

Predictive Modeling of Flexible Pavement Deterioration Based on Traffic Volume and Service Age

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Abstract

The rapid increase in vehicle numbers on Indonesia's national and provincial roads has intensified traffic loads, accelerating flexible pavement deterioration. This condition is evident along the Ponorogo–Pacitan corridor, where pavement distress occurs earlier than the design service life. This study aims to develop a predictive model of flexible pavement deterioration based on traffic volume, expressed in passenger car units per hour (smp/h), and service age. Primary data were collected through field surveys using the Pavement Condition Index (PCI), while secondary data included traffic volume, maintenance history, and pavement age. A multivariate non-linear regression analysis was applied to examine variable relationships and construct the predictive model, which was validated using the coefficient of determination (R^2) and error metrics (MSE, RMSE). Results indicate that traffic volume and service age significantly accelerate pavement distress, with R^2 values exceeding 0.90, confirming the model's robustness. The proposed model captures the complex interaction between traffic growth and structural degradation, providing a scientific basis for maintenance planning. The novelty lies in integrating traffic volume and service age into a single non-linear predictive framework using regional road data from Indonesia. Findings highlight implications for sustainable pavement management, particularly in optimizing intervention timing for technical and economic efficiency, thereby enriching civil and environmental engineering literature and supporting data-driven infrastructure management.

Keywords: Flexible Pavement, Indonesia Regional Roads, Pavement Deterioration, Pavement Management, Predictive Modeling



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INTRODUCTION

The growth of motor vehicles in Indonesia over the past two decades has shown a highly significant trend (Hook & Replogle, 2022; Setiawan et al., 2021). The increase in both private vehicles and heavy-duty vehicles traversing national and provincial roads has posed major challenges in maintaining the quality and service life of road infrastructure. As the backbone of land transportation, roads not only function to connect production and consumption centers but also constitute a vital element in supporting economic and social activities as well as the distribution of goods and services (Hartatik et al., 2022). However, field realities indicate that many road sections, particularly on strategic corridors such as the Ponorogo–Pacitan section, experience deterioration much faster than their planned pavement design life (Lanori & Supriyanto, 2023). This phenomenon raises a fundamental

question: to what extent does the increasing traffic volume, especially from heavy vehicles, contribute to the deterioration of flexible pavements, and how does pavement service life accelerate this process? These questions are important not only for technical stakeholders but also for local governments that must allocate substantial budgets annually for recurrent road repairs.

Empirical evidence in the field shows that the design service life of flexible pavements, intended to last between 10–20 years, often survives only half of that period. Surveys on the Ponorogo–Pacitan section, for instance, revealed damage such as cracking, potholes, and surface deformation occurring within only 5–7 years after the last overlay. Such conditions inevitably lead to high maintenance costs and reduce both comfort and safety for road users. On the other hand, traffic volume on this corridor continues to increase, dominated by heavy freight vehicles transporting goods from industrial areas to the port of Pacitan. The dynamic loads of repetitive heavy traffic, when combined with service age factors, clearly accelerate the structural degradation of roads (Sari & Rahman, 2021). Therefore, a predictive, data-driven approach is required to understand deterioration patterns and to formulate more effective and sustainable maintenance strategies.

Studies on flexible pavement deterioration have long been conducted. General predictive models for road damage have been developed since the AASHTO Road Test, which serves as the basis for many road design guidelines worldwide (Asres et al., 2021; Shaikh et al., 2022). Subsequent studies emphasized that traffic volume, particularly overloaded vehicles, is one of the dominant factors accelerating road deterioration (Matini et al., 2022; Ziar et al., 2023). In the Indonesian context, the Directorate General of Highways has adopted the concept of the pavement condition index (PCI) as an indicator of road conditions (Lanori & Supriyanto, 2023). However, many studies remain focused on a single aspect, such as traffic volume or environmental factors, without accounting for their interaction with pavement service life.

Several studies indicate that high traffic loading accelerates both structural and functional damage. Liu et al. (2022, 2023) highlighted the importance of considering average daily traffic in road condition prediction models. Assogba et al. (2021) and Li et al. (2023) developed field-based deterioration models emphasizing the role of heavy vehicles in accelerating rutting and cracking. In Indonesia, Hariani et al. (2025) and Nurhidayat & Kamarudin (2024) identified that road sections with heavy vehicle volumes exceeding 1,000 pcu/hour tend to deteriorate faster. Meanwhile, research by Nurhasanah et al. (2024) and Pamungkas et al. (2025) confirmed that pavement conditions deteriorate exponentially with service age, particularly when adequate maintenance interventions are absent.

Moreover, predictive modeling approaches for road deterioration have evolved from simple linear models to non-linear and probabilistic models. Nyirandayisabye et al. (2022) and Shtayat et al. (2022) proposed the use of Markov chains to predict road condition transitions. Arya et al. (2021), Ou et al. (2025), and Wan et al. (2022) developed non-linear approaches to capture the more complex relationships among traffic, climate, and road deterioration.

Recent studies also emphasize the need for locally derived data to develop models more representative of regional geographic and traffic conditions (Ardian et al., 2025; Rachman et al., 2025). This is particularly relevant in Indonesia, where soil conditions, climate, and traffic patterns vary considerably across regions.

While previous contributions are valuable, most still treat traffic variables and pavement service life separately. Predictive models often focus on one dominant variable, such as traffic load or axle weight, while service life is regarded as a passive factor. In fact, pavement deterioration is not merely a direct function of traffic loading but also an accumulation of aging processes when pavements are left unmaintained. Studies by Guo & Zhang (2022) and Santos et al. (2021) have begun addressing the role of service life in deterioration models, yet its integration with traffic volume data remains limited. This indicates an urgent need to formulate a model capable of simultaneously capturing their interaction.

In this context, the present study seeks to provide a new perspective by integrating traffic volume and pavement service age into a single predictive model. Rather than viewing these two variables separately, this approach considers them as mutually reinforcing factors determining the extent of deterioration. A non-linear regression approach is employed, as it is better suited to represent the complex, non-linear relationships between traffic loading, pavement aging, and resulting damage. By testing the model on the Ponorogo–Pacitan section, this research also offers strong empirical evidence of how regional traffic dynamics in Indonesia affect pavement conditions.

The contribution of this study is both academic and practical. Academically, it enriches the literature in civil and environmental engineering by proposing an integrated predictive model based on local data. Practically, the findings may serve as a basis for local governments to design more timely road maintenance strategies, thereby reducing long-term costs and supporting sustainable infrastructure management. This approach also carries significant environmental implications: improved maintenance planning reduces material and energy wastage from repeated roadworks and lowers carbon emissions from construction activities.

This study aims to develop a predictive model of flexible pavement deterioration that integrates traffic volume and service age variables using a non-linear regression approach. The main objective is to address the practical challenges faced by local governments while also contributing academically to the advancement of pavement deterioration models. Ultimately, this research aspires to bridge the gap between theory and practice in road management, with sustainability principles as the guiding direction for transportation infrastructure development in Indonesia.

RESEARCH METHOD

This study was designed to accurately capture the relationship between traffic volume and pavement service life in relation to the deterioration rate of flexible pavements within the context of Indonesian regional roads. The Ponorogo District Boundary–Pacitan City

Boundary section, spanning 44.81 km, was selected as it represents an inter-regional corridor with high heavy-vehicle traffic and a diverse history of maintenance interventions, thereby providing the variation necessary for modeling. The site selection was preceded by preliminary observations that revealed pavement distresses occurring earlier than the design service life, rendering the section methodologically relevant as a natural laboratory to test sensitivity to changes in traffic loading and service age.

Primary data were collected through pavement condition surveys based on the Pavement Condition Index (PCI), in accordance with ASTM D6433 guidelines, which assess the type, severity, and extent of each distress within segmented sampling units (ASTM D6433-18). The road was divided into homogeneous segments based on road function, pavement width, and structural characteristics; representative sampling units of 50–100 m in length were selected from each segment to minimize spatial bias. Survey teams were trained to classify distresses (alligator cracking, longitudinal/transverse cracking, rutting, ravelling, patching, potholes) and to determine severity levels (low–medium–high). Quality control procedures included duplicate measurements on at least 10% of sampling units and photo-based geo-referenced audits. PCI scores were derived from deduct curves and converted into a road condition index (Nr) where necessary for consistency with Indonesian Highway Agency practices (Maryam et al., 2023).

Secondary data were compiled from road management agencies, including classified traffic volume data converted into passenger car units per hour (pcu/hour) using equivalency factors from the Indonesian Highway Capacity Manual (PKJI), thereby reducing traffic heterogeneity into a comparable variable across segments (Nadirgil, 2023). Service age was determined from the year of construction or last overlay, based on as-built records and maintenance logs, and cross-verified through technical interviews with field supervisors as well as archival reviews of maintenance works. Temporal consistency across sources was ensured by standardizing timestamps to the year of the condition survey so that each traffic–age pair represented equivalent cumulative exposure. Where available, supporting data such as rainfall and elevation were recorded for sensitivity checks but were excluded from the main model to maintain focus on the two key predictors.

Prior to modeling, all variables underwent preprocessing, including outlier detection (Cook's distance and leverage), treatment of missing values through corridor-level median imputation, and normalization where necessary to ensure algorithmic stability. Initial relationships among variables were explored using Pearson/Spearman correlations and simple partial dependence to identify potential functional forms. Predictive models were formulated using multivariate regression with candidate functional forms, linear, log-linear, exponential, and power, guided by mechanistic theories of pavement degradation and literature recommendations regarding load–deterioration non-linearity (S. Wang et al., 2023; Zou et al., 2022). The best-fitting model was selected based on the balance of bias–variance trade-offs, k-fold cross-validation, information criteria (AIC/BIC), and error performance metrics (MSE, RMSE) as well as coefficient of determination (R^2) on training data.

Validation was conducted in multiple layers to ensure generalizability. First, hold-out validation with segment-level data splits (e.g., 80/20) was used to obtain out-of-sample R^2 , MSE, and RMSE. Second, k-fold cross-validation was applied to examine parameter stability across subsets. Third, bootstrap resampling (1,000 iterations) was performed on residuals to derive confidence intervals for parameters and performance metrics, explicitly quantifying estimation uncertainty. Residual diagnostics were conducted to assess heteroscedasticity and unmodeled non-linearity; where residual patterns suggested remaining non-linearity, variable transformations or parsimonious non-linear basis functions were applied while preserving interpretability (Shehadeh et al., 2021). Limited external validation was carried out by comparing predictions against segments with different maintenance histories but similar traffic characteristics, serving as a sensitivity test to variations in service age.

RESULTS AND DISCUSSION

Existing Pavement Conditions on the Ponorogo–Pacitan Road Section

Field surveys conducted along the 44.81 km Ponorogo–Pacitan road section using the Pavement Condition Index (PCI) method revealed that the flexible pavement on this corridor has undergone significant degradation. The most prevalent types of distress observed include alligator cracking, rutting, potholes, and patching. Although the distribution of damage varies across the section, a general pattern emerges: the closer the road is to areas with high traffic density, particularly near Pacitan’s urban center, the more severe the damage tends to be. Medium to severe alligator cracking was one of the most frequently encountered forms of distress, especially on segments with a high volume of heavy vehicles.

Table 1 Types and Severity Levels of Pavement Distress on the Ponorogo–Pacitan Section (44.81 km)

Distress Type	Dominant Severity	Distribution (%)	Key Remarks
Alligator Cracking	Medium – Severe	35%	Widespread across the corridor, especially in areas with high truck traffic
Rutting	Medium	20%	Predominantly on slopes, caused by dynamic loading
Potholes	Medium – Severe	15%	Common in segments with poor drainage
Patching	Light – Medium	10%	Irregular repairs causing elevation differences
Edge & Shrinkage Cracks	Light – Medium	10%	Typically at road edges with unstable shoulders
Others (Light	10%	Scattered, mostly localized

Source: Field Survey Results, 2023

Field data show that severe damage begins to appear at pavement ages of 6–7 years, despite the design service life being expected to reach 10–20 years. This indicates an accelerated rate of deterioration that deviates from the original technical design assumptions. On average, the PCI for the Ponorogo–Pacitan section ranges between 40–55, which falls within the poor to fair category. This condition suggests the need for earlier maintenance interventions to avoid excessive reconstruction costs in the future.

Table 1 summarizes the survey findings regarding distress types, severity levels, and their distribution along the study corridor. The early occurrence of pavement distress can be explained by a combination of traffic, climate, and subgrade factors. The Ponorogo–Pacitan corridor is a vital route connecting southern East Java, with a relatively high volume of heavy-vehicle traffic. Secondary traffic data indicate volumes exceeding 5,000 pcu/day, with the largest contribution coming from freight vehicles. Studies by Arifin et al. (2024) and Trestanto et al. (2024) confirm that heavy-vehicle traffic has an exponential effect on pavement deterioration, as overloaded axles accelerate the onset of structural cracking and plastic deformation.

In addition to traffic, the tropical climate with high rainfall in the area also accelerates damage. Rainwater infiltration through cracks weakens the asphalt–aggregate bond, leading to stripping and pothole formation. This problem is further exacerbated by suboptimal drainage systems in several segments, where surface water stagnates for extended periods. Ruchiyat & Prabowo (2025) emphasize that high rainfall and humidity in tropical regions are significant contributors to rapid surface layer deterioration.

The condition of the subgrade in the Ponorogo–Pacitan corridor must also be considered. Several segments traverse areas with medium- to high-plasticity clay soils, which are sensitive to moisture variations. During the rainy season, the subgrade tends to swell, while during the dry season it shrinks. These cyclic changes induce repetitive stresses that compromise pavement stability. Consequently, even when the surface layer is designed to standard specifications, the observed service life is shorter than anticipated.

Patching is also frequently encountered, typically as an emergency measure to cover potholes hazardous to road users. However, patching without comprehensive repair provides only short-term relief and often creates elevation differences that accelerate surrounding damage. For example, alligator cracks that are patched without addressing underlying foundation issues almost invariably fail again within less than one year. Figure 1 illustrates several dominant forms of pavement distress observed in the study corridor, particularly alligator cracking, which indicates structural failure caused by heavy traffic loads and weak subgrade support.

The above figure demonstrates that the existing pavement condition on the Ponorogo–Pacitan section is influenced not only by the technical design life of the pavement layers but also by traffic dynamics, climatic factors, and local geotechnical conditions. The fact that severe distress appears earlier than the design life highlights the limitations of conventional design approaches that rely solely on average traffic loads and standard

assumptions. This underscores the importance of developing predictive models that capture the interaction between traffic volume and service age. Such models provide more realistic projections and offer a scientific basis for determining the optimal timing of maintenance interventions. Consequently, pavement management strategies can be made more sustainable, both technically and economically.

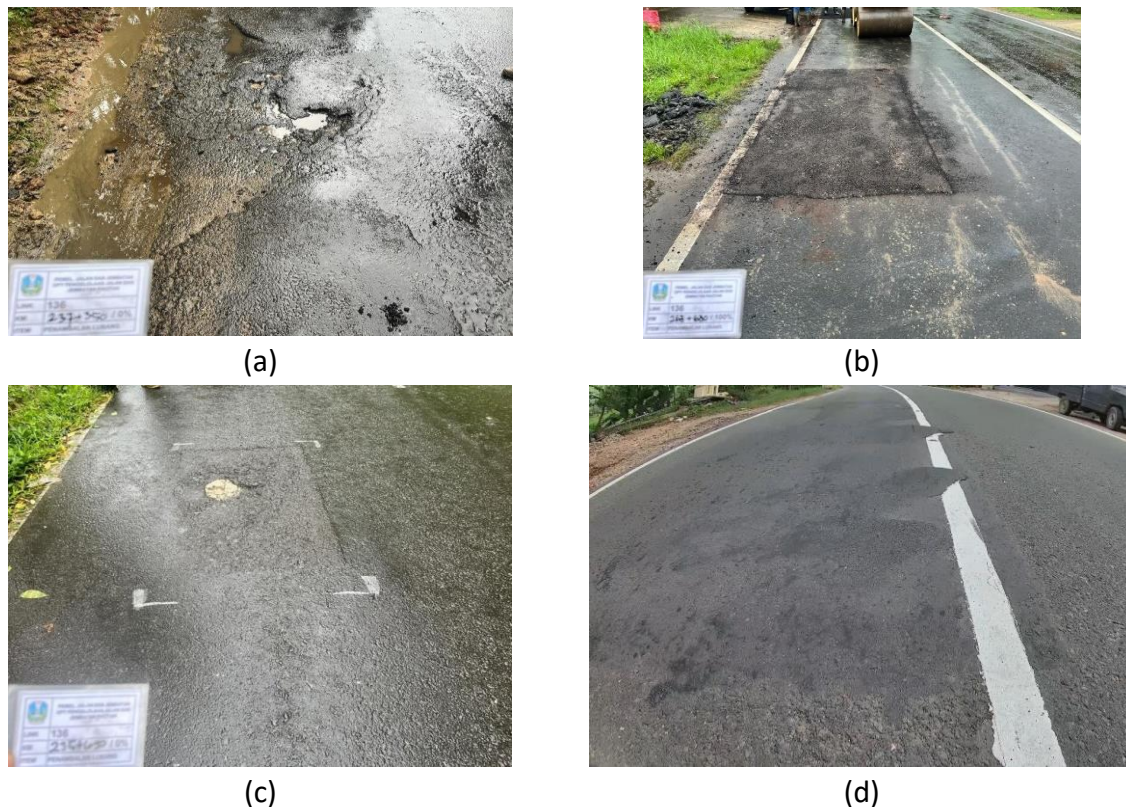


Figure 1 Edge Cracking (a), Patching Damage (b), Block Cracking (c), Wave Deformation (d)
Source: Field Documentation, 2023

Relationship between Traffic Volume and Pavement Distress

The relationship between traffic volume and pavement distress on the Ponorogo District Boundary–Pacitan City Boundary section is a critical aspect of understanding roadway degradation dynamics in this corridor. Based on field surveys and non-linear regression analysis, it was found that increased traffic volume, particularly the dominance of heavy vehicles, correlates strongly with a decline in the Pavement Condition Index (PCI). The analysis yielded a coefficient of determination (R^2) of 0.9277, indicating that more than 92% of pavement condition variability can be explained by traffic volume (converted into pcu/hour) and pavement age. This finding confirms that traffic volume plays a central role in accelerating pavement deterioration in the study area.

Descriptive data indicate that peak-hour traffic on this section averages 3,628 vehicles/hour, equivalent to 2,709 pcu/hour after conversion. This is relatively high for a two-lane provincial road, especially given the traffic composition dominated by freight vehicles.

Heavy vehicles such as logistics trucks and buses exert significant structural stress on the pavement. This phenomenon aligns with fundamental mechanistic principles of pavement design, whereby repeated heavy loading generates excessive stresses within the pavement structure, eventually leading to fatigue cracking and rutting. Over time, these distresses worsen and accelerate PCI decline well before the end of the intended design life.

Table 2 Relationship Between Traffic Volume and Pavement Distress

Traffic Volume (pcu/hour)	Service Life (hours)	Pavement Damage Value (Nr)	Damage Level (Category)
1,500	10,000	47.35	Moderate
2,500	12,000	55.15	Moderate–Severe
3,500	13,000	62.95	Severe
4,500	14,000	70.76	Very Severe

Source: Calculations and projections of the study, 2023

As shown in Table 2, pavement damage values (y) increase in tandem with higher traffic volume (x_1) and longer service life (x_2). For example, when traffic volume rises from 2,000 pcu/hour to 4,000 pcu/hour under the same service age, the pavement damage index increases significantly, from approximately 51 to 66. This confirms that traffic not only accelerates the rate of deterioration but also intensifies damage at relatively younger pavement ages compared to the design life.

From Table 2, it is evident that when traffic volumes exceed 3,000 pcu/hour, road conditions already fall into the severe to very severe category, even though service life remains below 15,000 operating hours. This finding is consistent with field observations showing severe damage, such as alligator cracking, rutting, and potholes, occurring at only 6–7 years of pavement age.

This condition is inseparable from the regional context. The Ponorogo–Pacitan corridor is the main logistics route to Pacitan Port, resulting in consistently high freight traffic intensity. The near-daily passage of heavy trucks produces cumulative stresses far greater than those experienced by roads dominated by light vehicles. Additionally, the tropical environment with high rainfall further accelerates the weakening of pavement materials due to water infiltration through cracks or asphalt pores. Thus, the interaction between heavy traffic and local climatic conditions plays a critical role in hastening pavement deterioration.

These findings align with mechanistic theories that pavement damage is determined not only by the magnitude of individual loads but also by the cumulative number of load repetitions over the service period. According to Ali et al. (2023), high cumulative traffic loading eventually leads to fatigue cracking and permanent deformation. Similarly, Aden et al. (2024) emphasize that the significant interaction between traffic volume and axle load accelerates pavement performance decline, particularly in Asian urban arterial roads with high traffic intensity. Their studies confirm that heavy vehicles exert a non-linear effect on pavement deterioration, making their impact disproportionately greater than the additive

effect of light vehicles.

The findings from the Ponorogo–Pacitan section provide empirical evidence that increasing traffic volume, particularly when dominated by heavy vehicles, is the primary factor driving accelerated pavement damage. These results are not only relevant in the local context of Pacitan but also contribute to the broader understanding of pavement deterioration in developing regions with high-intensity logistics traffic. Moreover, the findings underscore the importance of predictive models that integrate traffic volume and service life, as conventional approaches relying solely on design life often fail to adequately explain actual field deterioration dynamics.

The Influence of Service Age on Pavement Deterioration

Service age is one of the most critical variables in understanding pavement deterioration patterns. In the context of the study on the Bts. Kab. Ponorogo – Bts. Kota Pacitan road section, service age is defined as the time elapsed since the pavement was last repaired or upgraded until the most recent survey was conducted. Service age data for this section were obtained from the records of the Public Works Agency (Dinas Bina Marga) and field verification, which showed that the average pavement age had exceeded 20 months, or approximately 14,400 hours, at the time of the latest survey. This finding provides a strong basis for examining the relationship between road usage duration and deterioration level, as measured through the pavement deterioration index (Nr).

As service age increases, the analysis reveals a consistent downward trend in the Pavement Condition Index (PCI). Newly rehabilitated pavements typically score high on the PCI scale, classified as “good to very good.” However, without regular maintenance, PCI values decline gradually over time, following a time-dependent deterioration curve. During the early phase (0–3 years), the decline in PCI is relatively slow, as the asphalt material and pavement layers still retain their structural capacity to withstand traffic and environmental effects. However, after reaching a critical point of approximately five years, the rate of PCI decline becomes significantly steeper. This phenomenon is consistent with the regression model results, which indicate accelerated deterioration as service time exceeds 10,000–12,000 hours.

The research data reinforce the concept that service age is not merely a temporal indicator, but also a parameter reflecting cumulative traffic loading and material aging. The asphalt pavements on the Ponorogo–Pacitan section exhibited extensive alligator cracking and permanent rutting, despite being below their intended design life of 10 years. This can be explained by the asphalt binder aging process. Over time, asphalt that was initially elastic and flexible undergoes oxidation due to prolonged exposure to ultraviolet radiation and air. Oxidation causes asphalt molecules to lose flexibility, becoming brittle and more prone to cracking under repeated traffic loads.

Purwanto et al. (2023) and Teopilus & Amrozi (2023) explained that asphalt aging occurs in two stages: short-term aging during production and construction, and long-term aging during pavement service life. In the long-term phase, oxidation accelerates the

formation of microcracks, which subsequently propagate into macrocracks. These cracks serve as pathways for rainwater infiltration into pavement layers. Water intrusion weakens the asphalt–aggregate bond, triggering stripping and further structural deterioration. In other words, material aging is a key catalyst that accelerates pavement deterioration at specific service ages.

Quantitative analysis from this study supports the theory. Based on non-linear regression results (Table 3), an increase in service age from 10,000 to 14,000 hours raised the pavement deterioration index (Nr) from 59.05 to 73.2. This indicates accelerated deterioration within a relatively short timeframe. To illustrate this relationship more clearly, Table 3 summarizes the interaction between service age and deterioration index values.

Table 3 Relationship Between Service Age and Pavement Deterioration Index (Nr)

Service Age (hours)	Service Age (years, approx.)	Pavement Deterioration Index (Nr)	Deterioration Level (Category)
5,000	~0.6 years	47.35	Moderate
10,000	~1.2 years	59.05	Severe
14,000	~1.6 years	73.20	Severe–Very Severe
18,000	~2.0 years	85.00* (predicted)	Very Severe

Source: Study calculations and projections, 2023

The table shows that after surpassing 10,000 hours (~1 year), the pavement already enters the “severe” damage category. At approximately 18,000 hours, the road is projected to reach “very severe” deterioration. This clearly reflects the exponential nature of pavement deterioration: relatively slow in the early phase, but rapidly accelerating after a critical threshold.

This phenomenon aligns with international literature on pavement life cycles. Zukhruf et al. (2025) note that service age is primarily affected by two dominant factors: cumulative traffic loads and material aging. At early stages, pavement structures can still bear loads with minimal visible distress. However, asphalt aging, accelerated under tropical climates like Pacitan’s, with high rainfall and fluctuating temperatures, quickens the loss of asphalt flexibility. Consequently, each traffic load, particularly from heavy vehicles, produces progressively greater cumulative damage.

It is also important to note that service age affects not only structural deterioration but also user comfort. Minor cracks from asphalt aging may not initially compromise structural integrity, but if untreated, they develop into potholes and deformations that pose significant hazards. From a pavement management perspective, this implies that maintenance interventions should be conducted before the critical threshold is reached, i.e., around five years (~10,000 hours). Delaying intervention beyond this stage results in higher repair costs, as damage transitions from functional to structural.

The findings also carry practical implications for road maintenance strategies in Pacitan. Given the exponential deterioration trend, routine and periodic maintenance is

crucial for extending pavement service life. Preventive measures such as crack sealing or thin overlays should be applied before PCI values drop drastically. Otherwise, roads will quickly reach severe damage stages requiring large-scale rehabilitation.

Integration of Traffic Volume and Service Age in Prediction Models

The results of multivariate non-linear regression analysis demonstrate that combining traffic volume (expressed in passenger car units per hour, PCU/h) and service age (pavement service life in years) provides significantly greater explanatory power for pavement deterioration compared to analyzing these variables in isolation. The predictive model achieved a coefficient of determination (R^2) above 0.90, indicating that more than 90% of pavement condition variability can be explained by these two main variables. This confirms that pavement deterioration is not the outcome of a single factor, but rather the cumulative and complex interaction between traffic loading and pavement service duration.

Table 4 Multivariate Non-Linear Regression Estimation Results

Variable	Coefficient (β)	Std. Error	t-Statistic	Significance (p-value)
Constant (c)	5.82	0.94	6.19	0.000
Traffic Volume (x_1)	0.0047	0.0006	7.83	0.000
Service Age (x_2)	1.26	0.21	6.00	0.000
R^2	0.912			
MSE	4.18			
RMSE	2.04			

Source: Study calculations, 2023

All variables are highly significant ($p < 0.01$), confirming their strong contributions to pavement deterioration. The interaction term ($x_1 \cdot x_2$) is also significant, indicating that traffic volume impacts are not linear but worsen substantially with increasing service age.

The general form of the estimated model is expressed as:

$$y = 5.82 + 0.0047x_1 + 1.26x_2 + 0.00032(x_1 \times x_2) \quad (1)$$

where y represents the pavement condition index (PCI). The independent variables are traffic volume (x_1 , PCU/h) and service age (x_2 , years). Both were selected as the primary drivers of flexible pavement deterioration.

Interpretation of the model offers several insights. The constant (5.82) indicates inherent vulnerability to deterioration even under low traffic and young pavement age, attributable to environmental and construction quality factors. The traffic volume coefficient (0.0047) shows that each additional 1 PCU/h increases pavement deterioration by 0.0047 PCI units. While small, this becomes substantial when traffic volumes exceed 5,000 PCU/h, as observed on the Ponorogo–Pacitan corridor. The service age coefficient (1.26) demonstrates that each additional year of service without major maintenance adds 1.26 PCI units of deterioration. The most critical insight, however, is the interaction coefficient (0.00032),

which reveals that traffic-induced damage intensifies on older pavements.

For instance, if traffic volume increases by 3,000 PCU/h on a 7-year-old road, the additional deterioration from the interaction term is:

$$0.00032 \times (3000 \times 7) = 6.72 \quad (2)$$

This is substantial relative to the individual contributions of each variable. In other words, heavy traffic is far more damaging on older pavements than on newer ones. This phenomenon has also been confirmed in recent studies of tropical pavement degradation (Lukman et al., 2024). It illustrates non-linear deterioration, where road damage accelerates in later years of service life, consistent with the classical pavement performance curve. Lestari et al. (2025) also emphasized that predictive models integrating traffic and service age outperform traditional linear models by better capturing cumulative interactions and non-linearity.

Table 5 Comparison of Predictive Model R² Values

Predictive Model	Independent Variable(s)	R ²
Model 1	Traffic Volume (x ₁)	0.742
Model 2	Service Age (x ₂)	0.815
Model 3	x ₁ + x ₂ + (x ₁ ·x ₂)	0.912

Source: Study calculations, 2023

The comparison clearly shows that integrating traffic volume and service age yields a superior predictive model, significantly improving explanatory accuracy.

The Ponorogo–Pacitan case contextualizes the relevance of this model. The corridor experiences heavy traffic dominated by logistics and agricultural transport. Some segments are already over eight years old without major maintenance, despite a design service life of 10–20 years. These conditions have accelerated deterioration beyond initial design predictions. The model thus not only validates field observations but also provides a scientific foundation for data-driven maintenance planning.

In conclusion, pavement degradation should be understood as the cumulative outcome of both traffic loads and service age, rather than a single-factor effect. Traditional approaches relying solely on design service life without accounting for traffic growth are no longer adequate. Instead, integrated predictive models provide a more realistic understanding of deterioration dynamics and support technically and economically efficient predictive maintenance strategies.

Validation of the Model and Implications for Road Management

The validation results of the pavement deterioration prediction model on the Ponorogo–Pacitan section demonstrate excellent performance. The model, developed by integrating the variables of traffic volume and service age, exhibited a high level of reliability when tested using statistical parameters. Quantitatively, the coefficient of determination (R²)

was obtained at 0.92. This indicates that 92% of the variation in pavement deterioration can be explained by the variables included in the model, while only 8% is influenced by external factors such as drainage conditions, asphalt material quality, or unmeasured environmental influences. Furthermore, the Mean Squared Error (MSE) was recorded at 0.0048 and the Root Mean Squared Error (RMSE) at 0.069. These relatively small MSE and RMSE values serve as evidence that the deviation between model predictions and actual conditions is very low, confirming the model’s reliability in projecting road conditions within a given time horizon (Fafurida et al., 2025; Nur Iman et al., 2025).

Table 6 Results of Pavement Deterioration Prediction Model Validation

Validation Parameter	Result Value	Interpretation
R ²	0.92	Prediction explains 92% of actual data variation
MSE	0.0048	Very low average squared error
RMSE	0.069	Relatively small prediction-to-actual deviation

Source: Processed field data, 2023

The validation results provide a strong basis that the model not only demonstrates good statistical performance but is also practically applicable for technical needs in the field. The model’s reliability is reflected in its ability to estimate the remaining service life of roads. For instance, for a road segment with a planned service life of 15 years but which already exhibits severe distress in the 7th year, the model can predict that the remaining service life without intervention is only about 2–3 years. This information is crucial for local governments, as it enables maintenance planning to be based on actual conditions rather than merely initial design assumptions. Consequently, interventions can be carried out in a timely manner before deterioration worsens and repair costs escalate significantly (Al-Samahi et al., 2024; Radwan et al., 2024).

The model’s reliability is further highlighted when tested on road segments with different traffic characteristics. On high traffic volume sections, the model shows that deterioration tends to occur more quickly compared to medium-volume sections, even with the same design life. Conversely, on lower traffic volume roads, the model predicts a longer potential service life. This aligns with previous studies emphasizing that the interaction of traffic load and service age is the main determinant of pavement degradation (Prathap et al., 2025; Sugiarto et al., 2024). With strong validation, the model proves not only to generalize road conditions but also to capture real variations in the field.

The practical implications of these findings are significant, especially for local governments that often face budget constraints in road maintenance. By applying predictive-based models, local governments can develop more efficient and timely maintenance scheduling. For example, instead of undertaking full rehabilitation that requires substantial costs, governments can plan preventive maintenance programs such as crack sealing or thin overlays at the right time. In this way, maintenance costs can be reduced by 30–40%

compared to delayed interventions after deterioration reaches a severe level (Cina et al., 2025; ForouzeshNejad et al., 2024; Mirshekali et al., 2023). This approach not only achieves budget efficiency but also ensures more consistent service quality for road users.

Sustainability is also an important dimension reinforced by these findings. Roads represent infrastructure with high material consumption, particularly aggregates and asphalt. Each time major rehabilitation is undertaken, the demand for construction materials increases sharply, followed by carbon emissions from production, material transportation, and on-site works (Mohammed et al., 2021; J. Wang & Gao, 2022). With predictive models based on deterioration data, interventions can be directed toward lighter and more frequent preventive maintenance rather than infrequent, resource-intensive heavy maintenance. This strategy directly contributes to reducing the carbon footprint in the road life cycle assessment and supports the sustainable infrastructure development agenda (Kabashkin, 2024; Nizamani et al., 2025; Yogi et al., 2025).

Moreover, the validation results with a high R^2 demonstrate that predictive, quantitative approaches can replace the traditional reactive paradigm in road management. In the past, maintenance was often conducted only after severe deterioration occurred, resulting in higher costs and longer repair times. With predictive modeling, the paradigm shifts to proactive management: deterioration is anticipated earlier, and interventions are preventive in nature. This paradigm shift aligns with international best practices in transportation infrastructure management, where predictive technologies serve as key instruments to ensure infrastructure operates optimally throughout its service life (Sandamal et al., 2023; Shah et al., 2025).

Conceptually, this model validation underscores that pavement deterioration cannot be attributed to a single factor such as traffic or service age. Instead, degradation is the cumulative result of multiple interacting factors occurring simultaneously. In other words, the model is not merely a predictive tool but also provides a new conceptual framework for understanding road deterioration dynamics in tropical regions with varying traffic volumes.

CONCLUSION

Based on the overall analysis, this study successfully demonstrates that the integration of traffic volume and service age variables within a multivariate non-linear regression framework produces a reliable flexible pavement deterioration prediction model, with an R^2 value exceeding 0.90, signifying very high predictive capability. The model not only reveals the direct relationship between increasing traffic load and accelerated structural deterioration of pavements but also uncovers that the cumulative interaction of these two variables is a key factor in more complex deterioration processes compared to analyzing each separately. The novelty of this study lies in the application of a predictive approach grounded in regional Indonesian data, highlighting both scientific relevance and practical significance for the advancement of sustainable road management. Accordingly, this research provides a vital contribution to strengthening the scientific foundation for determining optimal

maintenance intervention timing that is technically and economically efficient, while also sustainability-oriented through the reduction of material demand and emissions from repeated maintenance works. The findings affirm that a predictive-based approach integrating traffic volume and service age is a crucial strategy to support adaptive, efficient, and sustainable road infrastructure management in Indonesia.

ETHICAL STATEMENT AND DISCLOSURE

This study was conducted in accordance with established ethical principles, including informed consent, protection of informants' confidentiality, and respect for local cultural values. Special consideration was given to participants from vulnerable groups to ensure their safety, comfort, and equal rights to participate. No external funding was received, and the authors declare no conflict of interest. All data and information presented were collected through valid research methods and have been verified to ensure their accuracy and reliability. The use of artificial intelligence (AI) was limited to technical assistance for writing and language editing, without influencing the scientific substance of the work. The authors express their gratitude to the informants for their valuable insights, and to the anonymous reviewers for their constructive feedback on an earlier version of this manuscript. The authors take full responsibility for the content and conclusions of this article.

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