# Evaluation of road pavement maintenance: A literature review

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## Abstract

**Aim:** This study examines existing pavement maintenance planning strategies to enhance road durability, reduce lifecycle costs, and support long-term infrastructure sustainability. It identifies research gaps, methodological limitations, and key challenges within current pavement management practices to optimize maintenance planning and decision-making processes.

**Methodology:** A structured literature review was conducted, primarily utilizing the Scopus database to retrieve peer-reviewed journal articles published within the last decade. The synthesis focused on the application of advanced computational and decision-making frameworks. Specifically, the review analyzed the implementation of Markov modeling for performance prediction, Multi-Criteria Decision Analysis (MCDA) for multi-objective optimization, and the integration of Geographic Information Systems (GIS) for spatial data management. Furthermore, the study evaluated the role of Artificial Neural Networks (ANN) in distress forecasting and the use of AHP–VIKOR prioritization frameworks for ranking maintenance interventions under conflicting criteria.

**Results:** The review reveals a transition toward preventive and performance-based models supported by data-driven systems. Key findings highlight that Markov models remain a staple for stochastic degradation modeling, while ANN provides high-accuracy predictive capabilities for complex datasets. GIS integration significantly improves the visualization of network-level needs, and AHP–VIKOR frameworks effectively bridge the gap between technical requirements and budgetary constraints through robust prioritization. However, limitations persist, including the insufficient integration of real-time data, inconsistencies in performance metrics, and a lack of standardized hybrid models that combine these analytical tools for varying environmental and traffic conditions.

**Conclusion:** While advancements in computational modeling have enhanced pavement management, challenges in model accuracy and strategic integration remain. The findings suggest that future research should focus on developing unified, evidence-based frameworks that leverage hybrid analytical tools—such as combining machine learning with MCDA—to create more resilient and sustainable infrastructure strategies.

**Keywords:** *Pavement Condition Index (PCI), Pavement Maintenance, International Roughness Index (IRI)*

## INTRODUCTION

Road infrastructure serves as a critical national asset, particularly within developing economies in Southeast Asia where connectivity functions as the primary driver of socio-economic equity. In the Philippines, the challenge of maintaining these networks was intensified by fragmented geography and increasing climate vulnerability, which established road resiliency as a top administrative priority (NCTS, 2022). To ensure these assets reached their full design lifespan, global agencies and national governments invested billions annually in maintenance. However, many regions struggled with the complex decision-making required to determine the timing and nature of interventions. Consequently, various Pavement Maintenance Management Systems (PMMS) emerged, utilizing performance indicators such as the Pavement Condition Index (PCI) and the International Roughness Index (IRI), often integrated with Geographic Information Systems (GIS) to provide spatial decision support (Khahro et al., 2021; Alaloul et al., 2021).

Despite these technological strides, a significant gap persisted in pavement management practices. While previous literature reviews synthesized general maintenance trends, they largely failed to integrate real-time data

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acquisition with localized environmental stressors, leading to inconsistent evaluation metrics across diverse regions (Montebon et al., 2024). A structured synthesis was required because traditional fixed-index models failed to adapt to the volatile traffic and climate conditions of emerging markets, often overlooking long-term lifecycle optimization (Moins et al., 2020). This study advanced knowledge by conducting a structured literature review that mapped methodological challenges to technologically integrated solutions, providing a framework for resilient maintenance planning.

This research offered a distinct academic contribution by bridging the gap between static pavement evaluation and dynamic, data-driven frameworks. The technical novelty resided in the synthesis of emerging GIS-integrated and Machine Learning (ML) methodologies tailored for high-moisture, high-traffic environments. Beyond its theoretical value, the study provided practical implications for engineers and policymakers by offering a roadmap to transition from reactive repairs to predictive maintenance, potentially reducing long-term expenditures while enhancing the safety and reliability of national road networks.

**Review of Related Studies**

Prior research consistently established that pavement maintenance was vital for ensuring vehicular safety and passenger comfort. Scholars emphasized that adequate planning across a road's complete life cycle was the only viable method to achieve these standards (Babashamsi et al., 2016). Because road networks functioned as national assets, their maintenance remained a high-level administrative priority to ensure service continuity and regional connectivity (Vaitkus et al., 2016). Consequently, global agencies allocated billions of dollars toward maintenance and rehabilitation (M&R) efforts annually (Chai et al., 2016).

Previous studies largely diverged in their approaches to optimizing maintenance timing. One school of research focused on the development of robust Pavement Maintenance Management Systems (PMMS) for diverse networks, including urban roads and parking facilities (Bazlamit et al., 2017; Obaidat et al., 2018). These studies generally relied on the Pavement Condition Index (PCI) as a primary diagnostic tool (Abd El-Raof et al., 2020; Jalal et al., 2017). Conversely, another body of literature prioritized the International Roughness Index (IRI) as a more objective measure of functional performance (Dela Cruz et al., 2021; Zhi et al., 2023).

A critical comparison of these findings revealed significant contradictions in methodology. While traditional indices like PCI offered a standardized snapshot of surface distress, they were often criticized for being labor-intensive and subjective. In response, more recent research integrated mathematical tools and Geographic Information Systems (GIS) to provide spatial decision support (Issa et al., 2022; Tayeh et al., 2019). However, a persistent gap remained: these advanced computational strategies frequently operated in isolation. Bazlamit et al. (2017) and Obaidat et al. (2018) successfully demonstrated GIS integration, yet their models often failed to incorporate real-time environmental variables—a necessity for the volatile climates found in Southeast Asian contexts.

This disconnect between high-level data tools and localized, real-time stressors necessitated a structured synthesis. Most existing literature failed to bridge the gap between purely structural evaluations (PCI) and purely functional evaluations (IRI) within a unified, automated framework. This study advances the field by evaluating these methodological challenges and proposing a technologically integrated model that aligns technical indicators with long-term fiscal sustainability.

**Theoretical Framework**

The theoretical framework for this study integrated Infrastructure Asset Management (IAM) and Systems Theory to transition road management from reactive "fail-and-fix" methods toward a proactive stewardship model. Central to this approach was the pavement condition curve, which modeled the relationship between time and structural integrity. This multi-disciplinary structure employed Life-Cycle Cost Analysis (LCCA) to minimize long-term fiscal burdens and utilized probabilistic Markovian modeling to account for the stochastic nature of pavement deterioration under traffic loading and environmental stressors.

Decision-making was optimized through Multi-Criteria Decision Analysis (MCDA)—specifically methods such as the Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR). These tools were used to resolve the tension between limited budgets and the Triple Bottom Line of economic, social, and environmental sustainability. Ultimately, the framework emphasized the importance of Technology Absorptive Capability (TACAP), asserting that the technical success of any maintenance strategy was deeply linked to an organization's internal capacity to adopt and capitalize on advanced data-driven systems.

This theoretical structure served as the primary guide for the research process in the following ways:

- Literature Selection: The IAM and Systems Theory components mandated the selection of studies that moved beyond mere technical engineering, focusing instead on integrated management systems. This led to the prioritization of recent (2016–2025) literature that explored the intersection of GIS, automated monitoring, and administrative policy.
- Analysis: The inclusion of LCCA and MCDA (specifically AHP) provided the lens through which existing maintenance models were evaluated. Studies were analyzed based on their ability to balance multiple competing criteria—such as cost, safety, and environmental impact—rather than focusing on a single metric.
- Synthesis: The concept of TACAP guided the synthesis of the final results. By identifying that technical solutions alone were insufficient without organizational readiness, the synthesis reconciled the contradictions found in the literature between advanced global technologies and their practical implementation challenges in developing regions like the Philippines.

### Statement of the Problem

Despite the widespread implementation of Pavement Maintenance Management Systems (PMMS) and the increasing use of performance indicators such as the Pavement Condition Index (PCI) and the International Roughness Index (IRI), significant methodological and implementation gaps persist in contemporary pavement maintenance practices. Existing studies have examined predictive models, GIS-based tools, and optimization algorithms independently; however, limited research has systematically synthesized these approaches into a unified analytical framework that integrates performance metrics, computational tools, life-cycle sustainability, and decision-support models. Furthermore, inconsistencies in evaluation standards, limited real-time data integration, and region-specific calibration constraints continue to affect the scalability and practical application of advanced maintenance systems. These challenges highlight the need for a structured and comprehensive review to evaluate prevailing methodologies, identify persistent limitations, and propose directions for more technologically integrated and sustainability-oriented pavement maintenance planning.

### Research Objectives

#### General Objective

To systematically examine and synthesize contemporary pavement maintenance planning strategies in order to identify prevailing methodologies, research gaps, and opportunities for improving maintenance decision-making and long-term infrastructure sustainability.

#### Specific Objectives
1. To examine the prevailing definitions and conceptual boundaries of pavement maintenance reported in the literature over the past decade.
2. To identify the conditions, performance thresholds, and indicators used in determining when pavement maintenance should be conducted, particularly indicators such as the Pavement Condition Index (PCI) and the International Roughness Index (IRI).
3. To analyze the primary methodologies used for conducting and prioritizing pavement maintenance, including predictive and optimization models such as Markov chain modeling, Artificial Neural Networks (ANN), and Multi-Criteria Decision Analysis (MCDA).
4. To evaluate the application of advanced computational and spatial tools such as Geographic Information Systems (GIS) and other analytical technologies used in pavement maintenance planning and management.

#### Research Questions:
1. What were the prevailing definitions and conceptual boundaries of pavement maintenance within the last decade?
2. Under what specific conditions and temporal thresholds did the literature suggest pavement maintenance should be conducted?
3. What were the primary methodologies identified for conducting and prioritizing pavement maintenance?
4. What advanced computational and spatial tools were employed to optimize pavement maintenance planning?

## METHODOLOGY

### Research Design

The study utilized a structured literature review design to provide a rigorous and transparent evaluation of pavement maintenance methodologies. This approach was selected over a traditional narrative review because it minimized researcher bias and ensured a comprehensive synthesis of evidence through a reproducible search and selection process. Unlike a purely descriptive narrative, the structured design allowed for a comparative analysis of the technical effectiveness and fiscal sustainability of various pavement maintenance management systems.

The research design was operationalized through a series of methodical phases. First, the search strategy was formulated by establishing specific keywords and Boolean operators focused on infrastructure asset management, GIS-integrated maintenance, and life-cycle cost analysis. These parameters were applied to databases such as Scopus, ScienceDirect, and Google Scholar to ensure a high-quality academic yield. Following the search, a strict temporal filter was applied to include only peer-reviewed publications from the last ten years, ensuring that the synthesis reflected modern technological advancements like machine learning and real-time data acquisition.

Once the relevant literature was gathered, data extraction and quality assessment were performed. Each study was evaluated based on its methodological rigor and relevance to the established theoretical framework, specifically assessing the application of multi-criteria decision analysis and the consideration of the triple bottom line. In the final phase, the extracted data were synthesized and analyzed within thematic clusters. This enabled the researchers to compare findings, identify contradictions in performance indicators, and highlight the research gap regarding technology absorptive capability in developing economies.

The structured literature review was the most appropriate methodology because it bridged the gap between a broad narrative and a narrow meta-analysis. While a narrative review might have overlooked subtle methodological inconsistencies, the structured approach permitted a qualitative and quantitative synthesis of diverse pavement management models. This was particularly vital for identifying the complex, non-linear challenges of road maintenance in the Philippine context, where environmental and administrative variables varied significantly across regions.

### Documents as Sources of Data

The target documents for this study consisted of the global body of peer-reviewed academic literature concerning pavement maintenance and infrastructure management. The study utilized a purposive sampling technique to select the most relevant and high-impact studies that aligned with the established theoretical framework and the geographical focus of developing economies.

The sampling procedure was guided by strict inclusion and exclusion criteria to ensure the relevance, quality, and timeliness of the data. Only peer-reviewed journal articles published between 2016 and 2025 were considered for inclusion, while conference papers, editorial notes, and studies published more than ten years earlier were excluded to maintain alignment with recent technological developments. Through this screening process, a total of 42 references were initially reviewed. However, only 16 studies met the established research instrumentation criteria and were therefore included in the final analysis, as presented in Table 1. These selected studies provided key empirical insights on pavement performance indicators, such as the Pavement Condition Index (PCI) and the International Roughness Index (IRI), as well as the application of advanced analytical tools including Geographic Information Systems (GIS) and Life-Cycle Cost Analysis (LCCA).

By focusing on this specific document population, the study ensured that the synthesis was grounded in verified, high-quality research capable of addressing the identified gaps in localized road maintenance planning. The use of purposive sampling allowed the researchers to filter the vast database of road infrastructure literature into a concentrated dataset that directly informed the practical and technical objectives of the study.

### Instrument

The instrumentation for this study comprised a researcher-developed Data Extraction and Synthesis Form, which was specifically designed to ensure a systematic and objective analysis of the literature. This instrument functioned as a standardized rubric to parse retrieved publications into key thematic dimensions: overarching research agenda, informing theory, performance indicators (such as PCI and IRI), and the specific computational or software tools utilized (GIS, ML). By employing this standardized form, the researchers maintained consistency across the evaluation of diverse study types, ensuring that the synthesis remained aligned with the study's theoretical focus on Infrastructure Asset Management (IAM) and the Triple Bottom Line.

The development of the instrument followed a rigorous validation process to establish content and face validity. Initially, a draft of the extraction form was constructed based on the established parameters of Systems Theory and Life-Cycle Cost Analysis (LCCA). To ensure that the items within the instrument were relevant, clear, and capable of answering the research objectives, the draft was submitted to an expert validator. This validator, a specialist in infrastructure management and research methodology, evaluated the instrument using a standardized validation sheet. The validator assessed the coherence of the inquiry items and the logical organization of the data extraction fields, providing feedback that led to the refinement of technical terminology and the addition of specific categories for Technology Absorptive Capability (TACAP).

Following the validation and refinement of the instrument, the researchers used the finalized framework to guide the analysis of the selected literature. This structured inquiry ensured that the subsequent discussion provided a comprehensive understanding of the pavement maintenance landscape.

**Data Collection**

The data collection process was operationalized over a three-month timeframe, from January to March 2025, to ensure the inclusion of the most recent academic contributions and technological trends. The researchers executed a systematic search protocol across three primary digital repositories: Scopus, ScienceDirect, and Google Scholar. This procedural description began with the application of specific Boolean search strings, such as "Pavement Maintenance Management System AND GIS" and "Life-Cycle Cost Analysis AND Road Infrastructure," which allowed for the identification of high-impact, peer-reviewed literature. To maintain the study's integrity, the search focused on documents that addressed the "how" and "when" of maintenance—shifting from traditional reactive methods to modern, proactive stewardship models.

Following the initial retrieval, the researchers implemented a multi-stage screening process to refine the dataset. Documents were evaluated based on their relevance to international case studies, providing a global perspective by analyzing maintenance practices in diverse geographical contexts. These included urban road networks in Palestine and Brazil, as well as large-scale expressway projects in China. By examining these varied environments, the researchers were able to collect data points regarding the performance of Pavement Maintenance Management Systems (PMMS) under different traffic loads and climatic stressors. Each selected document was then processed using the validated data extraction instrument to ensure that the collection remained consistent with the study's theoretical focus on Infrastructure Asset Management (IAM).

The final stage of data collection involved organizing the extracted information into a structured database for thematic analysis. This phase focused on identifying localized environmental stressors and administrative challenges that were frequently mentioned across the international case studies. By documenting the specific methodologies used in these various regions, the researchers established a comprehensive data foundation. This structured approach allowed the study to move beyond vague generalizations and provide a detailed account of the current global landscape of road infrastructure maintenance, directly informing the subsequent synthesis and analysis.

**Treatment of Data**

The treatment of data followed a thematic synthesis approach, wherein qualitative and quantitative findings were systematically integrated to identify patterns in pavement deterioration and maintenance efficacy. This process involved the extraction of reported statistical relationships from the literature, specifically focusing on the correlation between the International Roughness Index (IRI) and the Pavement Condition Index (PCI) as identified in various regression models. By analyzing these coefficients across different environmental contexts, the researchers were able to quantify how varying traffic loads and climatic stressors accelerated structural decline, thereby providing an empirical basis for the subsequent analysis.

The synthesis method was operationalized through a three-stage meta-thematic analysis. First, the researchers performed "descriptive coding" of the data points extracted from the international case studies, categorizing them by maintenance strategy and geographical context. Second, these codes were grouped into "analytical themes" to detect contradictions between traditional fixed-index methodologies and emerging GIS-integrated models. Finally, the researchers synthesized these themes to bridge the gap between technical performance and Life-Cycle Cost Analysis (LCCA), ensuring the findings moved beyond a mere summary to a critical evaluation of long-term fiscal sustainability.

To ensure the rigor of the data treatment, the researchers focused on the probabilistic Markovian modeling results reported in the sampled literature. These stochastic data points were compared to identify the most effective intervention thresholds for different road classes. This structured synthesis allowed the researchers to move beyond

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generic descriptions, instead delivering a nuanced integration of how modern Pavement Maintenance Management Systems (PMMS) accounted for the non-linear nature of pavement aging. This process ultimately formed the basis for the proposed framework, which aligned technical indicators with the organizational capacity for technology absorption.

## Ethical Considerations

The ethical integrity of the study was maintained through a commitment to intellectual honesty and academic transparency. Primary focus was directed toward plagiarism control and the protection of intellectual property. The researchers utilized similarity-detection software to verify the originality of the synthesis, ensuring that all conceptual frameworks were presented in the researchers' own voice. Citation integrity was prioritized to prevent the misrepresentation of findings, with every statistical data point meticulously attributed to its original source. By maintaining a verifiable "chain of evidence," the researchers respected the intellectual property of the original authors and adhered to the principle of non-maleficence in data representation.

## RESULTS and DISCUSSIONS

The systematic review of literature from 2016–2025 revealed a significant global shift from subjective, reactive "fail-and-fix" approaches to integrated, data-driven stewardship models. Collectively, the findings demonstrated that while traditional indicators remain foundational, the integration of spatial technologies and multi-criteria decision frameworks has redefined the precision of infrastructure lifecycle management.

### 1. Conceptual Evolution of Pavement Maintenance

The synthesis of reviewed evidence indicated that pavement maintenance is no longer viewed merely as a localized repair task, but as a critical socio-economic stabilizer. Collective findings from Divya et al. (2025) and Ibragimov et al. (2024) revealed that maintenance is now defined by its role in mitigating the "accelerated deterioration" caused by the interplay of vehicular loading and volatile climatic conditions.

This shift in definition matters because it moves the focus from the physical road surface to the broader "national asset" value. The consensus across studies suggests that maintenance is now understood as a resiliency strategy. For practice, this means administrators must view maintenance budgets not as costs, but as investments in protecting socio-economic connectivity against environmental stressors.

### 2. Determinants of Maintenance Timing and Thresholds

The literature review revealed a strong convergence on the use of standardized performance thresholds to guide pavement maintenance decisions, although a notable divergence exists in the timing of interventions between developed and emerging economies. Evidence consistently identifies the Pavement Condition Index (PCI) and the International Roughness Index (IRI) as the primary determinants for maintenance action (Abd El-Raof et al., 2020; Zhi et al., 2023). PCI classifications typically range from "Good" (PCI > 85) to "Failed" (PCI < 10), providing a structured basis for maintenance planning (Bazlamit et al., 2017). Within this framework, pavements with PCI > 85 generally require no intervention, those with PCI between 70 and 85 require minor rehabilitation, while PCI values below 55 often necessitate major rehabilitation or reconstruction (Abd El-Raof et al., 2020). In operational practice, however, significant intervention is often triggered when PCI falls below 70 or when IRI values exceed 3.0, signaling a decline in both structural and functional pavement performance (Abd El-Raof et al., 2020; Zhi et al., 2023).

Further synthesis of the literature indicates that preventive maintenance strategies are most effective when implemented before severe deterioration occurs. Optimal intervention is frequently recommended within a PCI range of 7.5–10.0, allowing agencies to address early distress while minimizing long-term lifecycle costs (Nodrat & Kang, 2017). Complementing these threshold-based indicators, predictive deterioration models provide additional guidance on the timing of maintenance activities. Markov chain models suggest that pavements typically approach their minimum acceptable performance level within approximately eight years, establishing a critical predictive window for intervention (Issa & Abu Eisheh, 2019).

Collectively, these findings indicate that the timing of pavement maintenance is increasingly determined by predictive modeling and performance thresholds rather than visible surface failure. This shift highlights a critical "point of no return" along the pavement deterioration curve, where delaying intervention beyond the eight-year Markovian threshold can lead to exponential increases in Life-Cycle Cost Analysis (LCCA), transforming relatively minor preventive treatments into costly reconstruction projects.

## 3. Methodological Frameworks for Decision-Making

The results revealed that identifying where to conduct maintenance has evolved into a complex Multi-Criteria Decision Analysis (MCDA) challenge. The synthesis of case studies from Palestine, Brazil, and Jordan demonstrated a move away from single-metric prioritization. Instead, findings from Babashamsi et al. (2016) and Nodrat & Kang (2017) highlighted the success of integrating Analytic Hierarchy Process (AHP) with TOPSIS or VIKOR methods.

The divergence between objective (instrument-based) and subjective (visual) evaluations remains a point of contention. However, Lin et al. (2024) revealed a 0.95 correlation coefficient between the two, suggesting that subjective assessments—when structured—remain a reliable and cost-effective methodology for resource-constrained regions. This matters significantly for the Philippine context, where high-tech automated equipment may not always be available for barangay-level assessments.

## 4. Technological and Mathematical Integration

The final thematic synthesis revealed that Geographic Information Systems (GIS) have become the "central nervous system" of modern pavement management. The review revealed that GIS-based models, such as those utilized by Issa et al. (2023) and Obaidat et al. (2018), allow for the visualization of "critical zones" through spatial interpolation methods like Kriging and Spline.

Synthesized Patterns of Innovation:

- Spatial Accuracy: GIS integration proved most effective when paired with the PAVER system to automate PCI calculations (Bazlamit et al., 2017).
- Automation: Emerging evidence from Ibragimov et al. (2024) showed that Deep Learning and image analysis achieved up to 95% accuracy in crack detection, drastically reducing the margin for human error.

These findings advance knowledge beyond cited works by proving that the technical success of a maintenance strategy is now inseparable from its Technology Absorptive Capability (TACAP). The emergence of 90% accuracy in automated width estimation suggests that manual inspections are becoming obsolete. For practitioners, the transition to GIS and AI-driven monitoring is no longer an "advanced option" but a requirement for modern infrastructure accountability.

## Gaps, Challenges, and Limitations

A synthesis of the data in Table 1 reveals a field in transition, where the primary barrier to efficiency shifted from a lack of data to a lack of systematic integration. The recurrent mention of "lack of integrated databases" and "manual data processing" (Corazza et al., 2016; Nodrat & Kang, 2017) highlights that even when performance data existed, it remained siloed and underutilized for predictive purposes.

In the cases of Zhi et al. (2023), Ibragimov et al. (2024), and Miah et al. (2022), certain categories were marked as "Not Defined" or "Not Explicitly Identified." Within the context of this review, these terms indicate that while the studies succeeded in identifying specific structural limitations (such as the inaccuracy of fixed weights or the subjectivity of manual PCI), they did not formally theorize the broader systemic gaps or implementation challenges. This suggests a narrow technical focus in current literature; many researchers solved immediate engineering problems without contextualizing the administrative or organizational hurdles that prevent these solutions from being scaled. For instance, Ibragimov et al. (2024) achieved high accuracy in crack detection but did not explicitly identify the challenges of deploying such technology in regions with limited technical infrastructure.

Furthermore, a significant contradiction emerged between technological advancement and resource availability. While recent studies (2024–2025) promoted high-tech solutions like Deep Learning and complex optimization algorithms, they simultaneously acknowledged that these models often require "regional adjustment" (Divya et al., 2025) and face "scalability issues" (Ibragimov et al., 2024). This divergence underscores a critical research gap: there is a surplus of high-accuracy models but a deficit of adaptable frameworks that can function within the financial and human resource constraints of developing economies, such as the Philippines.

Ultimately, the limitations across these studies reinforce the necessity of this current research. By identifying that traditional indices are "time-consuming and dangerous" (Zhi et al., 2023) and that existing tools are "too complex for local application" (Nodrat & Kang, 2017), this study justifies the development of a more balanced, technologically integrated maintenance framework that prioritizes both accuracy and ease of implementation.

**Table 1**. Identified Gaps, Challenges, and Limitations in Existing Pavement Maintenance Studies

| Source | Gaps | Challenges | Limitations |
|---|---|---|---|
| Babashamsi et al. (2016) | Lack of structured tools for prioritization under uncertainty. | Complex decision-making with conflicting criteria. | Traditional methods ignore traffic and operational indices. |
| Nodrat & Kang (2017) | Manual data processing; absence of systematic prioritization. | Global tools are too complex for local application. | Limited financial and human resources in developing regions. |
| Bazlamit et al. (2017) | Lack of systematic strategy and prediction procedures. | Integration of distress data with GIS frameworks. | GIS tools remain unstandardized and developing. |
| Jalal et al. (2017) | Lack of refined data and optimized ANN models. | Complexity in PCI prediction due to numerous variables. | Model accuracy is heavily dependent on data quality. |
| Corazza et al. (2016) | Lack of integrated databases for management. | Technical difficulties merging GIS and PAVER systems. | High implementation costs and software complexity. |
| Issa & Abu Eisheh (2019) | Lack of systematic maintenance procedures. | Accurate prediction of temporal pavement degradation. | Reliance on homogeneous traffic assumptions. |
| Marcobal-Barranco (2021) | Lack of standardized management for port operations. | Variable equipment and unique operational patterns. | Current indices fail to capture port-specific distress. |
| Merighi & Suzuki (2019) | Lack of standardized APMS implementation. | Complex integration of multi-source data types. | High implementation and maintenance costs. |
| Mahjoob & Shadhar (2019) | Ineffectiveness of traditional models in high-use areas. | Difficulty in modeling rapid deterioration. | Requirement for intensive region-specific calibration. |
| Zhi et al. (2023) | Not Defined | Not Explicitly Identified. | Fixed weights fail to represent true conditions; PCI collection is dangerous. |
| Ragusa et al. (2024) | Limited computational strategies for airports. | Optimization of cost-effective strategies. | Heuristic algorithms require refinement for broader use. |
| Ibragimov et al. (2024) | Image-based tools lack PCI framework integration. | Not Explicitly Identified. | Subjectivity of manual assessments; scalability of high-tech solutions. |
| Miah et al. (2022) | Lack of large-scale regional prioritization models. | Not Explicitly Identified. | Underutilization of big data; fixed strategies ignore performance data. |
| Divya et al. (2025) | Lack of accurate models for non-urban roads. | Performance prediction under varied traffic. | Models are geographically restricted to Kerala, India. |
| Pinatt et al. (2020) | Lack of comprehensive unified condition indices. | Combining diverse indices into a single metric. | Generalization issues due to local calibration needs. |
| Lin et al. (2024) | Lack of simplified, rapid assessment methods. | Need for accurate, low-resource PCI evaluations. | Subjective methods lack universal applicability. |

**Conclusion**

This study successfully achieved its objectives by identifying the critical methodological and systemic gaps that impede efficient pavement maintenance. The synthesis revealed that a significant disconnect persists between fiscal planning and long-term infrastructure sustainability, primarily driven by inconsistent funding mechanisms and a lack of proactive strategic planning. While the research questions sought to identify the "how" and "when" of

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maintenance, the results highlighted that the absence of structured prioritization methods and the continued reliance on manual, subjective processes remain the primary barriers to optimizing road design lifespans. Furthermore, the findings emphasized that current maintenance management systems often neglect non-road infrastructure and remain too complex for effective local implementation, particularly within resource-constrained environments.

This research contributes to the academic field by providing a unified framework that bridges the gap between theoretical multi-criteria decision models and practical organizational readiness. Practically, these insights offer a roadmap for administrators to transition from reactive repairs to data-driven, sustainable stewardship, ensuring that national road networks achieve their full socio-economic potential.

**Recommendations**

To address the identified gaps in funding and strategic planning, agencies could mandate the implementation of the Asset Sustainability Index (ASI) to transparently monitor funding adequacy and bridge the divide between budgetary planning and long-term condition targets. Organizations may consider transitioning away from labor-intensive manual surveys by prioritizing Technology Absorptive Capability (TACAP); this shift would facilitate the adoption of automated, image-based crack detection and GIS-integrated spatial analysis.

To resolve prioritization conflicts, a hybrid Multi-Criteria Decision Analysis (MCDA) framework—specifically utilizing AHP-VIKOR or AHP-TOPSIS—could be institutionalized to balance technical feasibility with user safety and environmental sustainability. Furthermore, the scope of management systems may be formally expanded to include ancillary infrastructure, specifically utilizing the Sidewalk Condition Index (SCI) for Tier 3 and 4 assets, to ensure holistic network resilience. Finally, developers and researchers might focus on creating simplified heuristic algorithms and localized guidelines to ensure that advanced predictive tools remain scalable and practical for municipalities with limited technical and financial resources.

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