# DEVELOPING A PREVENTIVE PAVEMENT MAINTENANCE MODEL BASED ON PAVEMENT CONDITION INDEX AND MAINTENANCE COST ANALYSIS

**Muhammad Haris Zalukhu[1)], Bimawijaya Laia[2)], Desman Telaumbanua[3)]**
[1)]Teknik Sipil, Fakultas Sains Dan Teknologi, Universitas Nias, Gunungsitoli, Indonesia
Email: muhhariszalukhu@gmail.com
[2)]Teknik Sipil, Fakultas Sains Dan Teknologi, Universitas Nias, Gunungsitoli, Indonesia
Email: bimawijayalaia12@gmail.com
[3)]Teknik Sipil, Fakultas Sains Dan Teknologi, Universitas Nias, Gunungsitoli, Indonesia
Email: desmantelaumb_4@gmail.com

**Abstract**
Preventive pavement maintenance is an important strategy for preserving road infrastructure serviceability and optimizing maintenance budget allocation. This study aims to develop a preventive pavement maintenance model based on the Pavement Condition Index (PCI) and maintenance cost analysis to support effective and economical maintenance prioritization. A quantitative descriptive and comparative approach was applied using hypothetical simulations of a 2,000-meter road section with a pavement width of 6 meters, divided into ten observation segments. The evaluated parameters included PCI values, surface distress characteristics, preventive treatment feasibility, maintenance quantities, estimated costs, and budget constraint scenarios. The simulation results indicated PCI values ranging from 35 to 88, with an average of 63.7. Four segments were identified as potential candidates for preventive maintenance under assumed technical feasibility criteria, requiring a total estimated cost of IDR 84,000,000. Under a budget scenario of IDR 55,000,000, the proposed prioritization model selected two segments with PCI values of 68 and 72, requiring IDR 54,000,000 and covering a total pavement area of 2,400 m². These findings suggest that integrating PCI assessment with maintenance cost analysis can support more systematic maintenance planning under limited budgets. However, the hypothetical results do not establish long-term treatment effectiveness or optimal budget allocation, as further validation using actual pavement condition surveys and maintenance performance data is required.
**Keywords:** Pavement Condition Index; Preventive Maintenance; Road Pavement; Cost Analysis; Maintenance Prioritization.

## INTRODUCTION

Roads are essential transportation infrastructure that plays a strategic role in supporting economic growth, improving interregional connectivity, and facilitating public mobility and goods distribution. The availability of road networks with satisfactory service conditions is an important factor in supporting social activities, economic development, and regional growth. However, as traffic intensity increases and pavement service life progresses, road pavement conditions deteriorate due to vehicle loading, environmental factors, material characteristics, and drainage conditions. Such deterioration may be characterized by various types of surface distress, including cracking, raveling, potholes, deformation, and pavement edge damage. The Federal Highway Administration (FHWA, 2025) explained that pavement preservation is an integral component of road asset management strategies aimed at maintaining infrastructure conditions through appropriate maintenance measures before deterioration becomes more severe. Therefore, effective road condition management requires a planned, systematic, and sustainable maintenance approach.

Pavement deterioration is a common challenge faced by road authorities because it can reduce driving comfort, increase vehicle operating costs, and affect road user safety. Initially minor pavement defects may develop into more extensive damage if they are not promptly addressed through appropriate maintenance measures. Such conditions may increase the need for rehabilitation or reconstruction, which generally requires greater expenditure than interventions undertaken during the early stages of deterioration. The Directorate General of Highways (2025), through the City Road Maintenance System Guidelines, emphasized the importance of continuous road condition management by considering field inspection results, pavement distress characteristics, and maintenance requirements. This indicates that road maintenance should not be performed only when pavement conditions have deteriorated severely but should instead be planned based on current condition assessments and anticipated pavement performance deterioration.

Preventive pavement maintenance is an approach intended to slow pavement deterioration by implementing maintenance measures before significant reductions in pavement condition occur. This strategy differs from corrective maintenance, which is generally conducted after pavement distress has developed and requires more intensive interventions. Preventive maintenance may include crack sealing, localized repairs, surface treatments, and other preservation measures appropriate to pavement conditions. The Federal Highway Administration (2005) explained that effective pavement preservation programs involve applying suitable maintenance treatments to the right pavement at the right time, thereby delaying the need for relatively expensive rehabilitation and reconstruction. Accordingly, the success of preventive maintenance depends not only on the selected treatment but also on the timing of implementation and its suitability for the

characteristics of pavement distress.

One of the primary challenges in pavement maintenance management is determining the severity of pavement deterioration objectively and consistently as a basis for selecting appropriate treatments. Assessments based solely on general observations may produce inconsistent interpretations among survey personnel, particularly when multiple distress types with varying severity levels are present. Therefore, an assessment method is needed to convert pavement condition observations into quantitative indicators. One such method is the Pavement Condition Index (PCI), a numerical index that represents pavement surface conditions based on the types, severity levels, and extent of identified distress. ASTM International (2024), through ASTM D6433-24, established procedures for visually surveying pavement conditions on roads and parking areas using the PCI method as a basis for condition assessment and maintenance planning. This approach enables pavement conditions to be expressed quantitatively, thereby supporting evaluation processes and maintenance prioritization.

The PCI method offers advantages because it provides a quantitative representation of pavement surface conditions through an index ranging from 0 to 100, with higher values indicating better pavement conditions. The assessment is conducted by identifying distress types, severity levels, and distress quantities within designated sample units. Survey results are subsequently processed to determine condition indices that can be compared across road segments. ASTM International (2024) explained that PCI provides an objective basis for identifying maintenance needs and priorities and can be used to monitor pavement deterioration over time. However, PCI does not directly measure pavement structural capacity, skid resistance, or surface roughness. Therefore, its application in selecting maintenance alternatives should be supplemented by other technical considerations, particularly when surface distress indicates potential problems within the pavement structure or underlying subgrade.

In addition to pavement condition assessment, cost considerations play an important role in determining the success of road maintenance programs. Budget constraints frequently require road authorities to prioritize certain road sections or segments based on maintenance needs and expected benefits. Under such circumstances, selecting maintenance programs solely according to the highest distress severity does not necessarily produce the most efficient allocation of financial resources. Road segments in relatively good condition or exhibiting minor deterioration may provide greater preservation benefits if treated before distress progresses. The Federal Highway Administration (2017) explained that maintenance treatment effectiveness should be evaluated by considering pavement condition improvements, treatment costs, and implementation timing. Consequently, maintenance prioritization requires an approach that integrates actual pavement conditions with treatment costs and expected technical benefits throughout the service period.

Maintenance cost analysis can be used to evaluate budget requirements for various pavement treatment alternatives. These costs are influenced by distress type, severity level, treatment area, construction methods, material prices, equipment requirements, and labor expenses. In addition to initial implementation costs, maintenance evaluations may consider repeated treatments and future rehabilitation requirements. Life-Cycle Cost Analysis (LCCA) is a relevant approach because it enables comparisons among maintenance alternatives based on costs incurred throughout an established analysis period. Kim et al. (2026) developed a framework for determining preventive maintenance timing on expressway pavements by integrating pavement deterioration models with life-cycle cost analysis. Their research demonstrated that maintenance timing influences long-term cost efficiency. Therefore, combining pavement condition indicators with economic analysis can provide a more rational foundation for decision-making than relying on either indicator independently.

Preventive maintenance planning is also closely related to pavement deterioration characteristics throughout its service life. Newly constructed pavements or pavements in good condition generally have different maintenance requirements from those experiencing moderate or severe deterioration. If maintenance treatments are implemented too early, the additional benefits may be relatively limited compared with the expenditure involved. Conversely, delayed intervention may allow pavement distress to develop further, requiring more expensive rehabilitation measures. Kim et al. (2026) demonstrated that integrating pavement deterioration modeling with LCCA could help identify more economically efficient maintenance timing. These findings indicate that preventive maintenance planning should consider relationships among initial pavement conditions, anticipated distress progression, maintenance treatment characteristics, and cost changes throughout the analysis period. Thus, developing effective maintenance models requires the integration of pavement condition indicators and economic evaluation approaches.

In the context of road management in Indonesia, pavement maintenance requires evaluation systems capable of supporting objective maintenance prioritization, particularly for regional road networks with limited financial and operational resources. The Directorate General of Highways (2025), through the City Road Maintenance System Guidelines, or City Road Management System (CRMS), developed a road asset management approach integrating condition inspections, data management, and maintenance planning. These guidelines emphasize the importance of periodic road condition assessments as a basis for evaluating pavement preservation program effectiveness. Nevertheless, the PCI method in this study should be positioned as a pavement surface condition assessment tool that complements road management systems rather than replacing all parameters within the CRMS framework. Integrating PCI survey results, pavement distress characteristics, and estimated treatment costs could provide a simpler and more practical decision-support approach for road authorities when determining preventive maintenance requirements.

Previous studies and technical guidelines have established foundations for developing pavement condition assessment methods and preventive maintenance strategies. ASTM International (2024) provided systematic procedures for

determining PCI values through visual surveys of pavement surface distress. The Federal Highway Administration (2017) discussed relationships among pavement performance changes, maintenance treatment effectiveness, and optimal intervention timing based on economic considerations. Kim et al. (2026) developed a preventive maintenance framework integrating pavement deterioration predictions and life-cycle costs for expressway networks. Meanwhile, the Directorate General of Highways (2025) provided a city road maintenance management framework supporting systematic road asset management. Collectively, these studies and technical guidelines demonstrate that pavement condition assessment, maintenance timing, and cost efficiency are essential components of road management systems. However, integrating these components requires adjustments based on road characteristics, data availability, and decision-making requirements at the road section or segment level.

Based on this literature review, the research gap addressed in the present study is the need to develop a preventive pavement maintenance model that integrates PCI assessment results, treatment alternatives, cost estimates, and maintenance priorities at the individual road segment level. Pavement condition assessment alone is insufficient to determine the most efficient maintenance alternative without evaluating treatment requirements and their cost implications. Similarly, selecting treatments solely according to the lowest implementation costs may not provide optimal outcomes if pavement conditions and technical requirements are overlooked. The proposed novelty of this study lies in developing an integrated evaluation framework incorporating PCI values, distress characteristics and severity levels, preventive maintenance alternatives, treatment unit costs, and cost-effectiveness indicators for maintenance prioritization. The proposed model is expected to provide a more measurable basis for determining appropriate treatments and allocating maintenance budgets while considering technical feasibility and potential preservation benefits.

Based on the identified problems, this study aims to develop a preventive pavement maintenance model based on the Pavement Condition Index and maintenance cost analysis to support effective and efficient decision-making. The analysis focuses on identifying pavement surface distress types and severity levels, determining PCI values for individual road segments, evaluating maintenance treatment alternatives according to distress characteristics, and estimating treatment costs based on work quantities and relevant unit prices. Subsequently, pavement condition and cost assessment results are integrated to develop a maintenance prioritization model that considers technical requirements, potential benefits, and budget limitations. This study is expected to contribute to the scientific development of data-driven preventive pavement maintenance approaches integrating pavement condition assessment and economic analysis. Furthermore, the proposed framework may serve as a reference for road authorities in planning more targeted, economical, and sustainable pavement preservation programs.

## RESEARCH METHODOLOGY

### 3.1. Research Design and Approach

This study was designed using a quantitative approach incorporating descriptive, evaluative, and comparative methods to develop a preventive pavement maintenance model based on the Pavement Condition Index (PCI) and maintenance cost analysis. The quantitative approach was employed to measure pavement distress conditions, determine the condition level of each road segment, calculate maintenance work requirements, and evaluate treatment costs for the proposed alternatives. The descriptive method was applied to identify pavement surface distress characteristics, while the evaluative method was used to assess the suitability of maintenance treatments for existing road conditions. Comparative analysis was conducted by examining maintenance alternatives based on estimated costs, distress characteristics, and anticipated technical benefits. The model development process aimed to establish a maintenance prioritization system that integrates actual pavement conditions, treatment requirements, and budget constraints. This approach incorporated pavement preservation principles that emphasize selecting appropriate treatments and implementing them at the right time to control pavement deterioration more effectively.

### 3.2. Research Object and Scope

The research focused on flexible road pavements with asphalt surface layers that had been operating as part of the land transportation network. The scope of the study included pavement surface distress identification, pavement condition assessment using the PCI method, selection of preventive maintenance alternatives, and estimation of treatment costs. The study was designed to be conducted on selected road sections based on the availability of geometric information, accessibility for pavement condition inspections, and maintenance evaluation requirements. The units of analysis consisted of road segments subdivided into sample units according to PCI survey procedures. The geometric characteristics considered included road section length, pavement width, surface area, and environmental conditions that could influence pavement deterioration, such as drainage conditions and vehicle activity. The study was limited to evaluating pavement surface functional conditions and maintenance requirements identifiable through visual surveys. Where indications of structural deterioration were identified, PCI assessment results were supplemented by recommendations for further investigation because PCI values cannot directly determine the structural capacity of pavement layers.

### 3.3. Types and Sources of Data

The research data consisted of primary and secondary information used to assess pavement conditions and maintenance cost requirements. Primary data were planned to be obtained through visual pavement surveys by recording

distress types, severity levels, affected areas or lengths, and distress locations within each sample unit. Primary data also included measurements of road segment lengths and widths, photographic documentation of field conditions, and observations of drainage and surrounding environmental conditions. Secondary data were obtained from road inventory documents, construction and maintenance histories, traffic information, construction unit price schedules, technical specifications, and available road maintenance planning documents. These data were used to characterize road sections and support calculations of maintenance work quantities and cost estimates. All information was organized according to road identification, road location or stationing, and sample unit to ensure that relationships among pavement distress, PCI values, maintenance treatments, and costs could be systematically traced.

### 3.4. Data Collection Techniques and Pavement Condition Surveys

Data collection was conducted through direct visual surveys of pavement surfaces following the principles of ASTM D6433-24 for pavement condition assessment using the PCI method. The survey process began with measurements of pavement length and width, followed by subdivision of the road section into sample units according to the applicable methodology. Each sample unit was subsequently inspected to identify distress types, severity levels, and distress quantities. The observed distress types included alligator cracking, longitudinal and transverse cracking, edge cracking, potholes, patching, rutting, raveling, and other distress forms relevant to flexible pavements. Distress severity was classified as low, medium, or high according to the evaluation procedures applicable to each distress type. Distress areas, lengths, or quantities were recorded using measurement units specified in ASTM D6433-24. Field observations were supported by photographic documentation and location records to ensure that the condition of each sample unit could be reviewed and verified. Surveys were performed with consideration for the safety of survey personnel and road users to minimize disruption to traffic operations.

### 3.5. Pavement Condition Index (PCI) Analysis

PCI analysis was conducted to obtain numerical indicators of pavement surface conditions based on distress survey results for each sample unit. Data processing began by determining distress density from the measured distress quantity relative to the sample unit area or other measurement units required by the standard. Subsequently, the Deduct Value (DV) was determined according to distress type, severity level, and density using the curves or procedures established in ASTM D6433-24. When multiple distress types were present within a sample unit, the deduct values were evaluated using the correction procedure to obtain the appropriate Corrected Deduct Value (CDV). PCI values were determined by subtracting the relevant corrected deduct value from the maximum pavement condition score. The resulting PCI values ranged from 0 to 100, with higher values representing better pavement surface conditions. PCI values at the road section level were determined by aggregating sample unit results using procedures consistent with the sampling design and standard requirements. The assessment results were then classified into pavement condition categories to identify deterioration levels and maintenance evaluation requirements for individual road segments.

### 3.6. Identification of Preventive Maintenance Alternatives

Preventive maintenance alternatives were identified based on PCI assessment results, dominant distress types, severity levels, and pavement characteristics within each road segment. Treatment alternatives were developed according to the objectives of preventive maintenance, namely slowing pavement deterioration and maintaining serviceability before more extensive rehabilitation becomes necessary. For segments exhibiting localized cracking without indications of structural failure, appropriate treatments could include crack filling or crack sealing using suitable materials. For segments with more widespread surface distress but adequate structural conditions, surface preservation treatments could be considered based on technical characteristics and implementation requirements. Localized patching could also be planned to repair specific damaged areas before applying other preservation treatments. Conversely, segments exhibiting severe distress, significant deformation, or indications of structural failure were not automatically included in preventive maintenance programs but were instead recommended for further investigation and rehabilitation assessment. Treatment alternatives were selected by ensuring compatibility among distress characteristics, maintenance objectives, and the ability of the proposed methods to preserve pavement performance.

### 3.7. Analysis of Maintenance Work Requirements

Maintenance work requirements were analyzed by identifying treatment quantities based on distress survey results and the selected maintenance alternatives. Each treatment was quantified using appropriate work units, such as the length of cracks requiring sealing, the area requiring patching, or the surface area requiring preservation treatments. Quantity calculations considered distress locations, severity levels, and treatment boundaries to avoid double counting overlapping work areas. For crack sealing, treatment requirements were determined based on the length of cracks meeting the applicable technical criteria. Patching quantities were calculated from distress areas or volumes according to the proposed construction methods. For surface preservation treatments, work requirements were determined based on the pavement area suitable for the selected treatment. Calculated quantities were subsequently grouped by road segment and maintenance alternative to provide the basis for cost estimation and budget requirement comparisons. This analysis aimed to establish a clear relationship between PCI survey findings and the quantities of maintenance work required to maintain road serviceability.

### 3.8. Pavement Maintenance Cost Analysis

Pavement maintenance costs were analyzed by estimating the implementation cost of each treatment alternative based on work quantities and relevant unit prices. Cost components included materials, labor, equipment, and supporting requirements associated with the selected construction methods. Unit prices were developed using appropriate pricing references and construction unit price analyses corresponding to the project location and planning period. The total cost of each alternative was calculated by summing the products of work quantities and their respective unit prices. Calculations were performed consistently to ensure that cost differences among road segments reflected variations in treatment types and work quantities. The analysis also considered relevant additional expenses, including equipment mobilization, traffic management, and location-specific implementation requirements. Cost estimates were used to compare the budget requirements of individual alternatives and identify treatments with costs appropriate to pavement conditions. Economic evaluation considered not only the lowest initial expenditure but also treatment suitability and the potential need for subsequent maintenance.

### 3.9. Maintenance Cost-Effectiveness Analysis

Cost-effectiveness analysis was conducted to evaluate the relationship between maintenance budget requirements and the technical benefits expected from each treatment alternative. Maintenance benefits were assessed according to the ability of treatments to maintain or improve pavement conditions, slow distress progression, and delay the need for more extensive rehabilitation. The evaluation involved comparing treatment costs with anticipated pavement condition changes over the analysis period. Where historical pavement condition data and maintenance treatment performance records were available, benefits could be estimated from changes in PCI values over time or the duration for which pavement conditions could be maintained at a specified serviceability level. However, when historical data were unavailable, the analysis was limited to comparisons of treatment costs and technical feasibility without claiming unverified extensions of pavement service life. Long-term economic evaluation could be developed using a Life-Cycle Cost Analysis (LCCA) approach that incorporates repeated maintenance costs, rehabilitation expenditures, and the time value of money over a consistent analysis period. The evaluation results were intended to identify maintenance alternatives offering greater potential technical benefits relative to their associated costs.

### 3.10. Development of a Preventive Maintenance Prioritization Model

The preventive maintenance prioritization model was developed by integrating PCI assessment results, distress characteristics, treatment feasibility, maintenance work requirements, and estimated costs. The initial stage involved classifying road segments according to pavement condition and dominant distress types. Each segment was then evaluated to determine whether preventive maintenance remained technically appropriate or whether alternative interventions were necessary. Segments meeting preventive maintenance requirements were subsequently assessed based on treatment urgency, implementation costs, and anticipated technical benefits. Priorities were established by considering treatment needs, the potential to prevent further deterioration, and available budget limitations. Where technical benefits could be quantified using historical performance data or validated pavement deterioration models, maintenance priorities were determined by comparing expected benefits with costs. When such data were unavailable, the model relied on assessments of technical feasibility, pavement condition, treatment requirements, and costs, while explicitly limiting its conclusions to preliminary maintenance priorities. Through this approach, the model was expected to generate systematic recommendations concerning treatment types, intervention locations, priority rankings, and estimated budget requirements.

### 3.11. Maintenance Budget Scenario Analysis

Budget scenario analysis was conducted to evaluate the model's ability to determine appropriate maintenance programs under limited funding conditions. Several scenarios were developed based on variations in available budgets for treating road segments considered suitable for preventive maintenance. Under each scenario, maintenance alternatives were selected according to established priorities while considering the number of segments that could be treated, estimated costs, and anticipated technical benefits. Treatment programs were selected to ensure that total implementation costs did not exceed the specified budget limits. Where multiple treatment alternatives were available for the same road segment, the model was designed to select one alternative considered most appropriate based on technical feasibility and economic evaluation, thereby preventing double counting of costs or benefits. The results were compared to determine how changes in available budgets influenced maintenance coverage and the quantities of work remaining untreated. This approach enabled the model to illustrate the technical and economic consequences of road maintenance funding constraints.

### 3.12. Validation and Evaluation of the Maintenance Model

Model validation was conducted by examining the consistency of maintenance prioritization results, the suitability of maintenance alternatives for identified distress characteristics, and the accuracy of estimated costs. PCI values incorporated into the model were checked against survey data and the applied calculation procedures, while recommended treatment types were evaluated in accordance with pavement maintenance principles and relevant technical requirements. Cost verification involved tracing relationships among treatment areas or quantities, unit prices, and total estimated budgets.

Where previous maintenance implementation data were available, model outputs could be compared with completed treatments to assess the appropriateness of the recommendations. Pavement engineering specialists could also be involved in reviewing the technical feasibility of the proposed alternatives. Sensitivity testing was conducted by varying unit costs and budget limits to evaluate the stability of maintenance priority rankings. Validating long-term maintenance benefits would require post-treatment pavement condition data or calibrated deterioration models. Therefore, validation distinguished between the consistency of planning-stage decisions and evidence demonstrating maintenance effectiveness throughout the pavement service period.

### 3.13. Data Processing and Interpretation Techniques

Data obtained from PCI surveys, pavement distress inventories, and cost calculations were processed using descriptive and comparative quantitative analysis. Initial data processing involved checking the completeness of distress records, identifying sample units, and calculating PCI values in accordance with the specified procedures. The resulting condition assessments were then organized by road segment to identify distress distributions and maintenance requirements. Treatment quantity data were processed to estimate the costs of individual alternatives, which were subsequently compared with pavement conditions and budget constraints. The analytical results were presented through PCI distribution tables, pavement condition graphs, alternative treatment cost comparisons, and maintenance priority matrices to clarify the relationships between technical and economic indicators. Interpretation considered treatment suitability, potential preservation benefits, cost efficiency, and model limitations. Research conclusions were developed from the integrated evaluation results to ensure that preventive maintenance recommendations could provide a basis for more targeted, economical, and sustainable pavement preservation planning.

## RESULTS AND DISCUSSION

### 4.1. Road Section Characteristics and Initial Pavement Conditions

This study employed a simulation model of a flexible pavement road section measuring 2,000 meters in length and 6 meters in width, resulting in a total pavement surface area of 12,000 m². The road section was divided into ten segments, each measuring 200 meters in length and covering an area of 1,200 m². This segmentation was used as the basis for comparative analysis to evaluate variations in pavement conditions and maintenance requirements. In actual PCI applications, each segment must be further subdivided into sample units in accordance with ASTM D6433 and the applicable sampling procedures. The pavement conditions in this model were assumed to exhibit varying levels of deterioration caused by traffic loading, service age, environmental influences, and drainage conditions. The types of pavement distress considered included longitudinal cracking, transverse cracking, alligator cracking, raveling, potholes, and other localized surface defects.

The simulated initial conditions indicated variations in pavement deterioration among road segments. Segments in relatively good condition exhibited limited surface distress, whereas segments in moderate condition showed greater distress quantities and severity levels. In several segments, combinations of extensive cracking, potholes, and localized deformation indicated the need for further investigation to determine whether preventive maintenance remained technically appropriate. These differences suggested that applying a single maintenance treatment uniformly across an entire road section might not produce efficient results. Maintenance interventions should therefore consider the characteristics of individual road segments to ensure that the selected treatments correspond to their technical requirements.

### 4.2. Pavement Condition Index (PCI) Analysis

Pavement condition analysis was conducted using the Pavement Condition Index (PCI) as the primary indicator for representing pavement surface conditions. In the simulation model, PCI values for the ten road segments were sequentially assigned as 88, 82, 76, 72, 68, 64, 58, 52, 42, and 35. All values were hypothetical assumptions representing variations in pavement conditions rather than results calculated from actual distress inventories using Deduct Value (DV) and Corrected Deduct Value (CDV) procedures. Because all segments had equal surface areas, the average PCI value was calculated as 63.7. This value indicated that pavement conditions varied considerably, ranging from relatively good conditions to segments exhibiting more extensive deterioration.

The differences in PCI values demonstrated the importance of selecting maintenance interventions according to individual segment conditions. Segments with PCI values of 88 and 82 were assumed to remain in relatively good surface condition and could therefore be considered for minor maintenance activities or periodic monitoring. Segments with PCI values of 76, 72, and 68 were considered potential candidates for preventive maintenance, provided that the identified distress types satisfied the relevant technical criteria. Meanwhile, segments with PCI values of 64, 58, and 52 required more detailed technical evaluations because their maintenance requirements might involve more extensive localized repairs. Segments with PCI values of 42 and 35 were not automatically included in the preventive maintenance program due to the possibility that rehabilitation or structural capacity assessments would be necessary.

These results indicated that PCI values could provide an initial basis for categorizing maintenance requirements but should not be used as the sole criterion for selecting appropriate treatments. Two road segments with identical PCI values may require different maintenance measures when their distress types and severity levels differ. For example, pavement exhibiting nonstructural surface cracking may require treatments different from those appropriate for pavement with

alligator cracking and deformation indicating deterioration in underlying structural layers. Consequently, PCI interpretation should be integrated with pavement distress inventories and relevant technical investigations.

### 4.3. Identification of Pavement Distress Types and Maintenance Requirements

Pavement distress identification in the research model was performed by distinguishing minor, moderate, and severe deterioration based on assumed visual characteristics within each segment group. Minor distress was predominantly represented by longitudinal and transverse cracking without indications of structural failure. Moderate distress included combinations of cracking, raveling, and localized damage requiring repair before surface treatment applications. In segments exhibiting poorer pavement conditions, distress was assumed to include more extensive cracking, potholes, and localized deformation, indicating the need for further investigation to determine the depth and underlying causes of deterioration.

Based on these characteristics, the maintenance alternatives considered included crack sealing, localized patching, and surface preservation treatments. Crack sealing was intended for pavement areas exhibiting cracking that satisfied the relevant technical criteria, primarily to reduce water infiltration into pavement layers. Localized patching was considered for repairing limited damaged areas, while surface preservation treatments were proposed for maintaining pavements that retained adequate structural integrity. The selection of maintenance treatments should consider pavement material characteristics, drainage conditions, traffic characteristics, and applicable technical specifications.

The conceptual evaluation suggested that preventive maintenance was most appropriate for road segments that retained adequate structural conditions and exhibited surface distress that could be effectively controlled through preservation treatments. Conversely, applying surface treatments to conceal structural deterioration could produce limited benefits because the underlying causes of pavement failure would remain unresolved. Therefore, the maintenance model should incorporate a mechanism for distinguishing segments suitable for preventive maintenance from those requiring rehabilitation.

### 4.4. Development of the Preventive Pavement Maintenance Model

The preventive pavement maintenance model was developed by integrating PCI values, pavement distress characteristics, technical feasibility, and maintenance cost requirements. Within the proposed framework, the evaluation process began by identifying pavement conditions in each road segment and subsequently determining whether the observed distress could be treated through preventive maintenance. Segments satisfying the technical requirements were then compared according to maintenance urgency, implementation costs, and anticipated preservation benefits. This approach was designed to prevent maintenance decisions from being based exclusively on the lowest PCI values or the least expensive treatment alternatives.

The model employed three principal decision-making stages. The first stage involved technical feasibility assessment to determine whether the proposed maintenance treatment was suitable for the existing pavement conditions. The second stage involved evaluating maintenance requirements by considering distress severity and the risk of further deterioration if treatment was delayed. The third stage consisted of cost comparisons to identify maintenance alternatives that could be implemented within available budget limitations. In the simulation model, segments with PCI values ranging from 68 to 82 were assumed to represent the primary candidates for preventive maintenance. Segments in better condition were assigned to periodic monitoring and minor treatments when necessary. Meanwhile, segments with PCI values of 64 or lower required additional assessments before determining whether preventive maintenance remained appropriate or whether other interventions were necessary.

The proposed model provided a more structured approach to maintenance planning by evaluating pavement conditions, distress characteristics, and cost requirements simultaneously. Nevertheless, the PCI thresholds used in this illustration represented research-specific decision rules rather than universal requirements automatically determining the suitability of all maintenance treatments. Practical implementation would require adjustments based on distress characteristics, maintenance histories, traffic conditions, and the technical specifications of individual treatment methods.

### 4.5. Pavement Maintenance Cost Analysis

Maintenance cost analysis was performed to estimate the budget requirements associated with each treatment alternative based on assumed pavement conditions and distress characteristics. In the research model, four segments with PCI values of 82, 76, 72, and 68 were selected as preventive maintenance candidates after being assumed to satisfy preliminary technical feasibility assessments. Each segment covered an area of 1,200 m², resulting in a total candidate treatment area of 4,800 m². Cost calculations considered different maintenance requirements, ranging from crack treatments and localized repairs to surface preservation interventions. The unit prices used in the simulation represented assumed treatment package costs per unit of segment area rather than officially established construction unit price analyses.

The hypothetical calculations indicated that the segment with a PCI value of 82 required an estimated maintenance cost of IDR 12,000,000, while the segment with a PCI value of 76 required IDR 18,000,000. For the segment with a PCI value of 72, the estimated cost increased to IDR 24,000,000, whereas the segment with a PCI value of 68 required IDR 30,000,000. Consequently, the total estimated budget required to treat all four segments reached IDR 84,000,000. These cost differences reflected the assumption that declining pavement conditions were associated with increasing treatment

areas or work intensity. However, this relationship does not necessarily apply to all road conditions because maintenance costs are also influenced by treatment types, distress severity, equipment mobilization, and site-specific construction characteristics.

The simulation results illustrated that increasing maintenance requirements in deteriorated segments emphasized the importance of implementing appropriate interventions before pavement distress became more severe. Nevertheless, these findings did not demonstrate that earlier maintenance interventions would always result in lower life-cycle costs. Establishing long-term economic benefits would require data concerning pavement deterioration rates, treatment effectiveness periods, repeated maintenance costs, and potential future rehabilitation requirements. Therefore, the cost estimates developed in this study were intended to support preliminary budget allocation rather than to establish definitive life-cycle cost savings.

### 4.6. Evaluation of Preventive Maintenance Cost-Effectiveness

Maintenance cost-effectiveness was evaluated by considering the relationship between estimated expenditures and the technical benefits expected from each maintenance treatment. In preventive maintenance, the primary benefit does not necessarily involve an immediate and substantial increase in PCI values following treatment implementation. Instead, benefits may include slowing pavement deterioration and postponing the need for rehabilitation. Consequently, treatments producing relatively small immediate improvements in pavement surface conditions may still provide substantial value if they maintain adequate serviceability over longer periods.

Within the simulation model, segments with PCI values of 82 and 76 required lower maintenance expenditures than those with PCI values of 72 and 68. This illustrated that treating pavement during the early stages of deterioration could potentially require smaller maintenance budgets. However, selecting the least expensive treatment does not necessarily represent the optimal decision when other segments exhibit more urgent maintenance requirements or greater risks of progressive deterioration. Cost-effectiveness should therefore be evaluated according to anticipated preservation benefits rather than initial expenditures alone.

In a more comprehensive model, economic effectiveness could be analyzed using Life-Cycle Cost Analysis (LCCA), incorporating initial treatment costs, recurring maintenance requirements, potential rehabilitation expenditures, and pavement service periods. Such an approach would enable evaluation of the long-term consequences of maintenance interventions. However, because the research model did not include historical PCI deterioration data or verified treatment effectiveness periods, the present evaluation was limited to cost comparisons and technical feasibility assessments. These results could still support preliminary treatment selection but could not establish definitive long-term economic benefits.

### 4.7. Maintenance Priority Analysis Based on Pavement Conditions and Costs

Maintenance prioritization was conducted by integrating PCI values, distress characteristics, technical feasibility, and estimated treatment costs. Within the simulation model, four road segments with PCI values of 82, 76, 72, and 68 were identified as preventive maintenance candidates under the assumption that their deterioration could still be addressed without structural rehabilitation. Priority rankings were then determined by emphasizing segments with more urgent preservation requirements while considering the potential progression of deterioration if treatment was postponed. To illustrate the application of the model, the segment with a PCI value of 68 was assigned the highest priority, followed by segments with PCI values of 72, 76, and 82.

This ranking represented a hypothetical prioritization rule based on the assumption that all four segments had comparable traffic conditions, road functions, and environmental risks. Under actual operating conditions, segments with higher PCI values could receive greater priority if they experienced heavier traffic, performed strategic transportation functions, or exhibited distress types likely to deteriorate more rapidly. Conversely, segments with lower PCI values might require rehabilitation rather than preventive maintenance. Therefore, PCI values were used as one of several indicators in prioritization rather than as the sole basis for maintenance decisions.

This approach demonstrated the importance of integrating pavement condition evaluations with budget requirements to establish more targeted maintenance programs. The model could assist road authorities in identifying segments requiring intervention, selecting appropriate treatments, and estimating financial requirements. However, the effectiveness of these decisions would remain dependent on survey data quality, accurate distress assessments, and consistent treatment selection criteria.

### 4.8. Analysis of Maintenance Budget Constraint Scenarios

Budget limitations represent one of the major factors influencing the implementation of pavement maintenance programs. In this simulation, the total estimated maintenance cost for the four preventive maintenance candidate segments amounted to IDR 84,000,000, while the assumed available budget was limited to IDR 55,000,000. This condition resulted in a funding shortfall of IDR 29,000,000 if all proposed treatments were implemented within the same period. Therefore, selecting maintenance interventions according to established priorities and available financial resources was necessary.

Using the hypothetical priority rankings, the segments with PCI values of 68 and 72 were selected for treatment during the first implementation period. Their estimated costs were IDR 30,000,000 and IDR 24,000,000, respectively, producing a combined expenditure of IDR 54,000,000. This amount remained below the available budget of IDR

55,000,000, leaving an unallocated balance of IDR 1,000,000. The two selected segments had a combined length of 400 meters and a total treatment area of 2,400 m², representing 50% of the total area of the four preventive maintenance candidates. Meanwhile, the segments with PCI values of 76 and 82 were not allocated maintenance funding during the initial period and were scheduled for monitoring and potential treatment in subsequent periods, depending on their condition development.

These simulation results demonstrated that the prioritization model could be used to develop maintenance programs compatible with financial constraints. However, selecting two segments with a combined cost of IDR 54,000,000 did not establish that this combination would maximize benefits compared with other possible treatment combinations. Demonstrating optimality would require comparable benefit indicators, such as the estimated extent of deterioration prevented, predicted changes in pavement conditions over the analysis period, or preservation benefits established using historical performance data. Therefore, the treatment selection presented in this study was interpreted as an illustrative application of prioritization rules rather than the outcome of a validated mathematical optimization model.

### 4.9. Performance Evaluation of the Preventive Pavement Maintenance Model

Model performance was evaluated by examining the ability of the proposed decision-making framework to integrate pavement conditions, maintenance requirements, and treatment costs. Based on the simulation, the model distinguished segments in relatively good condition, segments considered suitable for preventive maintenance, and segments requiring further technical investigation. The model also generated estimated maintenance costs and treatment priority rankings based on predefined assumptions. These outcomes suggested that integrating PCI assessment and cost analysis could support more systematic pavement maintenance planning.

One of the principal advantages of this approach was its ability to link pavement condition information with budget requirements at the road segment level. By using consistent analytical units, road authorities could identify distress locations, pavement conditions, potential maintenance alternatives, and estimated funding requirements. Such information could improve transparency in maintenance program development because treatment selection could be explained using measurable technical and economic indicators.

Nevertheless, the developed model remained limited in its ability to evaluate long-term maintenance effectiveness. The PCI values were not derived from actual pavement surveys, while estimated costs were not calculated using verified distress quantities and construction unit prices. Furthermore, the model did not incorporate post-maintenance pavement performance data, preventing empirical assessment of treatment effects on pavement service life. Consequently, the evaluation at this stage demonstrated the internal consistency of the decision-making framework and budget calculations rather than the technical effectiveness of maintenance interventions implemented in actual road projects.

### 4.10. Implications for Sustainable Road Infrastructure Management

The development of a preventive pavement maintenance model integrating PCI and cost analysis has implications for improving road infrastructure management effectiveness, particularly under limited maintenance budgets. An approach combining pavement condition assessment, distress characteristics, treatment requirements, and costs could reduce dependence on maintenance decisions based solely on general visual observations or the most severe pavement deterioration. Consequently, maintenance planning could be directed toward preserving pavement conditions before extensive rehabilitation becomes necessary.

From a technical perspective, the model provided a basis for distinguishing preventive maintenance treatments from rehabilitation requirements according to pavement distress characteristics. From an economic perspective, it enabled the development of cost estimates and maintenance priorities consistent with financial constraints. From a sustainability perspective, appropriately timed preventive maintenance could potentially extend pavement service life and reduce the demand for new construction materials compared with more extensive rehabilitation. However, the magnitude of these potential benefits would still require verification through life-cycle assessment and actual pavement performance data.

In practical applications, the model could be further developed into a decision-support system for regional road networks by integrating PCI survey results, road inventories, maintenance histories, traffic data, and construction unit prices. Such a system could support periodic pavement condition evaluations, maintenance requirement updates, and the preparation of annual priority-based maintenance programs. Therefore, model development would not only address existing pavement deterioration but also support the prevention of further distress progression and improvements in long-term road asset management efficiency.

### 4.11. Research Limitations and Future Development

This study has several limitations because all numerical data were derived from hypothetical simulations. PCI values, pavement distress characteristics, maintenance costs, and priority rankings were not obtained through actual field inspections or evaluations of completed road projects. Therefore, the findings cannot be used directly as a basis for implementing maintenance interventions on specific road sections without additional surveys, calculations, and technical verification.

Future research should incorporate actual pavement distress survey data collected in accordance with ASTM D6433 procedures, including distress types, severity levels, distress quantities, and PCI calculations for individual sample units.

These data should be supplemented with traffic information, drainage conditions, pavement structural characteristics, and maintenance histories to ensure the appropriate selection of preventive treatments. Maintenance cost analysis should also use work quantities derived from actual pavement conditions and unit prices corresponding to the project location and planning period.

To strengthen the scientific contribution of the model, future studies could investigate relationships between changes in PCI values and maintenance treatment effectiveness using periodic pavement condition monitoring data. The resulting information could support life-cycle cost analysis and budget allocation optimization, allowing maintenance priorities to be determined not only from initial pavement conditions but also from anticipated preservation benefits throughout the pavement service period. Through this approach, the preventive pavement maintenance model could be further developed into a more measurable, practical, and technically and economically defensible decision-support tool.

## CONCLUSIONS

Based on the results of the analysis and discussion, it can be concluded that the development of a preventive pavement maintenance model based on the Pavement Condition Index (PCI) and maintenance cost analysis has the potential to improve the effectiveness of road maintenance planning through a measurable, systematic, and economically efficient approach. The hypothetical simulation results for a 2,000-meter-long road section with a pavement width of 6 meters indicated that pavement conditions exhibited varying levels of deterioration, with PCI values ranging from 35 to 88 and an average value of 63.7. These variations highlighted the importance of selecting appropriate maintenance treatments based on the characteristics and severity levels of pavement distress within each road segment. Segments with relatively good pavement conditions could be considered for minor maintenance or periodic monitoring, while segments experiencing moderate deterioration could potentially receive preventive maintenance treatments, provided that they satisfied the relevant technical requirements. Meanwhile, segments exhibiting more severe deterioration required further investigation to determine whether rehabilitation was necessary. Therefore, PCI assessment should be integrated with distress identification and technical evaluation to ensure that the selected maintenance treatments are appropriate for existing pavement conditions.

From an economic perspective, the simulation results indicated that four road segments assumed to meet the criteria for preventive maintenance required a total estimated budget of IDR 84,000,000. Under an available budget constraint of IDR 55,000,000, the developed prioritization model produced a maintenance scenario involving two segments with PCI values of 68 and 72, requiring a total expenditure of IDR 54,000,000. These interventions covered a combined road length of 400 meters and a pavement area of 2,400 m², representing 50% of the total area of the segments identified as preventive maintenance candidates. These findings demonstrated that integrating pavement condition indicators with cost estimates could provide a basis for establishing maintenance priorities according to available financial resources. Nevertheless, the selected interventions were based on hypothetical prioritization rules and did not demonstrate that the chosen combination would maximize technical or economic benefits. Evaluating long-term cost-effectiveness would require historical pavement deterioration data, information on maintenance treatment effectiveness and service life, and comprehensive Life-Cycle Cost Analysis (LCCA).

Overall, this study demonstrated that developing a preventive pavement maintenance model integrating PCI values, distress characteristics, technical feasibility, treatment alternatives, and cost analysis could provide a practical decision-support approach for road infrastructure management. The proposed model has the potential to assist road authorities in identifying priority locations, selecting appropriate maintenance treatments, and allocating financial resources more effectively. The implementation of appropriate preventive maintenance measures is expected to slow pavement deterioration, maintain road service quality, and reduce the need for more extensive rehabilitation in the future. However, because the study relied entirely on hypothetical simulation data, the findings cannot be generalized to actual pavement conditions. Therefore, further research should incorporate verified PCI survey data, construction unit price analyses reflecting actual project conditions, and monitoring of pavement condition changes following maintenance implementation. Through these improvements, the proposed model could be further developed into a more accurate, efficient, and sustainable preventive maintenance planning system to support effective road asset management.

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