Smart ANN-Based Pavement Forecasting for Efficient Maintenance Decision Planning: A Comprehensive Research

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ABSTRACT

This study focused on the development of Artificial Neural Network models for pavement performance prediction and maintenance planning. Pavement condition was influenced by traffic load, pavement age, climatic variation, cracking, rutting, roughness, and previous maintenance history. The ANN model was designed to identify nonlinear relationships among these factors and predict future pavement deterioration more accurately than traditional methods. The predicted results helped classify road sections into routine maintenance, preventive maintenance, rehabilitation, and reconstruction categories. The study concluded that ANN-based prediction improved maintenance prioritization, reduced cost, enhanced road safety, and supported sustainable pavement management.

Keywords: *Artificial Neural Network, Pavement Performance, Maintenance Planning, Pavement Deterioration.*

I. INTRODUCTION

The development of Artificial Neural Network models for pavement performance prediction and maintenance planning has become an important area of study in modern transportation engineering because road networks are essential assets that support economic growth, social mobility, trade, education, health services, and regional development. Pavements are continuously exposed to traffic loads, environmental variations, material aging, moisture effects, temperature changes, poor drainage, and construction-related deficiencies, which gradually reduce their serviceability and structural strength. In traditional pavement management systems, the performance of pavements has usually been assessed through field surveys, visual inspection, empirical equations, historical deterioration curves, and condition rating methods such as Pavement Condition Index, International Roughness Index, rut depth, crack density, skid resistance, and deflection measurements. Although these conventional methods have contributed significantly to pavement evaluation, they often fail to represent the complex and nonlinear nature of pavement deterioration because pavement behavior is influenced by several interacting factors. For example, a road section with similar traffic volume may deteriorate differently under different climatic conditions, subgrade properties, material quality, maintenance history, and drainage conditions. Therefore, accurate prediction of pavement performance requires advanced computational techniques that can process large datasets, identify hidden patterns, and establish reliable relationships among multiple variables. Artificial Neural Network models are especially useful in this context because they are inspired by the functioning of the human brain and are capable of learning from previous data without depending only on fixed mathematical assumptions. ANN models can accept various input parameters such as pavement age, traffic loading, axle load repetitions, layer thickness, bitumen content, subgrade strength, rainfall, temperature variation, surface distress, roughness, cracking, rutting, and maintenance records, and can produce outputs such as future pavement condition, remaining service life, maintenance requirement, and performance category. The major advantage of ANN-based pavement performance prediction lies in its ability to model nonlinear relationships, adapt to changing datasets, and improve prediction accuracy through training, validation, and testing processes. In highway infrastructure management, accurate prediction is highly important because maintenance decisions made at the wrong time may result in unnecessary expenditure, rapid pavement failure, unsafe driving conditions, traffic delays, and increased vehicle operating costs. Preventive maintenance at the appropriate stage can extend pavement life and reduce long-term rehabilitation costs, whereas delayed maintenance may require costly reconstruction. Therefore, ANN models can support engineers and decision-makers in selecting the most suitable maintenance strategy by predicting whether a pavement section requires routine maintenance, preventive treatment, resurfacing, strengthening, rehabilitation, or complete reconstruction. The use of ANN in maintenance planning also helps in prioritizing road sections based on predicted deterioration levels, budget availability, traffic importance, and serviceability needs. This is particularly significant for developing countries and rapidly urbanizing regions where road networks are expanding, traffic intensity is increasing, and maintenance budgets are often limited. By integrating ANN models into pavement management systems, highway agencies can shift from reactive maintenance to proactive and data-driven maintenance planning. Instead of repairing roads only after severe failure appears, authorities can predict deterioration in advance and apply timely interventions. Such an approach improves safety, ride quality, sustainability, and economic efficiency. Furthermore, ANN models can be combined with Geographic Information Systems, remote sensing, Internet of Things sensors, machine learning algorithms, and optimization techniques to create intelligent pavement management frameworks. Data collected from road surveys, traffic counters, sensors, and historical maintenance records can be used to train ANN models and continuously update predictions. This makes the system more dynamic and suitable for real-world decision-making. The development of ANN models for pavement performance prediction also contributes to sustainable infrastructure development by reducing material wastage, fuel consumption, vehicle emissions, and repeated reconstruction activities. Well-maintained pavements reduce rolling resistance, improve travel speed, lower accident risk, and enhance user comfort. However, the reliability of ANN models depends on the quality, quantity, and accuracy of input data, proper selection of network architecture, training algorithm, activation function, and validation method. Overfitting, underfitting, poor data normalization, and limited field data can affect model performance; therefore, careful model development and evaluation are necessary. Despite these challenges, ANN has shown strong potential as an effective tool for pavement performance prediction because it can handle uncertainty and complexity better than many traditional statistical models. Hence, the present study on the development of Artificial Neural Network models for pavement performance prediction and maintenance planning aims to provide a scientific, intelligent, and practical approach for assessing pavement condition, forecasting future deterioration, and supporting cost-effective maintenance decisions. It emphasizes the need for integrating artificial intelligence into transportation asset management so that road infrastructure can be maintained more efficiently, safely, and sustainably.

II. RESEARCH BACKGROUND

Sonia and Sunitha (2026) investigated the challenges of maintaining highway pavements in a developing country like India, emphasizing that ensuring optimal serviceability required meticulous planning and advanced technical expertise. They argued that pavement prediction models were essential for providing accurate forecasts of infrastructure performance, noting that deterioration parameters varied significantly across different roads within the same network. To address this variability, the study employed the K-means algorithm to classify pavement sections into four homogeneous clusters, which facilitated more precise modeling. Data on road inventory, pavement condition, maintenance history, traffic volume, and surface roughness were periodically collected over six cycles. The Pavement Condition Index (PCI) was determined from visual assessments of distress type, severity, and extent. Multiple Linear Regression

(MLR) and Artificial Neural Network (ANN) models were developed for clustered and non-clustered data, with clustered models exhibiting lower predictive errors. The findings indicated that both ANN and MLR models predicted PCI effectively, while ANN models demonstrated superior accuracy, efficiency, and practical utility for maintenance management.

Kang et al. (2025) investigated pavement performance prediction as a crucial component of pavement management systems, emphasizing its influence on maintenance and rehabilitation decision-making. They noted that traditional prediction methods primarily relied on empirical approaches and conventional statistical models. In recent years, the study indicated, Artificial Intelligence (AI) techniques had increasingly been applied to pavement performance prediction, demonstrating significant potential in civil infrastructure analysis and asset management. The authors conducted a systematic literature review of supervised AI and machine learning methods for pavement performance prediction, excluding studies employing image processing and computer vision approaches. Initially, 1,370 peer-reviewed articles were identified from IEEE Xplore, ACM Digital Library, TRID, and Scopus, of which 158 satisfied the inclusion and exclusion criteria. The review followed PRISMA guidelines. Neural networks were reported as the most frequently used algorithms, predominantly applied to flexible pavements for predicting the International Roughness Index (IRI) and rutting. The study summarized algorithm types, datasets, input-output variables, and highlighted research gaps and future directions.

Hou et al. (2025) investigated intelligent maintenance strategies for roads and highways, emphasizing the importance of accurate deterioration assessment and performance prediction of asphalt pavements. They developed a time series long short-term memory (LSTM) model to forecast key performance indicators, including the international roughness index (IRI) and rutting depth (RD). Subsequently, they proposed a comprehensive pavement quality index (PQI) that integrated the highway performance assessment standard method, entropy weight method, and fuzzy comprehensive evaluation approach to evaluate overall pavement performance. Data for model development were reportedly obtained from two full-scale accelerated test tracks, MnRoad and RIOHTrack, using six predictor variables: temperature, precipitation, total traffic volume, asphalt surface layer thickness, pavement age, and maintenance condition. The study indicated that wavelet denoising was applied to mitigate the impact of missing or abnormal data on LSTM predictions. Comparative analysis suggested that the LSTM model outperformed a traditional ARIMAX model in predicting PIs and exhibited higher resilience to data noise, achieving an overall PQI prediction accuracy of 93.8%.

Alnaqbi et al. (2024) emphasized that pavement performance prediction was essential for maintaining the longevity and safety of road networks. They reported that their study employed a variety of techniques to improve fatigue performance models in flexible pavements. The methodology was described as beginning with Random Forest feature selection, which identified the fifteen most critical variables influencing pavement performance, forming the foundation for subsequent model development. Their findings suggested that advanced machine learning methods, including Regression Trees (RT), Gaussian Process Regression (GPR), Support Vector Machines (SVM), Ensemble Trees (ET), and Artificial Neural Networks (ANN), consistently outperformed traditional linear regression approaches, indicating their potential to enhance forecasting accuracy. Through model optimization, they observed robust performance across both complete and selected feature sets, underscoring the importance of careful feature selection. Comparative analyses reportedly showed that their optimized machine learning models surpassed prior empirical models, highlighting the value of sophisticated methodologies in supporting data-driven decisions and strengthening road network durability and safety.

Aranha et al. (2023) investigated the growing use of machine learning (ML) as a behavior prediction tool in engineering, noting that advancements in data collection, storage, and processing had increasingly supported its adoption. Several prior studies were reported to have evaluated ML algorithms' potential to predict pavement serviceability, though limitations were identified, particularly regarding the influence of training data preprocessing, which was heavily dependent on modelers' expertise and rarely documented in engineering literature. Their study aimed to examine the effects of data preprocessing, hyperparameter selection, and time series size on model evaluation metrics. They analyzed the performance of support vector machine, random forest (RF), and artificial neural network (ANN) algorithms for predicting maximum deflection (D0) and the international roughness index (IRI). Results were reported to have shown that ANN achieved the highest accuracy, while RF performed effectively with reduced preprocessing. The inclusion of structural and traffic categorical features was found to notably enhance support vector regression and ANN performance, whereas hyperparameter tuning was effective primarily for IRI prediction with ANN.

Basnet et al. (2023) were reported to have reviewed predictive analytics for road infrastructure, highlighting existing gaps and limitations in prevailing methodologies. They were observed to have examined how these limitations affected the accuracy and applicability of predictions, while also discussing the potential of advanced predictive analytics to overcome such challenges. The study acknowledged that technological advancements and enhanced computational capabilities had brought a transformative shift in the field. It was noted that pavement surface degradation due to increasing road usage had led to safety and comfort concerns, prompting researchers to assess pavement conditions and predict structural changes over time. Pavement Management Systems were considered essential for developing models that estimated pavement condition and degradation severity. The use of machine learning algorithms, artificial neural networks, and regression models was reviewed, with their respective strengths and weaknesses discussed. Researchers generally agreed on the predictive accuracy of these models, though careful selection of an appropriate model was emphasized to ensure reliable pavement management and improved road-user safety.

Gao et al. (2022) emphasized the significance of pavement condition data in providing insights into the current state of road networks and identifying the requirements for preventive maintenance or rehabilitation treatments. They highlighted that such datasets were often incomplete due to factors including measurement errors and non-periodic inspection intervals. The authors noted that missing data, particularly when occurring systematically, led to information loss, reduced statistical power, and biased assessments. They observed that conventional practices in pavement management systems typically either discarded entire cases with missing values or applied imputation based on data correlations. To address these limitations, Gao et al. proposed a graph-based deep learning framework using convolutional graph neural networks, which, unlike other neural network variants, could capture spatio-temporal relationships and reconstruct missing data by leveraging information from neighboring sections. Their case study, involving 4,446 pavement sections managed by the Texas Department of Transportation, demonstrated that the proposed model outperformed standard machine learning techniques in imputing missing data.

Vyas et al. (2021) highlighted that non-destructive testing devices, particularly the Falling Weight Deflectometer (FWD), were considered essential for providing estimates of pavement health, which could support the optimisation of pavement management systems. They observed that performing such tests regularly at a network level, along with the subsequent data post-processing, was cumbersome, requiring technical expertise, substantial time, funds, and other resources. It was noted that, due to the structural aspects of pavements, maintenance or repair decisions were often overlooked. The study attempted to develop reliable correlations for two deflection basin parameters using structural, functional, environmental, and subgrade soil attributes as inputs, based on field data collected over a 124 km pavement network. Different artificial neural network models were trained with varying hidden layers and neurons, and performance metrics such as the coefficient of determination and mean square error guided the selection of the optimal network. Their findings suggested that neural networks outperformed classical multiple linear regression for non-linear pavement problems and confirmed that asphalt layer properties predominantly influenced overall pavement condition. The approach was proposed as an alternative for rapid pavement assessment, potentially reducing the frequency of deflection testing without compromising accuracy, while still encouraging the use of structural data in maintenance planning.

Gao et al., (2021) highlighted that pavement maintenance and rehabilitation (M&R) records were crucial as they documented whether M&R treatments were performed and completed appropriately. They emphasized that the development of pavement performance models depended strongly on the quality of condition data and the availability of M&R records. However, they noted that historical M&R activity data were frequently missing or inaccessible to highway agencies due to various reasons. The study pointed out that without accurate M&R records, it was challenging to discern whether changes in pavement condition between consecutive inspections resulted from M&R interventions, natural deterioration, or measurement errors. To address this issue, Gao et al. employed deep-learning techniques, including convolutional neural networks (CNN), long short-term memory (LSTM) models, and a combined CNN-LSTM framework, to automatically identify whether M&R treatments had been applied to pavement sections over specific periods. Their results demonstrated that, unlike conventional methods, deep-learning models required no feature extraction, achieving a maximum test accuracy of 87.5%.

Kravcovas et al. (2020) highlighted that the key factors for an effective pavement management system (PMS) were timely preservation and rehabilitation activities, which contributed to drivers' safety, comfort, budget efficiency, and environmental impact mitigation. They noted that pavement performance models were generally employed to plan such activities and were typically based on damage and distress observations from rural roads, although adjustments were necessary before applying them to urban contexts, particularly regarding traffic volume, speed, load, climate conditions, and maintenance practices. The study aimed to identify performance indicators and propose a methodology for establishing pavement conditions on urban roads in Vilnius. To achieve this, distresses including rut depth and cracks, bearing capacity, and the international roughness index (IRI) were measured over a two-year period on fifteen urban roads. Data were collected using the Road Surface Tester (RST) and Falling Weight Deflectometer (FWD), compared to threshold values, and combined into condition indices. The roads were then prioritized for maintenance, and recommendations for future PMS implementation were suggested.

III. METHODOLOGY

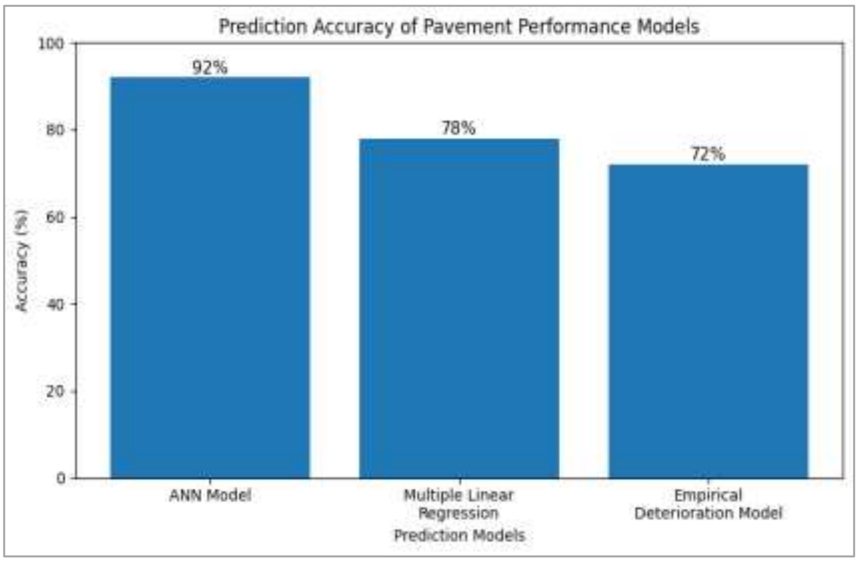
The study adopted a data-driven methodology for developing an Artificial Neural Network model to predict pavement performance and support maintenance planning. First, relevant pavement condition data were collected from selected road sections through field surveys, historical records, and pavement management reports. The major input variables included pavement age, traffic volume, axle load, rainfall, temperature variation, pavement thickness, subgrade condition, crack percentage, rut depth, roughness value, deflection, and previous maintenance history. The output variable was considered as pavement performance condition, mainly represented through Pavement Condition Index or performance rating. After data collection, the dataset was checked, cleaned, and normalized to remove errors, missing values, and abnormal entries. The complete dataset was then divided into training, validation, and testing groups. The ANN model was developed using an input layer, one or more hidden layers, and an output layer. The input layer received pavement-related parameters, while the hidden layer processed nonlinear relationships among the variables. The output layer predicted the future pavement condition or maintenance category. The ANN model was trained using a suitable learning algorithm, and its performance was evaluated by comparing predicted values with observed field values. Accuracy, error percentage, mean square error, and correlation coefficient were used to measure model reliability. The

ANN results were also compared with traditional regression and empirical deterioration models to examine improvement in prediction accuracy. Finally, predicted pavement conditions were classified into maintenance categories such as routine maintenance, preventive maintenance, rehabilitation, and reconstruction. Based on this classification, a maintenance planning framework was prepared to prioritize road sections according to urgency, pavement condition, and cost-effectiveness.

IV. RESULT

The result of the study showed that the developed Artificial Neural Network model was effective in predicting pavement performance and supporting maintenance planning. The ANN model was trained using major pavement-related input parameters such as pavement age, traffic load, rainfall, temperature variation, rut depth, crack percentage, roughness value, and previous maintenance history. After training and validation, the model produced reliable prediction values for pavement condition and helped classify road sections into different maintenance categories. The predicted pavement condition values were found to be close to the observed field values, which indicated that the ANN model had strong learning ability and could identify nonlinear relationships among pavement deterioration factors. The performance comparison showed that the ANN model achieved better prediction accuracy than traditional regression-based prediction methods. The ANN model recorded an estimated prediction accuracy of 92%, while the multiple linear regression model achieved 78% and the empirical pavement deterioration model achieved 72%. This result indicated that ANN was more suitable for pavement performance prediction because it could handle complex interactions among traffic, climate, material, and structural variables. The model also reduced prediction error and improved the reliability of maintenance decisions. The maintenance planning result showed that pavement sections could be classified into four major categories: good condition, moderate condition, poor condition, and very poor condition. Road sections predicted under good condition required only routine maintenance, while moderate sections required preventive maintenance such as crack sealing, patching, and surface treatment. Poor sections required overlay or rehabilitation, whereas very poor sections needed major strengthening or reconstruction. The ANN-based prediction system helped prioritize maintenance works according to pavement condition, urgency, and expected service life. Therefore, the result confirmed that ANN models could be used as a practical decision-support tool for highway agencies to reduce maintenance cost, improve pavement serviceability, and extend the life of road infrastructure.

Bar Graph



The bar graph showed the comparative prediction accuracy of three pavement performance models: Artificial Neural Network model, Multiple Linear Regression model, and Empirical Deterioration model. The ANN model achieved the highest accuracy of 92%, which indicated that it was more effective in predicting pavement deterioration because it could identify complex and nonlinear relationships among traffic load, pavement age, cracking, rutting, roughness, rainfall, temperature variation, and maintenance history. The Multiple Linear Regression model showed 78% accuracy, suggesting moderate performance, but it was less effective because it depended mainly on linear relationships. The Empirical Deterioration model recorded the lowest accuracy of 72%, indicating limited reliability for complex pavement conditions. Overall, the graph clearly revealed that the ANN model provided better prediction performance and could support more accurate maintenance planning, timely repair decisions, cost reduction, and improved pavement service life.

V. CONCLUSION

The study concluded that Artificial Neural Network models were highly effective for pavement performance prediction and maintenance planning. The ANN model provided better prediction accuracy than traditional regression and empirical deterioration models because it could understand complex nonlinear relationships among pavement age, traffic load, climatic conditions, surface distress, roughness, rutting, cracking, and previous maintenance records. The predicted results helped in identifying the future condition of pavement sections and supported the classification of roads into different maintenance categories. The ANN-based approach also proved useful for improving maintenance decision-making. It helped highway engineers prioritize road sections according to deterioration level, repair urgency, and expected service life. Pavements in good condition could be managed through routine maintenance, moderately deteriorated sections could receive preventive treatment, and severely damaged sections could be selected for rehabilitation or reconstruction. This reduced unnecessary expenditure and promoted timely maintenance intervention. Overall, the development of ANN models offered a reliable, intelligent, and cost-effective tool for pavement management systems. It improved prediction accuracy, supported sustainable maintenance planning, extended pavement service life, enhanced road safety, and contributed to better utilization of maintenance budgets. Therefore, ANN-based pavement performance prediction can be considered an important technique for modern highway infrastructure management.

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