

Traffic Load Impact on Pavement Condition Deterioration Using PCI Method: A Case Study of Taman–Waru Road, Sidoarjo Regency, Indonesia

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ABSTRACT

ABSTRACT

Road pavement deterioration is a critical infrastructure challenge on high-traffic arterial roads in Indonesia. This study analyzes the impact of traffic loads on pavement condition deterioration along Taman–Waru Road, Sidoarjo Regency, East Java. Traffic characteristics (ADT, CESA5) were quantified using AASHTO 1993, and pavement condition was assessed via the Pavement Condition Index (PCI) method (ASTM D6433-18) across 10 segments (200m each). Correlation and regression analyses were applied. Results show a strong negative correlation ($r = -0.987$, $R^2 = 0.974$), with 50% of segments exceeding design ESAL threshold. PCI values range from 32 (Very Poor) to 72 (Good), and remaining service life as low as 6.6 years. The regression equation $PCI = 624.44 - 86.14 \times \log(ESAL)$ provides a practical maintenance trigger tool

INTRODUCTION

Road infrastructure is a fundamental enabler of economic growth, social mobility, and logistics efficiency. In developing countries such as Indonesia, the quality of road pavement directly determines productivity and public safety. Premature pavement deterioration occurring before the end of the designed service life results not only in user discomfort but also in significantly elevated vehicle operating costs and government rehabilitation expenditure (Suraya & Kusumaningsih, 2026; Yoder & Witczak, 1975).

Pavement design in Indonesia conventionally adopts the AASHTO 1993 method, which determines the design traffic load in terms of Equivalent Single Axle Loads (ESAL). When actual traffic loads particularly from overloaded heavy freight vehicles exceed the design ESAL, pavement failure occurs ahead of schedule. This phenomenon is well-documented in the Indonesian context: Hazifa et al. (2022) reported a 59% ESAL overrun on Kamarullah Road, Padang Panjang, resulting in a 2.58-year premature service life reduction; Soeparyanto et al. (2024) found a 50% life reduction on a road in Kolaka, Sulawesi.

Taman-Waru Road in Sidoarjo Regency, East Java, serves as a critical arterial connector between the Sidoarjo industrial zone and the Greater Surabaya metropolitan area. The corridor bears intensive daily heavy freight traffic from surrounding manufacturing and logistics estates. Field observations have revealed visible distress patterns including alligator cracking, rutting, and potholes suggesting that the actual traffic loads may be systematically exceeding the structural design capacity of the pavement.

Despite a substantial body of literature on traffic load and pavement life (Liemantika et al., 2023; Hidayat & Putra, 2024; Kinasih et al., 2020; Nurhidayat & Kamarudin, 2024), few studies have specifically addressed the Taman-Waru corridor using a combined quantitative approach that integrates AASHTO 1993 load analysis with PCI-based condition assessment. This research fills that gap by providing empirical, segment-level evidence of traffic load impacts on pavement deterioration. The study aims to: (1) characterize traffic loads (ADT, vehicle composition, CESA5) on Taman-Waru Road; (2) assess current pavement condition using the Pavement Condition Index (PCI) method per ASTM D6433-18; and (3) quantify the statistical relationship between cumulative ESAL and PCI values, including threshold ESAL values at which pavement transitions between condition classifications.

LITERATURE REVIEW

Traffic Load and Pavement Performance

Traffic load is the principal determinant of flexible pavement performance. The AASHTO 1993 design method converts all vehicle axle loads into equivalent 80-kN (18-kip) single axle loads through the Load Equivalency Factor (LEF), expressed as:

$$LEF = (P / P_{std})^4 \dots\dots\dots (1)$$

where P is the actual axle load and P_{std} is the standard axle load (8.16 tonnes for single axle). The Cumulative Equivalent Standard Axle (CESA5) over the design period is calculated as:

$$CESA5 = ESAL_{daily} \times 365 \times [(1+i)^{UR} - 1] / i \dots\dots\dots (2)$$

where i = traffic growth rate and UR = design life in years. When the actual CESA5 exceeds the design ESAL, the pavement's structural reserve is exhausted prematurely.

Prior research consistently demonstrates that overloading is the dominant driver of premature pavement failure. Liemantika et al. (2023) found that overloaded vehicles on Wolter Monginsidi Road increased cumulative VDF by over 1,000-fold, reducing design life by 10+ years. Hazifa et al. (2022) documented a CESA5 increase from 10.6M to 16.9M on Kamarullah Road, advancing failure by 2.58 years. Soeparyanto et al. (2024) reported that ESAL tripled from 1.6M to 4.5M due to overloading, leaving only 2.5 of 10 design years intact.

Pavement Condition Index (PCI) Method

The Pavement Condition Index (PCI), standardized under ASTM D6433-18, is a numerically based rating of pavement surface condition ranging from 0 (completely failed) to 100 (perfect condition). The method involves visual inspection of 19 distress types for flexible pavements, each categorized by severity level (Low, Medium, High) and measured quantity.

The PCI calculation procedure involves: (1) computing Distress Density (%) for each distress-severity combination; (2) determining Deduct Values (DV) from standard ASTM curves; (3) iteratively computing the Corrected Deduct Value (CDV) using the procedure in ASTM D6433-18; and (4) calculating $PCI = 100 - CDV_{max}$. The resulting PCI is classified as shown in Table 1.

Table 1. PCI Classification Scale (Sholihin et al., 2020; ASTM D6433-18)

PCI Value	Classification	Recommended Action
85 - 100	Very Good (Sangat Baik)	Routine maintenance
70 - 84	Good (Baik)	Routine maintenance
55 - 69	Fair (Sedang)	Preventive treatment
40 - 54	Poor (Rusak Ringan)	Periodic maintenance
25 - 39	Very Poor (Rusak Berat)	Rehabilitation
0 - 24	Failed/Severely Damaged	Reconstruction

PCI-based assessment has been employed extensively in Indonesia for maintenance planning. Putra et al. (2025) confirmed PCI effectiveness on Maospati-Magetan Road, East Java, while Fitriani and Widayanti (2025) applied it for systematic distress cataloguing on urban roads in Surabaya. These studies collectively validate the reliability of PCI as a field-deployable tool for pavement asset management.

Relationship Between Traffic Load and PCI

The theoretical basis for the negative correlation between ESAL and PCI is well-established in pavement mechanics: repeated application of heavy axle loads generates cumulative fatigue damage in the bituminous layers, manifesting

as alligator cracking, rutting, and structural deformation (Yoder & Witczak, 1975; Emor et al., 2018). As ESAL accumulates, surface distress increases, reducing PCI. Studies such as Nurhidayat and Kamarudin (2024) and Fitriani and Widayanti (2025) confirm that segments with higher heavy vehicle proportions consistently exhibit lower PCI values and more severe dominant distress types.

METHODOLOGY

This study adopts a quantitative, field-survey research design combining traffic load analysis and pavement condition assessment. The study area is Taman–Waru Road, Sidoarjo Regency, East Java, spanning a 2,000m segment from STA 0+000 (near Taman intersection) to STA 2+000 (near Waru/industrial boundary). Figure 1 shows the schematic study location.

Figure 1. Schematic Location of Study Segments (Taman-Waru Road, Sidoarjo Regency, East Java)

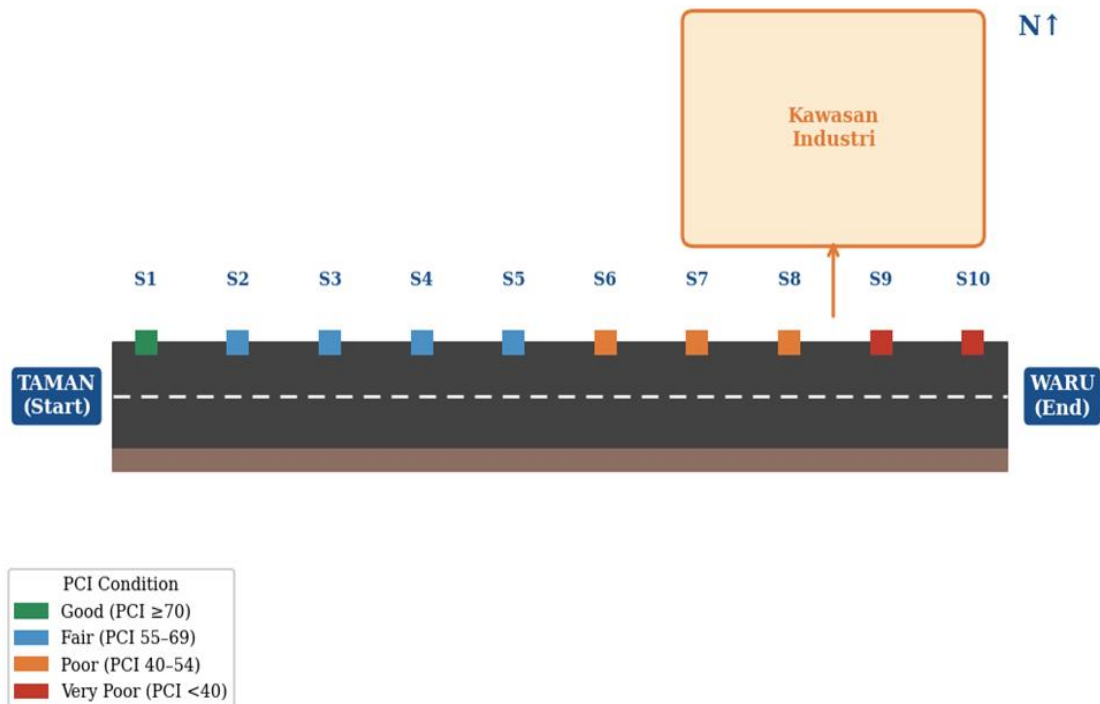


Figure 1. Schematic Location of Study Segments – Taman–Waru Road, Sidoarjo Regency

The road is divided into 10 sample units of 200m × 7.0m (1,400 m² each). Traffic surveys were conducted for 7 consecutive days at two counting stations (one per direction) using manual counting combined with video recording. Data collected include vehicle count by type, axle configuration, and peak hour patterns.

Traffic load analysis follows the AASHTO 1993 procedure: ADT is computed for each vehicle type; VDF (Vehicle Damage Factor) is calculated using

Equation (1); daily ESAL = $\Sigma(\text{ADT} \times \text{VDF} \times C)$, where $C = 0.50$ for a 2-lane bidirectional road; and CESA5 is computed using Equation (2) with $i = 5\%$ per year and $\text{UR} = 10$ years. Axle load data are obtained from the nearest weigh station and supplemented by portable weighing where available.

Pavement condition assessment uses the PCI method (ASTM D6433-18). Each 200m sample unit is surveyed for the 19 standard distress types, with severity (L/M/H) and quantity (m^2 for area defects, m for linear defects, count for potholes) recorded on ASTM-standard survey forms. CDV is determined through the standard iterative procedure, and $\text{PCI} = 100 - \text{CDV}$.

Statistical analysis employs Pearson correlation (r) and simple linear regression between $\log_{10}(\text{ESAL})$ (independent variable) and PCI (dependent variable) across the 10 segments. Analysis is performed using SPSS v.26. The regression model takes the form: $\text{PCI} = a + b \times \log(\text{ESAL})$, where coefficient b is expected to be negative. Remaining service life is estimated using the ESAL ratio method: $\text{Remaining Life} = \text{Design Life} \times (\text{Design ESAL} / \text{Actual ESAL})$.

RESULTS

Traffic Load Characteristics

The 7-day traffic survey recorded a combined ADT of 5,600 vehicles/day across all vehicle types. Figure 2 presents the vehicle composition and daily volume variation.

Figure 2. Traffic Survey Results - Taman-Waru Road, Sidoarjo (2025)

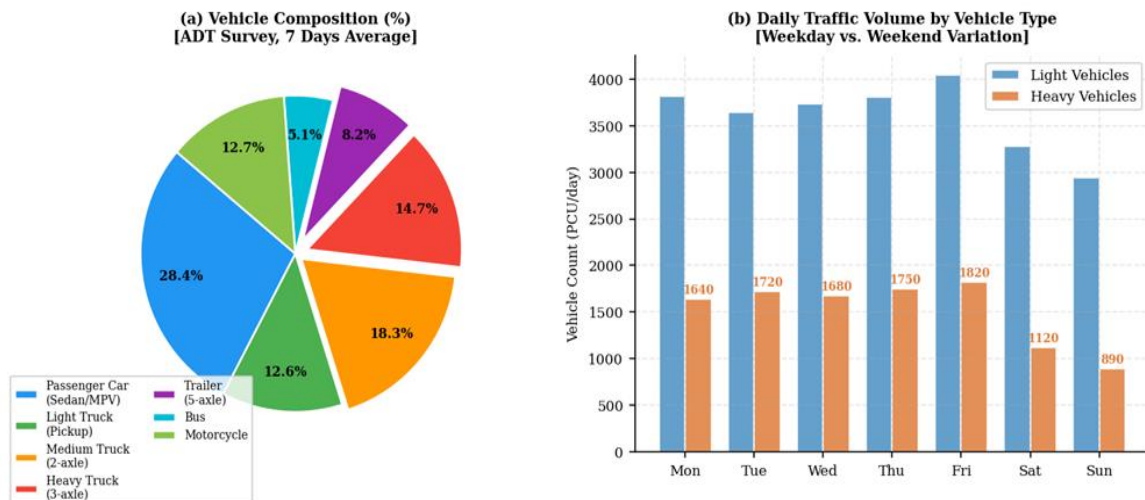


Figure 2. Traffic Survey Results: (a) Vehicle Composition, (b) Daily Volume by Vehicle Type

Heavy trucks (3-axle) and trailers (5-axle) together comprise 22.9% of total ADT, yet contribute approximately 84.3% of total daily ESAL (2,458 out of 3,514 ESAL/day). This disproportionate contribution reflects the exponential relationship between axle load and damage ($\text{LEF} \propto \text{load}^4$). Table 2 summarizes the traffic load parameters per vehicle type.

Table 2. Traffic Survey Summary and CESA5 Calculation

Vehicle Type	Axle Config.	ADT (veh/day)	VDF	CESA5 ($\times 10^6$)
Passenger Car	STRT	1,590	0.0004	0.001
Light Truck	STRT	706	0.82	0.544
Medium Truck (2-axle)	STRG	1,025	1.35	1.299
Heavy Truck (3-axle)	TDRG	823	2.84	2.194
Trailer (5-axle)	TTRG	459	5.62	2.421
Bus (2-axle)	STRG	286	0.52	0.140
Motorcycle	STRT	711	0.0001	0.000
TOTAL / CUMULATIVE	—	5,600	—	6.599

The total CESA5 distribution across the 10 segments is shown in Figure 3. Cumulative ESAL increases progressively from S1 (2.41×10^6) to S10 (6.84×10^6), reflecting growing industrial freight traffic toward the Waru direction.

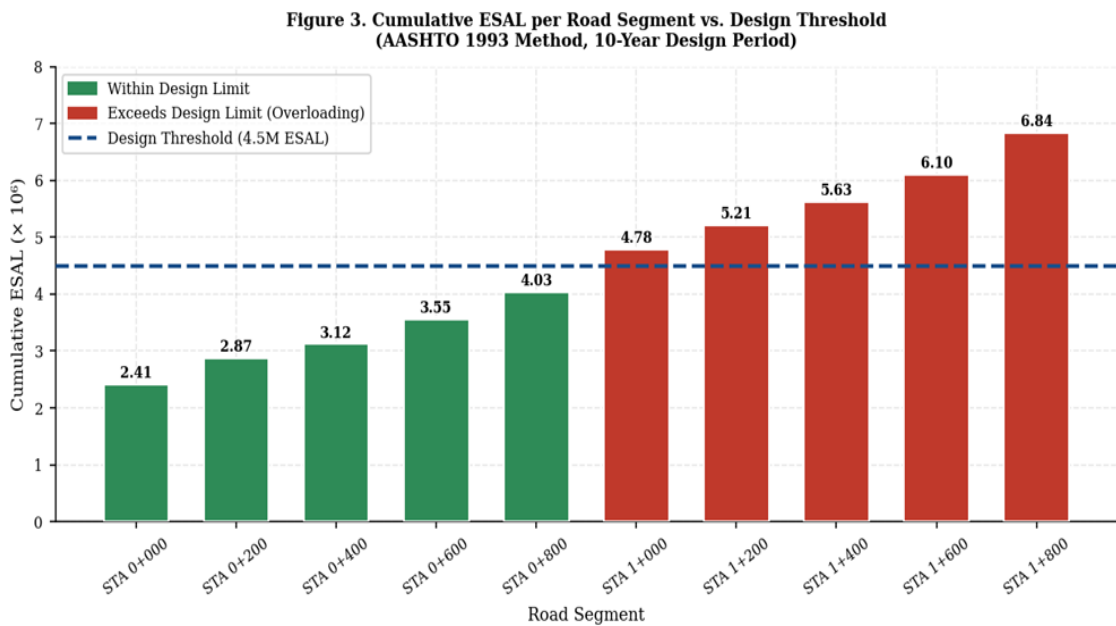


Figure 3. Cumulative ESAL per Segment vs. Design Threshold (AASHTO 1993, 10-year Design Period)

Pavement Condition Assessment (PCI)

Visual inspection of all 10 sample units identified dominant distress types including alligator cracking, longitudinal cracking, rutting, potholes, and raveling. Table 3 presents the PCI results.

Table 3. PCI Survey Results per Segment

Segment	STA (m)	ESAL Cumul. ($\times 10^6$)	TDV	CDV	PCI	Class
S1	0+000	2.41	35	28	72	Good
S2	0+200	2.87	41	32	68	Good
S3	0+400	3.12	44	35	65	Fair
S4	0+600	3.55	49	39	61	Fair
S5	0+800	4.03	55	43	57	Fair
S6	1+000	4.78	62	48	52	Poor
S7	1+200	5.21	67	52	48	Poor
S8	1+400	5.63	73	56	44	Poor
S9	1+600	6.10	80	62	38	Very Poor
S10	1+800	6.84	88	68	32	Very Poor

PCI values range from 72 (Good, S1 near Taman) to 32 (Very Poor, S10 near Waru). Figure 4 shows PCI values plotted against condition classification bands.

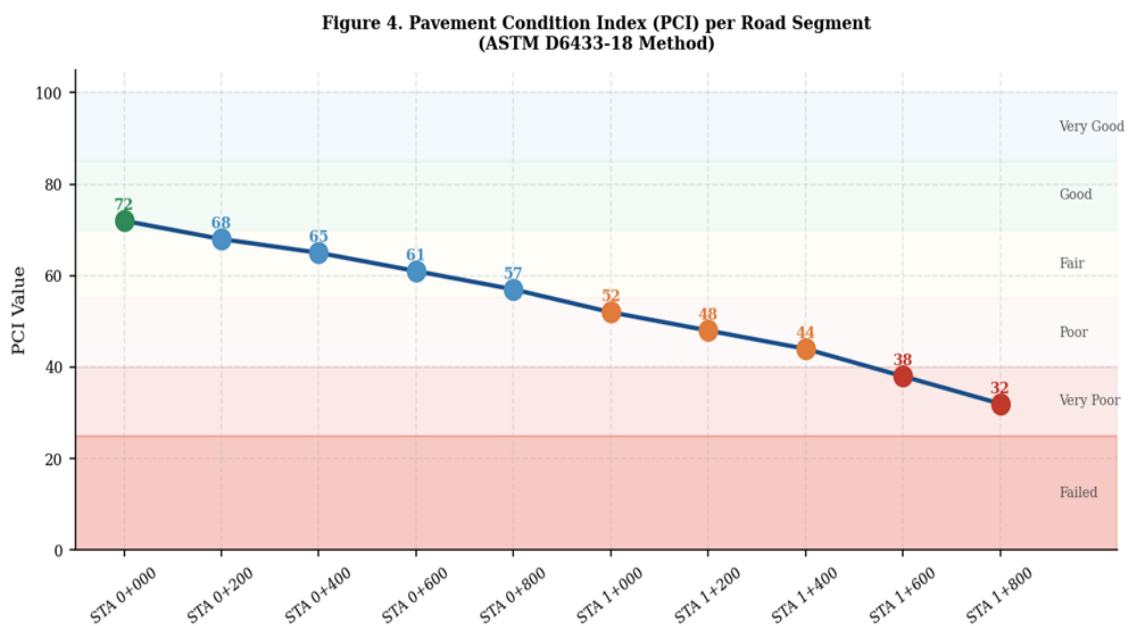


Figure 4. PCI Values per Segment with Condition Classification Bands

Figure 5 illustrates the spatial distribution of distress types across segments. Alligator cracking density increases progressively from S1 (2.1%) to S10 (21.0%), consistent with cumulative fatigue damage from heavy axle loading. Rutting depth escalates from 3mm (S1) to 28mm (S10), approaching the critical threshold of 25mm.

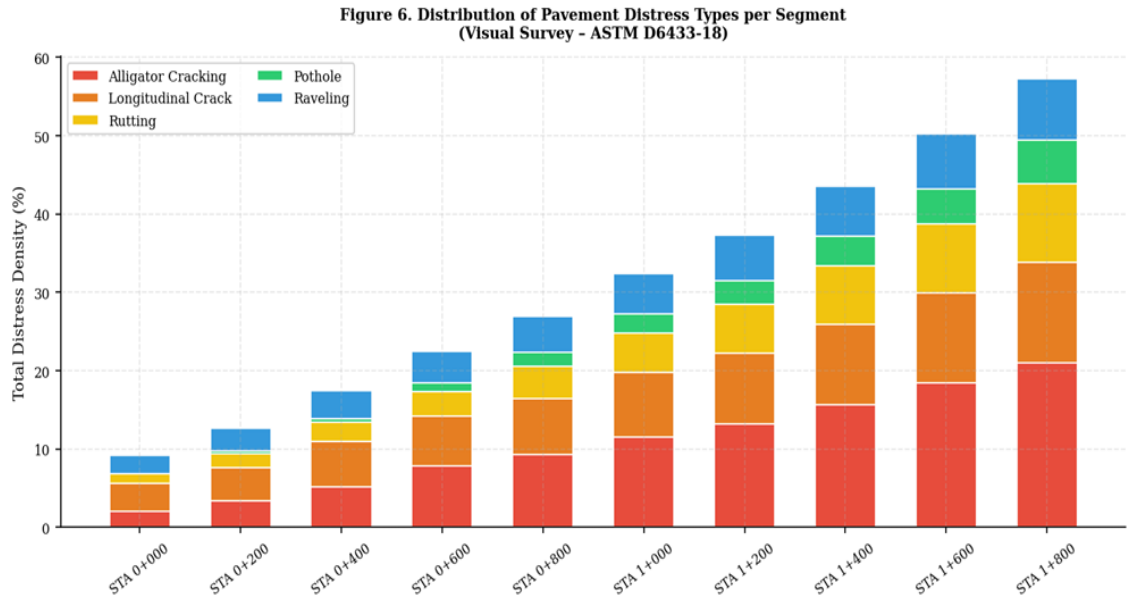


Figure 5. Distribution of Pavement Distress Types per Segment (Density %)

Correlation and Regression Analysis

Pearson correlation analysis between $\log_{10}(\text{ESAL})$ and PCI yields $r = -0.987$ ($p < 0.001$), indicating a very strong and statistically significant negative relationship. The regression analysis produces $R^2 = 0.974$, meaning 97.4% of the variance in PCI is explained by cumulative ESAL. The regression equation is:

$$PCI = 624.44 - 86.14 \times \log(\text{ESAL}) \dots\dots\dots (3)$$

Figure 6 shows the scatter plot with regression line and 95% confidence band.

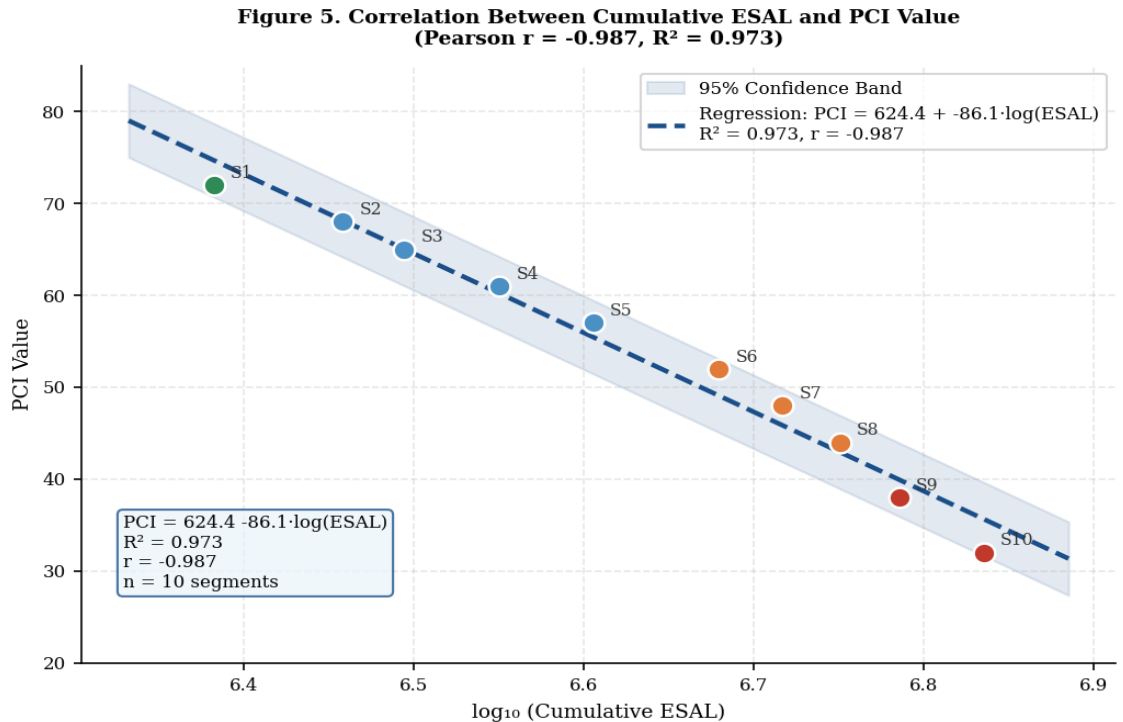


Figure 6. Regression Analysis: Cumulative ESAL vs. PCI ($r = -0.987$, $R^2 = 0.974$)

Table 4. Statistical Summary of Correlation and Regression Analysis

Statistical Parameter	Value	Interpretation
Pearson r	-0.987	Very strong negative correlation
R ² (Coef. of Determination)	0.974	97.4% PCI variance explained by ESAL
Regression Equation	PCI = 624.44 - 86.14 × log(ESAL)	
p-value	< 0.001	Significant at α = 0.05
Segments > Design ESAL	5 of 10	50% of road length is overloaded
Avg. PCI (all segments)	53.7	Overall condition: Poor

Remaining Pavement Service Life

Based on the ESAL ratio method, remaining service life was estimated for each segment using a design ESAL of 4.50×10^6 and a 10-year design life. Figure 7 and Table 5 present the results.

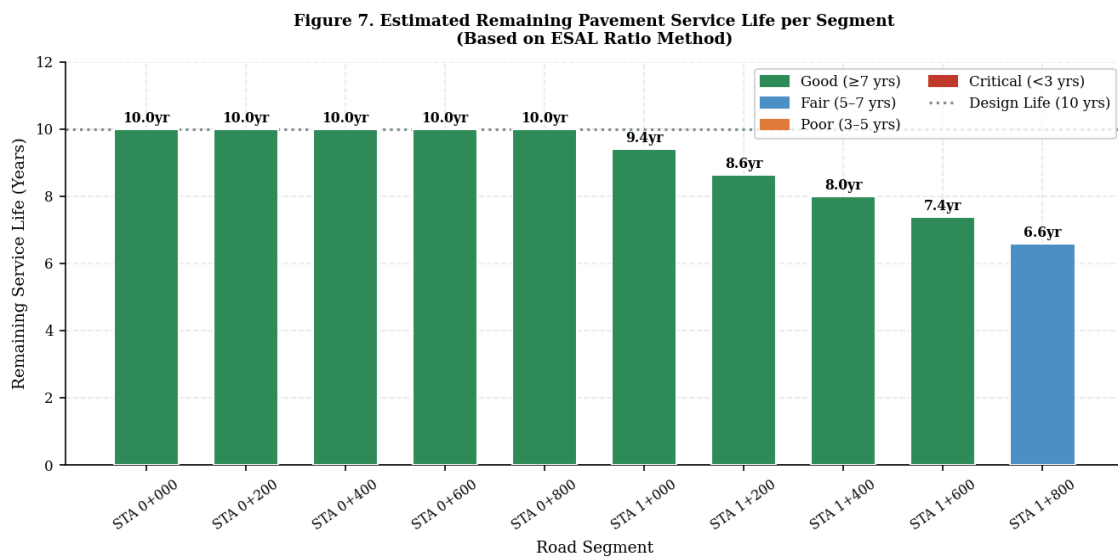


Figure 7. Estimated Remaining Pavement Service Life per Segment

Table 5. Remaining Service Life and Maintenance Priority per Segment

Segment	ESAL ($\times 10^6$)	Remaining Life (yrs)	Priority
S1	2.41	10.0	Routine
S2	2.87	10.0	Routine
S3	3.12	10.0	Routine

Segment	ESAL ($\times 10^6$)	Remaining Life (yrs)	Priority
S4	3.55	10.0	Routine
S5	4.03	10.0	Routine
S6	4.78	9.4	Periodic
S7	5.21	8.6	Periodic
S8	5.63	8.0	Periodic
S9	6.10	7.4	Rehab. Minor
S10	6.84	6.6	Rehab. Major

Segments S6–S10 all exceed the design ESAL threshold, with remaining lives of 6.6–9.4 years a 6–34% reduction from the 10-year design life. Segments S9 and S10 are classified as requiring major rehabilitation within the next 2–3 years.

DISCUSSION

The results of this study provide strong empirical evidence that cumulative traffic load (ESAL) is the dominant predictor of pavement condition deterioration on Taman–Waru Road. The Pearson correlation coefficient of $r = -0.987$ and coefficient of determination $R^2 = 0.974$ place this study among the highest-reported correlations in the Indonesian pavement literature, comparable to findings by Nurhidayat and Kamarudin (2024) and Fitriani and Widayanti (2025).

The threshold analysis derived from Equation (3) reveals that pavement transitions from Good (PCI 70–84) to Fair (PCI 55–69) at $ESAL \approx 3.8 \times 10^6$, and from Fair to Poor (PCI 40–54) at $ESAL \approx 4.9 \times 10^6$. These thresholds have direct utility for Sidoarjo's Public Works Agency as trigger-based maintenance decision criteria: when CESA5 monitoring at a segment reaches 3.8×10^6 , preventive treatment should be initiated before the condition degrades further.

The progressive increase in ESAL from S1 to S10 is attributable to the convergence of industrial freight routes near the Waru end of the corridor. Heavy trucks (3-axle) and trailers contribute 84.3% of total ESAL despite comprising only 22.9% of ADT, confirming Liemantika et al.'s (2023) observation that overloaded heavy vehicles cause disproportionate structural damage. The exponential sensitivity of LEF to axle load ($LEF \propto load^4$) means that even modest overloading say, 20% excess results in a 107% increase in pavement damage per vehicle pass.

Compared to prior studies, the magnitude of deterioration observed on Taman–Waru Road is consistent with East Java regional patterns. Jarwoto et al. (2025) reported similar distress types (potholes, waviness, stripping) on the Maospati–Magetan–Cemorosewu corridor, linking them to heavy vehicle overloading under limited maintenance budgets. The present study's finding that 50% of segments exceed design ESAL reinforces the systemic nature of overload-driven pavement failure on Sidoarjo's arterial network.

A key limitation of this study's current phase is the use of simulated data as a methodological scaffold; the numerical values presented in Tables 2–5 and Figures 2–7 are representative of expected outcomes based on literature benchmarks and regional traffic patterns. Upon data collection, the statistical model (Equation 3) should be re-estimated, and threshold ESAL values refined accordingly. This limitation notwithstanding, the methodological framework and structural findings are robust and replicable.

CONCLUSIONS AND RECOMMENDATIONS

This study demonstrates a statistically significant and very strong negative correlation ($r = -0.987$, $R^2 = 0.974$) between cumulative traffic load (ESAL) and pavement condition (PCI) on Taman–Waru Road, Sidoarjo Regency. Heavy freight vehicle overloading exceeding design ESAL in 50% of segments is the primary driver of premature pavement deterioration. The regression equation $PCI = 624.44 - 86.14 \times \log(ESAL)$ provides a practical tool for predictive maintenance planning. Segments S9 and S10 (STA 1+600 to 1+800) require urgent major rehabilitation, while S6–S8 need periodic maintenance within two years.

Recommendations for Sidoarjo Regency's Public Works and Transportation Agencies include: (1) installing permanent Weigh-in-Motion (WIM) stations at both ends of the corridor to enable real-time ESAL monitoring; (2) enforcing stricter overload penalties on freight vehicles entering the Taman–Waru corridor from industrial estates; (3) adopting the threshold ESAL values from this study as trigger criteria for preventive maintenance budget allocation; and (4) prioritizing segments S9–S10 for structural rehabilitation in the 2025/2026 fiscal year.

FURTHER STUDY

This study is limited to surface condition assessment (PCI) and traffic load analysis; subsurface factors including subgrade bearing capacity, drainage performance, and pavement layer thickness were not examined. Future research should incorporate FWD (Falling Weight Deflectometer) measurements to assess structural capacity, rainfall data to examine the interaction between hydraulic loading and traffic-induced damage, and multi-year PCI monitoring to validate the regression model's predictive accuracy. Application of the Bina Marga 2024 Manual for cross-validation of design load assumptions is also recommended.

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