performance Using an Expert System. *Applied Sciences (Switzerland)* 2022;12. <https://doi.org/10.3390/app12104802>.
- [10] Issa A, Samaneh H, Ghanim M. Predicting pavement condition index using artificial neural networks approach. *Ain Shams Engineering Journal* 2022;13. <https://doi.org/10.1016/j.asej.2021.04.033>.
- [11] Sirhan M, Bekhor S, Sidess A. Implementation of Deep Neural Networks for Pavement Condition Index Prediction. *Journal of Transportation Engineering, Part B: Pavements* 2022;148. <https://doi.org/10.1061/jpeodx.0000333>.
- [12] Mahmood M, Anuraj U, Mathavan S, Rahman M. A unified artificial neural network model for asphalt pavement condition prediction. *Proceedings of the Institution of Civil Engineers: Transport* 2023;176. <https://doi.org/10.1680/jtran.19.00111>.
- [13] Boonsiripant S, Athan C, Jedwanna K, Lertworawanich P, Sawangsuriya A. Comparative Analysis of Deep Neural Networks and Graph Convolutional Networks for Road Surface Condition Prediction. *Sustainability* 2024;16:9805. <https://doi.org/10.3390/su16229805>.
- [14] Sharma A, Aggarwal P. IRI Prediction Using Machine Learning Models. *Wseas Transactions on Computer Research* 2023;11:111–6. <https://doi.org/10.37394/232018.2023.11.10>.
- [15] Bashar MZ, Torres-Machi C. Performance of machine learning algorithms in predicting the pavement international roughness index. *Transp Res Rec* 2021;2675:226–37.
- [16] Radwan MM, Mousa A, Zahran EMM. Enhancing Pavement Sustainability: Prediction of the Pavement Condition Index in Arid Urban Climates Using the International Roughness Index. *Sustainability (Switzerland)* 2024;16. <https://doi.org/10.3390/su16083158>.
- [17] Molinero-Pérez N, Montalbán-Domingo L, Sanz-Benlloch A, García-Segura T. Dual Model for International Roughness Index Classification and Prediction. *Infrastructures (Basel)* 2025;10:23. <https://doi.org/10.3390/infrastructures10010023>.
- [18] Ghavami S, Naseri H, Jahanshahi FS. Enhanced Prediction and Uncertainty Modeling of Pavement Roughness Using Machine Learning and Conformal Prediction. *Infrastructures (Basel)* 2025;10:166. <https://doi.org/10.3390/infrastructures10070166>.
- [19] Ibrahim RA, Elsheikh AH, Elasyed Abd Elaziz M, Al-qaness MAA. Chapter one - Basics of artificial neural networks. In: Elsheikh AH, Abd Elaziz ME, editors. *Artificial Neural Networks for Renewable Energy Systems and Real-World Applications*, Academic Press; 2022, p. 1–10. <https://doi.org/https://doi.org/10.1016/B978-0-12-820793-2.00002-1>.
- [20] Sigdel T, Pradhananga R, Shrestha S. Artificial Neural Network-based model to predict the International Roughness Index of national highways in Nepal. *Transp Res Interdiscip Perspect* 2024;25. <https://doi.org/10.1016/j.trip.2024.101128>.

- [21] Sharma A, Sachdeva SN, Aggarwal P. Predicting IRI Using Machine Learning Techniques. *International Journal of Pavement Research and Technology* 2023;16. <https://doi.org/10.1007/s42947-021-00119-w>.
- [22] Wang C, Xu S, Yang J. Adaboost Algorithm in Artificial Intelligence for Optimizing the IRI Prediction Accuracy of Asphalt Concrete Pavement. *Sensors* 2021;21:5682. <https://doi.org/10.3390/s21175682>.
- [23] Abaza KA. The Use of IRI Data in Developing Optimal Pavement Rehabilitation Plan for Developing Countries: Palestine as a Case Study 2023. <https://doi.org/10.21203/rs.3.rs-3247799/v1>.
- [24] Rifai M. Evaluation of Functional and Structural Conditions on Flexible Pavements Using Pavement Condition Index (PCI) and International Roughness Index (IRI) Methods. *E3s Web of Conferences* 2023;429:05011. <https://doi.org/10.1051/e3sconf/202342905011>.
- [25] Chen K, Torbaghan ME, Thom N, Faramarzi A. Physics-guided neural network for predicting international roughness index on flexible pavements considering accuracy, uncertainty and stability. *Eng Appl Artif Intell* 2025;142. <https://doi.org/10.1016/j.engappai.2024.109922>.
- [26] Chen L, Li H, Wang S, Shan F, Han Y, Zhong G. Improved model for pavement performance prediction based on recurrent neural network using LTPP database. *International Journal of Transportation Science and Technology* 2024. <https://doi.org/10.1016/j.ijtst.2024.08.005>.
- [27] Kwon K, Choi H, Pham K, Kim S, Bae A. Influence Analysis of Pavement Distress on International Roughness Index Using Machine Learning. *KSCE Journal of Civil Engineering* 2024. <https://doi.org/10.1007/s12205-024-0093-9>.
- [28] Oktopianto Y, Antonius A, Rochim A. An Artificial Neural Network Approach for Predicting Pavement Distress: A Case Study Toward Sustainable Road Maintenance. *Advance Sustainable Science, Engineering and Technology (ASSET)* 2025;7. <https://doi.org/10.26877/asset.v7i3.2133>.
- [29] Ali AA, Esekbi M, Sreh M. Development of International Roughness Index From Pavement Distress Using Artificial Neural Networks (ANNs). *International Journal of Advanced Engineering and Business Sciences* 2023;4:179–92. <https://doi.org/10.21608/ijaebs.2023.165192.1054>.
- [30] Plati C, Armeni A, Kyriakou C, Asoniti D. AI for Predicting Pavement Roughness in Road Monitoring and Maintenance. *Infrastructures (Basel)* 2025;10. <https://doi.org/10.3390/infrastructures10070157>.
- [31] Sun Y, Gao Q, Li F, Du Y. Distress-Level Prediction of Pavement Deterioration with Causal Analysis and Uncertainty Quantification. *Applied Sciences (Switzerland)* 2025;15. <https://doi.org/10.3390/app152011250>.
- [32] Famewo BG, Shokouhian M. A Review of Pavement Performance Deterioration Modeling: Influencing Factors and Techniques. *Symmetry (Basel)* 2025;17. <https://doi.org/10.3390/sym17111992>.
- [33] Afridi MA, Erlingsson S. Enhancing municipal pavement condition predictions using machine learning models. *Journal of Road Engineering* 2026. <https://doi.org/10.1016/j.jreng.2025.10.002>.
- [34] Basnet KS, Shrestha J, Shrestha R. Artificial Neural Networks and Multiple Linear Regression in Pavement Deterioration Forecasting. *Journal on Transportation System and Engineering* 2025;1. <https://doi.org/10.3126/jotse.v1i2.87728>.
- [35] Rosada A, Arliansyah J, Buchari E. Evaluation Pavement Deteriorating Condition on Surface Distress Index (SDI) Data Using Radial Basis Function Neural Networks (RBFNN). *J. Phys. Conf. Ser.*, vol. 1198, 2019. <https://doi.org/10.1088/1742-6596/1198/3/032008>.