Development of Statistical Model For Predicting Flexible Pavement Deterioration Due To Traffic Loading

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Abstract

Flexible pavements are critical transportation components but are highly susceptible to deterioration caused by traffic loading, pavement conditions, and environmental factors. This study develops a predictive model to estimate pothole deterioration rates using traffic count and pavement structural strength. Data were collected from the Talba-Mandela road in Minna, Niger State Nigeria, over 14 weeks including weekly measurements of pothole volume, traffic counts and pavement structural numbers. A multiple linear regression model was calibrated, achieving a R^2 of 80.8%. Validation indicated less than 10% deviation between observed and predicted data. These findings provide a data-driven approach to optimizing pavement maintenance schedules, reducing costs, and improving road durability.

Keywords: Flexible pavements; Statistical Modeling; Pavement Deterioration; Predictive Modeling; Structural Number; Traffic Loading.

1. Introduction

Roads form the backbone of economic development, enabling the movement of goods and services. However, the frequent deterioration of flexible pavements due to traffic and environmental stressors poses significant challenges, especially in developing countries like Nigeria. Poorly maintained roads lead to increased vehicle operating costs, reduced safety, and inefficient transportation systems. Traditional maintenance practices are often reactive and resource-intensive, highlighting the need for predictive tools to optimize road management.

Traffic loading, characterized by the weight, frequency, and types of vehicles, exerts significant stress on pavements, accelerating their wear and tear. Environmental factors such as temperature fluctuations, precipitation further compound this deterioration (Buhari *et al.*, 2018). Material properties, including the quality of asphalt and base layers, play a critical role in determining pavement resilience. Given these complexities, accurate prediction models are essential for proactive pavement management.

Statistical models have emerged as promising tools for predicting pavement performance. By analyzing historical data and identifying patterns, these models can forecast future pavement conditions, enabling timely interventions and cost-effective maintenance (Agunwamba et al., 2024). This research aims to develop a comprehensive statistical model that incorporates both deterministic and stochastic elements to predict flexible pavement deterioration due to traffic loading.

The persistent issue of pavement deterioration, particularly pothole development, affects the functionality and safety of roadways. Existing maintenance strategies lack the predictive capability to address these challenges proactively, often leading to inefficient resource allocation and escalating repair costs Therefore This study aims to develop a statistical model that integrates traffic volume and pavement structural parameters to predict pothole deterioration rates. The objective is to provide actionable insights for proactive maintenance planning and resource optimization, particularly in regions with limited infrastructure budgets.

2. Literature Review

Flexible pavement deterioration in Nigeria has been extensively studied, with a primary focus on the impact of traffic loading (Irokwe et al., 2022; Owolabi et al., 2012; Obeta & Njoku, 2016). The relationship between traffic intensity and pavement degradation is well-documented, underscoring its significance in pavement design and maintenance (Adetoyinbo et al., 2023). Several studies have examined how increasing traffic volumes and axle loads accelerate pavement distress, leading to failures such as rutting, cracking, and pothole formation.

Owolabi et al. (2012) investigated the deterioration of flexible pavements in Lagos, Nigeria, emphasizing the role of traffic-induced stress. Their findings revealed that heavy truck traffic significantly accelerated pavement failure, resulting in surface cracking and potholes. This observation is particularly relevant to Minna, where the presence of heavy vehicles and increasing traffic volumes present similar challenges. In another study, Michael et al. (2019) utilized traffic volume and axle load data to develop a deterioration model for flexible pavements in southwestern Nigeria. They found that pavement deterioration rates were significantly influenced by traffic loads, especially where material properties were suboptimal. This underscores the necessity of incorporating local traffic characteristics and material behavior into predictive models for more accurate performance assessments.

Similarly, Maduagwu and Ugwu (2022) examined the impact of traffic-induced strain on flexible pavements, demonstrating that repetitive loading leads to gradual structural damage and fatigue failure. Their research employed regression analysis to establish a statistical correlation between traffic loading and pavement distress, providing a quantitative basis for predicting pavement performance in Nigerian road networks.

In Minna, Niger State, Amadi et al. (2013) conducted a forensic investigation into premature pavement failures. Their study identified traffic loading, inadequate drainage, and material deficiencies as primary contributors to pavement deterioration. The authors emphasized the critical need for accurate traffic data collection to improve pavement life predictions and optimize maintenance strategies.

Beyond traffic loading, environmental factors such as rainfall, temperature fluctuations, and soil moisture content also interact with traffic-induced stress to influence pavement performance. Bhandari et al. (2021) highlighted the importance of integrating climate and traffic data into performance prediction models, demonstrating how such an approach enhances the accuracy of forecasting pavement deterioration under varying environmental conditions.

Recent advancements in predictive modeling have incorporated sophisticated statistical and machine learning techniques for pavement deterioration assessment. (Shafiee et al. 2024) developed a neural network-based model to predict flexible pavement performance under different traffic and climatic conditions. Their model exhibited high predictive accuracy, proving particularly useful for evaluating pavement deterioration in urban areas with dynamic traffic and environmental variations.

Despite the wealth of research in this area, there remains a gap in localized studies focusing on Minna, Niger State. Capturing the unique traffic patterns and environmental conditions of the region is essential for refining statistical models and optimizing pavement management strategies. The reviewed studies emphasize the significance of traffic loading in pavement deterioration across Nigeria, with statistical models providing valuable predictive tools.

However, the accuracy of these models can be enhanced by incorporating region-specific data. Future research should prioritize the development of localized predictive models tailored to Minna's traffic and environmental conditions, thereby informing more effective pavement design, maintenance, and rehabilitation strategies.

3.0 Methods

3.1 Data Collection and Distribution of Pavement Condition

Data were collected from the Talba-Mandela road over 14 weeks in 2024. The dataset included:

Pothole Measurements: The length, width, and depth of two selected potholes were recorded daily. Volumes were calculated using the formula: Volume (m^3) = Length (m) x Width (m) x Depth (m) in accordance with BS EN 13108-21:2021 (Bituminous mixtures- Guidelines for condition assessment).

The model calibration involved gathering parameters over a 14-week period, with an average interval of 24 hours for the pothole deterioration data. IBM SPSS Statistics (Version 25) utilized a numerical ranking system that assigned relative weights to the factors contributing to pavement deterioration at the pothole locations. The potholes on the selected sections were aggregated into two sizes.

Traffic Volume: Vehicles were manually counted daily for six hours (7:00 AM to 10:00 AM and 4:00 PM to 7:00 PM). Traffic was categorized into motorcycles, tricycles, passenger cars, buses, and trucks. This was carried out by manual count procedures given in BS7669-1:1994 (Traffic count- manual method.

Pavement Structural Number (SN): SN values were calculated from field measurements of asphalt and base course thicknesses to represent pavement strength as outlined in BS EN 1991-1-1:2002 (Eurocode1-Actions and Structures).

3.2 Development of Regression Model

Pavement deterioration was modeled using a multiple linear regression framework using the guidelines outlined in BS ISO 3534-1 with traffic count (TC) and structural number (SN) as independent variables.

The general form of the model is

$$DR = \beta0 + \beta1(TC) + \beta2(SN) \quad (1)$$

Pothole deterioration rates DR were calculated based on changes in pothole volumes over time.

Data were collected over 14 weeks, including weekly pothole measurements (length, width, and depth), traffic counts, and structural number values derived from field surveys.

The model was calibrated using SPSS, and coefficients were estimated by maximizing the likelihood function. Observed and predicted pothole deterioration rates were compared to validate the model.

3.3. Validation: Model accuracy was assessed using comparisons between observed and predicted pothole volumes. These were evaluated according to Standards outlined in BS ISO 5725-1:2003. Residual analysis was performed to examine variance and ensure consistency with regression assumptions.

3.4 Data Aggregation: Weekly data were aggregated to calibrate the model and evaluate the relationship between traffic loading, structural strength, and pothole deterioration in line with statistical data handling Practices from BS ISO 10241-1:2011.

4.0 Results and Discussions

Traffic Volume Distribution:

Figure 4.1 below shows the average traffic distribution after conducting the traffic survey.

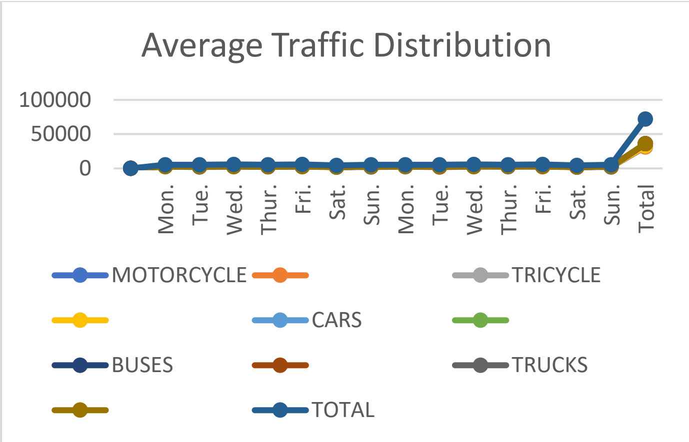

Figure 1: Graph showing Average Traffic Distribution

Traffic data revealed that motorcycles dominated, accounting for 87.35% of total vehicles. Trucks and buses constituted a smaller fraction, reflecting limited heavy-load traffic. Fluctuations in daily total vehicle counts highlight variations in traffic demand, likely influenced by weekday and weekend activities. Furthermore as Shown in Figure 2, the traffic count in relation to pothole data on the road is shown.

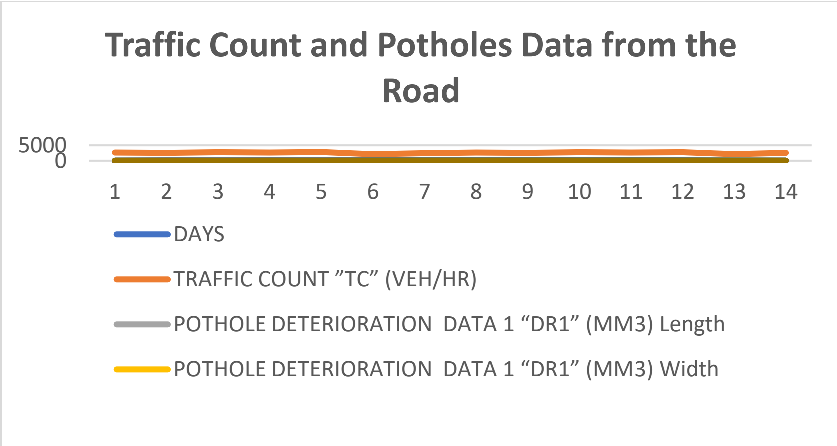

Figure 2: Graph showing Traffic Count and selected Potholes Data from the Road

The deterioration of selected potholes was monitored over 14 weeks, with pothole volume increasing as traffic loading intensified. The structural number (SN) remained constant at 27.00 for the first seven weeks and increased slightly to 27.50 thereafter as shown in Table 1. This suggests that while pavement strength plays a role, it alone cannot mitigate the rate of deterioration without intervention measures. Pothole sizes showed consistent growth over 14 weeks. Higher traffic counts were correlated with larger increases in pothole sizes, emphasizing traffic loading as a significant factor in pavement deterioration. Pothole size 1 deteriorated more rapidly than Pothole size 2, potentially due to differences in initial structural conditions.

The observed trend in pothole deterioration aligns with previous studies indicating that pavement damage progresses non-linearly with increasing traffic loading. The findings suggest that despite moderate structural integrity, continual vehicular loading induces distress, necessitating timely maintenance interventions (Bhandari et al., 2022).

Table 1**: Dependent and Independent Variables for the Calibration of Potholes Model**

WEEKS	INDEPENDENT VARIABLES		INSITU DETERIORATION RATE (DEPENDENT VARIABLE)	
	Traffic count ”TC” (Veh/hr)	Structural number “SN”	Sizes 1 (Pothole)	Size 2 (Pothole)
1	2672	27.00	0.52981	0.34483
2	2569	27.00	0.53505	0.34859
3	2724	27.00	0.54230	0.35545
4	2624	27.00	0.55950	0.36542
5	2823	27.00	0.57302	0.38405
6	2112	27.00	0.58219	0.38758
7	2484	27.00	0.59096	0.39161
8	2659	27.50	0.60465	0.39514
9	2508	27.50	0.61261	0.41029
10	2769	27.50	0.62474	0.41340
11	2655	27.50	0.63002	0.42848
12	2805	27.50	0.63848	0.43168
13	2147	27.50	0.64765	0.43648
14	2502	27.50	0.65651	0.43755

4.2 Regression Model Calibration

The calibrated regression models for the two sizes of potholes were as follows:

Pothole 1: DR = -3.220 – 4.041x10-5(TC) – 0.144(SN). (2)

Pothole 2: DR = -2.457 – 3.102x10-5(TC) – 0.108(SN) (3)

Where; DR = Deterioration Rate; TC = Traffic Loading; SN = Structural Number

4.3 Model Validation

The predictive model was formulated using traffic count and pavement strength as independent variables. The regression analysis yielded high coefficients of determination (R = 80.80% and 76.90% for Potholes sizes 1 and 2, respectively), indicating strong predictive capability. The significance of structural number ($p < 0.001$) underscores its importance in deterioration modeling, while traffic loading, though statistically significant, had a lower impact coefficient. This suggests that, while traffic is a primary driver of distress, underlying pavement structural deficiencies amplify the deterioration rate.

Validation results demonstrated less than a 10% deviation between observed and predicted pothole volumes, confirming the model's reliability. Residual analysis showed minimal variance, with error distributions following expected patterns.

4.4 Model Performance Evaluation

A multiple linear regression analysis was conducted and the results are presented in section 4.2 above. The comparison between predicted and observed deterioration rates were used to validate the models as shown in Table 2, supporting the model's accuracy validated by residual analysis according to BS ISO 5725-1:2023.

Table 2: **Comparison of In-Situ and Predicted Road Pavement Deterioration**

	POTHOLE SIZE 1				**POTHOLE SIZE 2**			
WEEKS	Insitu Deterioration	Model Deterioration	Difference	% Difference	Insitu Deterioration	Model Deterioration	Difference	% Difference
1	0.52981	0.55496	0.0251	4.75	0.34483	0.36513	0.0203	5.89
2	0.53505	0.55912	0.0241	4.50	0.34859	0.36833	0.0197	5.66
3	0.54230	0.55286	0.0106	1.95	0.35545	0.36352	0.0081	2.27
4	0.55950	0.55690	0.0026	0.47	0.36542	0.36662	0.0012	0.33

5	0.57302	0.54886	0.0242	4.22	0.38405	0.36045	0.0236	6.15
6	0.58219	0.57759	0.0046	0.79	0.38758	0.38251	0.0051	1.31
7	0.59096	0.56255	0.0284	4.81	0.39161	0.37097	0.0206	5.27
8	0.60465	0.62739	0.0227	3.76	0.39514	0.41934	0.0242	6.13
9	0.61261	0.63349	0.0209	3.41	0.41029	0.42403	0.0137	3.35
10	0.62474	0.62294	0.0018	0.29	0.41340	0.41593	0.0025	0.61
11	0.63002	0.62755	0.0025	0.39	0.42848	0.41947	0.0090	2.10
12	0.63848	0.62149	0.0170	2.66	0.43168	0.41481	0.0169	3.91
13	0.64765	0.64808	0.0004	0.07	0.43648	0.43523	0.0013	0.29
14	0.65651	0.63373	0.0228	3.47	0.43755	0.42421	0.0133	3.05

The comparison between in-situ and predicted deterioration shows percentage differences below 10% in all cases, reinforcing the model's reliability. The lowest deviation (0.07%) and highest deviation (6.15%) suggest that while the model is robust, variations in environmental conditions and material properties could introduce minor discrepancies. These findings align with literature advocating for multi-factor predictive models incorporating environmental and geotechnical parameters for enhanced accuracy.

5. Conclusions

The rise in the volume of road traffic contributes to both minor and substantial damage, leading to the degradation of pavement surfaces. Potholes emerged as the predominant form of failure identified on the surveyed road. Although the current rate of road deterioration, measured in mm^3, is gradual and it remains consistent.

The deterioration rate of the potholes was assessed and documented over fourteen (14) weeks. Additionally, other parameters examined included traffic count (vehicles per hour) and the structural number of pavement materials within the analyzed section.

A predictive mathematical model was formulated, yielding R^2 and adjusted R^2 values of 80.80% and 77.30%, respectively, with a significance level of 0.000. Validation results demonstrated the model's ability to predict pavement deterioration with considerable accuracy, as evidenced by a percentage difference of less than 10% between actual and predicted deterioration. Consequently, the model can be employed to update pavement condition data before each maintenance program, eliminating the necessity for extensive and time-consuming data collection on pavement conditions before maintenance activities, which can be both costly and time-intensive.

Future research should extend this model's application to broader datasets, exploring long-term trends and integrating additional environmental variables.

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