Lifecycle Performance and Economic Evaluation of Periodic Resurfacing and Condition-Based Pavement Preservation Strategies for Highway Maintenance

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Abstract

Effective maintenance planning is critical for sustaining highway infrastructure performance and efficiency. Conventional time-based resurfacing approaches often allow pavements to deteriorate before rehabilitation, increasing lifecycle costs and affecting serviceability. This study compares periodic resurfacing and condition-based pavement preservation strategies using an analytical framework for pavement performance modelling. The methodology integrates traffic and deterioration assumptions, alternative maintenance schedules, and lifecycle performance indicators including roughness evolution, intervention frequency, and maintenance costs.

The results demonstrate that maintenance intervention timing significantly influences long-term pavement behaviour. Condition-based preservation strategies maintain pavement roughness largely below 4 m/km International Roughness Index (IRI) across most of the lifecycle and reduce the occurrence of major rehabilitation interventions compared with periodic resurfacing regimes. Lifecycle expenditure analysis further indicates that preventive maintenance strategies can lower cumulative agency maintenance costs by approximately 20-25 percent by avoiding advanced deterioration states requiring structural rehabilitation.

The findings highlight the importance of adopting condition-triggered preservation frameworks supported by systematic pavement condition monitoring and lifecycle planning tools to enhance the sustainability and economic efficiency of highway asset management.

Keywords: Pavement Preservation; Lifecycle Cost Analysis; Pavement Performance Modelling; Preventive Maintenance; Highway Asset Management; International Roughness Index (IRI).

1. Introduction

Highway maintenance in India has traditionally followed fixed resurfacing cycles at intervals of five to six years, largely independent of actual pavement condition (IRC 82, 2012; MoRTH, 2013). While this approach offers administrative simplicity and facilitates budget planning, it assumes uniform deterioration across diverse traffic, environmental, and structural conditions. In practice, pavement performance varies significantly due to axle loading, drainage, material characteristics, construction quality, and climatic influences (Haas et al., 1994; Shahin, 2005). Consequently, periodic resurfacing can lead to premature treatment of adequately performing sections while allowing other segments to deteriorate beyond optimal intervention stages, resulting in inefficient resource utilisation and compromised serviceability (Walls and Smith, 1998).

The need for more efficient maintenance strategies has intensified with rapid expansion of highway infrastructure, increasing freight movement, and constrained maintenance budgets. India’s extensive road network, coupled with rising traffic loads, has increased pressure on highway agencies to maintain serviceability under limited financial resources. International practice increasingly emphasises pavement asset management frameworks that prioritise condition-based maintenance over fixed schedules, enabling timely interventions based on performance indicators such as roughness, cracking, and rutting (FHWA, 2013; PIARC, 2019). Preventive maintenance applied during early stages of deterioration has been shown to extend pavement life and reduce lifecycle costs by avoiding expensive rehabilitation at advanced stages (OECD, 2001; Shahin, 2005). Although Indian Roads Congress guidelines advocate systematic condition evaluation and performance-based decision-making, implementation remains inconsistent across agencies.

India possesses one of the largest road networks globally, exceeding 6.3 million km, with national highways serving as the primary backbone for long-distance mobility. Traditional periodic resurfacing strategies may not ensure optimal allocation of maintenance resources or sustain acceptable serviceability levels. The scale of India's highway network, increasing freight traffic, and fiscal constraints highlight the need for systematic pavement asset management approaches that integrate condition monitoring and performance-based maintenance planning consistent with IRC principles (IRC 82, 2012).

These challenges are particularly significant for strategic highway corridors subjected to variable environmental and operational conditions, where deterioration behaviour can differ across regions and even within road sections. Under such conditions, fixed resurfacing cycles are often inefficient and economically suboptimal. Effective maintenance planning therefore requires integration of condition monitoring, performance modelling, and lifecycle-based decision frameworks. Highway infrastructure management integrates condition monitoring and lifecycle decision-making to optimize network performance (Haas et al., 2015). Pavement preservation emphasizes timely preventive interventions to extend service life (Smith et al., 2008). Preventive maintenance during early deterioration can stabilise pavement condition and reduce rehabilitation needs (Morian et al., 2011). Lifecycle methods assess maintenance alternatives for long-term outcomes (Santos et al., 2017). Maintenance effectiveness depends on intervention timing relative to deterioration (Mills et al., 2010). However, many highway programmes still use periodic resurfacing rather than preservation-based lifecycle management. This gap highlights the need for frameworks that align condition assessment, prioritisation, and lifecycle evaluation with institutional decision-making processes, enabling a transition from time-based resurfacing to condition-responsive pavement preservation.

2. Scope and Organisation of the Paper

This paper develops a planning-level framework for evaluating and transitioning from time-based resurfacing to condition-based pavement preservation for highway networks. It integrates pavement deterioration concepts, HDM-4 based lifecycle analysis, and institutional considerations. The subsequent sections present the methodology, comparative lifecycle evaluation of maintenance strategies, and associated policy and implementation insights.

3. Research Objectives and Contributions

3.1. Research Objectives

The transition from time-based resurfacing toward performance-triggered pavement preservation requires engineering evaluation and institutional changes. Given expanding highway networks and increasing traffic in India, systematic evaluation of maintenance philosophy is needed for evidence-based infrastructure management. The research addresses three questions: How does maintenance timing influence lifecycle pavement performance by comparing periodic and condition-based strategies? What economic differences exist between periodic and condition-triggered maintenance strategies regarding expenditure and resource efficiency? What institutional reforms enable effective implementation of condition-based preservation? The study aims to provide a framework for condition-responsive pavement management in highway networks as per Indian Roads Congress guidelines.

3.2. Research Contributions

This study integrates HDM-4 based lifecycle analysis with an implementation-oriented framework to evaluate alternative pavement maintenance strategies at the network level. It demonstrates the influence of intervention timing on pavement performance and lifecycle costs, highlighting the economic advantages of condition-based preservation over periodic resurfacing. The research further proposes a practical institutional transition framework linking condition monitoring, lifecycle evaluation, and maintenance prioritisation, enabling highway agencies to adopt performance-based pavement management in line with Indian Roads Congress guidelines.

4. Theoretical Framework: Pavement Deterioration and Preservation

The transition from periodic to condition-based pavement preservation is founded on principles of pavement deterioration and intervention timing. Modern pavement management recognizes that lifecycle performance depends on structural design and maintenance interventions during service life (Haas et al., 1994; Shahin, 2005).

4.1. Pavement Deterioration Concept

Highway pavements deteriorate due to traffic loading, environmental exposure, ageing, and drainage conditions. Deterioration follows a non-linear trajectory in HDM-4 models, where condition decline is initially gradual but rapidly accelerates after a critical threshold (Prozzi and Madanat, 2004). During early pavement life, structural capacity remains intact despite minor surface distress. Once deterioration advances beyond this phase, distress propagation accelerates, increasing rehabilitation costs. Studies show restoring pavements after advanced deterioration costs several times more than preventive treatment applied earlier (Walls and Smith, 1998; OECD, 2001; Shahin, 2005). Understanding this deterioration behaviour is crucial for preservation-oriented maintenance planning.

4.2. Preservation Logic

Pavement preservation is a proactive maintenance strategy aimed at extending the service life of pavements by maintaining them rather than restoring assets that have already failed. Preservation programs emphasize early, cost-effective surface treatments that slow down deterioration and protect structural layers (FHWA, 2016). In contrast, rehabilitation, which occurs after significant deterioration, is reactive, capital-intensive, and diminishes lifecycle efficiency (OECD, 2001; Shahin, 2005). The preservation approach shifts maintenance from periodic renewal to sustained management of network conditions.

4.3. Condition-Based Trigger Philosophy

Condition-based pavement management replaces fixed resurfacing cycles with interventions based on performance indicators. Maintenance occurs when pavement condition reaches predefined thresholds for optimal timing. Key indicators include International Roughness Index (IRI), cracking extent, rut depth, and composite condition indices. Monitoring enables intervention before accelerated deterioration, stabilising costs and maintaining network serviceability (PIARC, 2019). For strategic highways under severe conditions, identifying intervention timing is critical. This approach reframes maintenance from repair to asset management through monitoring. The deterioration concept and condition-trigger philosophy establish the framework for subsequent analysis.

5. Review of Practices and Institutional Benchmarking

Highway maintenance practice in India has progressively evolved toward more structured pavement management over the past two decades (MoRTH, 2013; IRC 82, 2012). Technical guidelines issued by the Indian Roads Congress provide established procedures for condition surveys, roughness measurement, distress assessment, and overlay design (IRC 82, 2012; IRC 37, 2018). While many highway agencies undertake periodic condition surveys and have initiated Pavement Management Systems (PMS), their integration into maintenance planning and prioritisation remains limited. In practice, maintenance decisions are still largely programme-driven and influenced by budget allocations rather than systematic lifecycle optimisation. As a result, time-based resurfacing continues to coexist with condition-based approaches, reflecting an ongoing transition rather than full adoption of asset management principles (World Bank, 2017).

In contrast, international highway agencies have institutionalised condition-based pavement management supported by comprehensive PMS frameworks (PIARC, 2019; Austroads, 2017). These systems integrate network-level condition monitoring, calibrated performance models, lifecycle-based treatment selection, and economic prioritisation within structured planning cycles. Maintenance decision-making is embedded within broader asset management governance, linking engineering analysis with budgeting, execution, and performance feedback (OECD, 2001; ISO, 2014). Such integrated approaches enable timely preventive interventions, optimise resource allocation, and ensure long-term network performance.

The comparison indicates that the principal challenge in Indian highway maintenance systems is institutional rather than technological. While technical standards, data collection capabilities, and analytical tools are increasingly available, their systematic integration into decision-making workflows remains limited. Key gaps include weak linkage between condition assessment and maintenance prioritisation, limited use of lifecycle evaluation in budgeting, and absence of closed-loop performance feedback mechanisms. Addressing these gaps requires frameworks that align condition monitoring, lifecycle analysis, and institutional processes, enabling a structured transition from periodic resurfacing toward condition-based pavement preservation.

6. Research Methodology

6.1. Study Design

This study evaluates alternative pavement maintenance approaches for strategic highway networks, comparing lifecycle implications of time-based resurfacing and condition-triggered preservation. The analysis integrates pavement deterioration theory and maintenance evaluation within a planning framework consistent with HDM-4 applications. It examines system behaviour under alternative maintenance rules to derive policy insights for highway asset management, comparing two strategies under identical conditions to assess intervention timing effects.

6.2. HDM-4 Consistent Modelling Framework

The analytical framework follows HDM-4 system's strategic planning philosophy for evaluating road investment and maintenance policies. Pavement deterioration, maintenance effects, and economic implications are represented through generalized engineering relationships rather than project-level calibration. Pavement condition evolves over the analysis horizon under traffic loading, environmental exposure, and ageing effects. Maintenance interventions modify deterioration by restoring condition and delaying structural distress.

The model represents pavement deterioration, maintenance intervention logic, and lifecycle performance evaluation to assess how intervention rules influence pavement condition, maintenance frequency, and expenditure patterns.

Figure 1 provides a framework integrating input parameters, HDM-4 pavement deterioration modelling, and maintenance strategy simulation. Lifecycle indicators including pavement condition, intervention frequency, and maintenance costs are evaluated, enabling comparison of periodic resurfacing and condition-triggered preservation approaches.

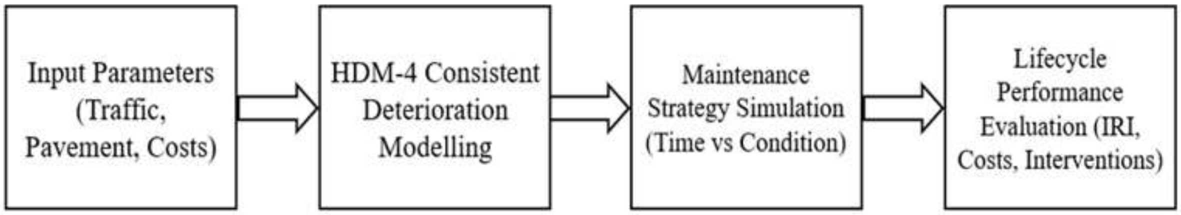

Figure 1. Analytical workflow for lifecycle evaluation of pavement maintenance strategies.

6.3. Simulation Inputs

Lifecycle evaluation used representative parameters reflecting typical operating conditions of a two-lane bituminous highway in developing traffic environments. The analysis period was 20 years with annual evaluation intervals and an 8 percent economic discount rate, consistent with infrastructure appraisal practice. Traffic conditions were represented by initial daily traffic of 4,500 vehicles with 30 percent heavy vehicles and 5 percent annual growth. Pavement structural characteristics correspond to a flexible pavement comprising bituminous concrete surface over granular base with a subgrade strength of 8 percent CBR.

Initial pavement condition represented a recently resurfaced road with moderate roughness and minimal structural distress. Preventive and rehabilitation treatment costs were assigned values derived from typical highway maintenance estimates used in planning-level analyses.

6.4. Maintenance Strategies Evaluated

Two maintenance philosophies were evaluated in the lifecycle analysis.

The first strategy represents conventional periodic resurfacing where overlay interventions occur at fixed intervals regardless of pavement condition. This approach reflects traditional maintenance programming in many highway systems due to administrative simplicity and budget predictability. The second strategy represents condition-based preservation where maintenance actions are triggered by performance indicators. Preventive treatments like crack sealing and thin overlays are applied when distress indicators exceed thresholds, while structural overlays are done when pavement condition approaches rehabilitation levels. The evaluation enables examination of how intervention timing influences deterioration and maintenance requirements.

6.5. Evaluation Indicators

Performance of maintenance strategies was assessed using engineering and economic indicators common in pavement management studies. Engineering performance was evaluated through pavement serviceability trends shown by roughness evolution and major rehabilitation frequency. Economic evaluation focused on lifecycle maintenance costs and cumulative agency costs over the analysis horizon. Additional interpretation considered maintenance expenditure stability and strategy effectiveness in maintaining acceptable pavement performance. These indicators enable systematic comparison of maintenance approaches and support interpretation for infrastructure management policy and planning.

7. Conceptual HDM-4 Based Analytical Modelling

This study adopts a planning-level analytical framework consistent with the Highway Development and Management System (HDM-4) to evaluate lifecycle implications of alternative pavement maintenance strategies. The objective is comparative assessment of maintenance philosophies: periodic resurfacing and condition-based preservation under a common set of traffic, environmental, and structural conditions. The approach focuses on identifying system-level performance trends and policy insights rather than predicting section-specific pavement behaviour.

The analytical model integrates three core components. First, pavement deterioration is represented through generalized non-linear behaviour reflecting traffic loading, environmental exposure, and ageing effects. Second, maintenance intervention logic is defined for two strategies: fixed-interval resurfacing and condition-triggered preservation based on performance thresholds. Interventions restore pavement condition and influence subsequent deterioration trajectories. Third, lifecycle performance is evaluated over the analysis period using indicators such as pavement condition (IRI progression), intervention frequency, and cumulative maintenance expenditure.

To ensure transparency and comparability, the framework adopts simplified but rational assumptions consistent with planning-level HDM-4 applications. These include representative traffic growth, typical pavement structural characteristics, and uniform treatment effectiveness. The analysis is conducted over a defined lifecycle horizon with annual evaluation intervals and an appropriate economic discount rate. Such abstraction enables systematic comparison of maintenance strategies while maintaining relevance to real-world highway conditions.

The key input parameters used in the simulation, including traffic characteristics, pavement structure, initial condition, maintenance triggers, and treatment costs, are summarised in Table 1. These inputs represent typical conditions for a two-lane bituminous highway operating under developing traffic environments.

The modelling framework enables evaluation of how intervention timing influences pavement performance, maintenance requirements, and lifecycle costs. It thus serves as a decision-support tool linking engineering deterioration behaviour with maintenance policy formulation, supporting the transition toward condition-based pavement management.

Table 1: HDM-4 Simulation Input Parameters Used in Lifecycle Evaluation

Parameter Category	Parameter	Assumed Value	Unit	Basis/Source
Analysis Configuration	Analysis period	20	years	Typical lifecycle evaluation horizon
	Discount rate	8	%	Standard infrastructure economic evaluation

	Evaluation interval	1	year	HDM-4 standard modelling interval
Traffic Characteristics	Initial AADT	4,500	vehicles/day	Representative two-lane national highway
	Heavy vehicle proportion	32	%	Freight-dominated highway corridor
	Traffic growth rate	5	% per year	Typical developing corridor growth
	Average axle load	80	kN	Standard commercial vehicle loading
Pavement Structure	Surface type	Bituminous concrete	–	Typical flexible pavement
	Surface thickness	40	mm	IRC design practice
	Base layer	Granular base	–	Standard flexible pavement structure
	Subgrade CBR	8	%	Representative subgrade strength
Initial Pavement Condition	Initial IRI	2.5	m/km	Newly resurfaced pavement
	Cracked area	2	%	Early service condition
	Rut depth	3	mm	Typical post-construction condition
Maintenance Strategies Evaluated	Strategy 1	Periodic resurfacing	–	Overlay every 6 years
	Strategy 2	Condition-based preservation	–	Triggered by performance thresholds
Preservation Interventions	Crack sealing trigger	Crack area > 10%	–	Preventive maintenance practice
	Thin overlay trigger	IRI > 4.0	m/km	Performance-based intervention
	Major overlay trigger	IRI > 6.0	m/km	Structural rehabilitation threshold
Treatment Costs	Crack sealing	1.2	lakh/km	Typical maintenance cost estimate
	Thin overlay	9	lakh/km	Bituminous overlay cost
	Structural overlay	28	lakh/km	Rehabilitation cost

8. Quantitative Illustration and Lifecycle Economic Evaluation

8.1. Purpose of Quantitative Demonstration

A quantitative analytical illustration was conducted using the conceptual modelling framework to examine alternative maintenance philosophies. The analysis aims to demonstrate comparative lifecycle behaviour under two maintenance strategies: periodic resurfacing and condition-based pavement preservation. The analysis evaluates how intervention timing influences pavement performance trajectories, maintenance frequency, and cumulative lifecycle expenditure. This comparative assessment enables interpretation of preservation-based maintenance strategies in terms of engineering performance and economic efficiency for strategic highway networks.

8.2. Analytical Scenario Definition

A flexible pavement operating under typical traffic and environmental conditions was considered for lifecycle analysis. Pavement deterioration was represented using generalized performance relationships consistent with HDM-4 modelling applications. The simulation assumes deterioration of pavement serviceability under traffic loading and environmental exposure. Both maintenance strategies were evaluated over an identical horizon to isolate the influence of intervention timing on lifecycle outcomes.

8.3. Pavement Performance Behaviour

Figure 2 illustrates the simulated evolution of pavement roughness expressed through the International Roughness Index (IRI) under the two alternative maintenance philosophies. The curves represent idealised, continuous deterioration behaviour consistent with HDM-4 planning-level modelling, illustrating comparative trends rather than discrete intervention events.

Under periodic resurfacing, maintenance occurs at fixed intervals regardless of pavement condition. Pavement roughness increases between resurfacing cycles and reaches high levels before overlay restoration. This deterioration results in periods where serviceability falls below optimal levels. The condition-based preservation strategy introduces preventive interventions triggered by pavement performance thresholds. Maintenance treatments are applied before deterioration accelerates. As shown in Figure 2, the preservation approach maintains pavement roughness within a narrower band and reduces deterioration cycles.

These results demonstrate that pavement performance is strongly influenced by intervention timing. Preventive treatments applied during early deterioration stages help maintain serviceability and delay structural rehabilitation.

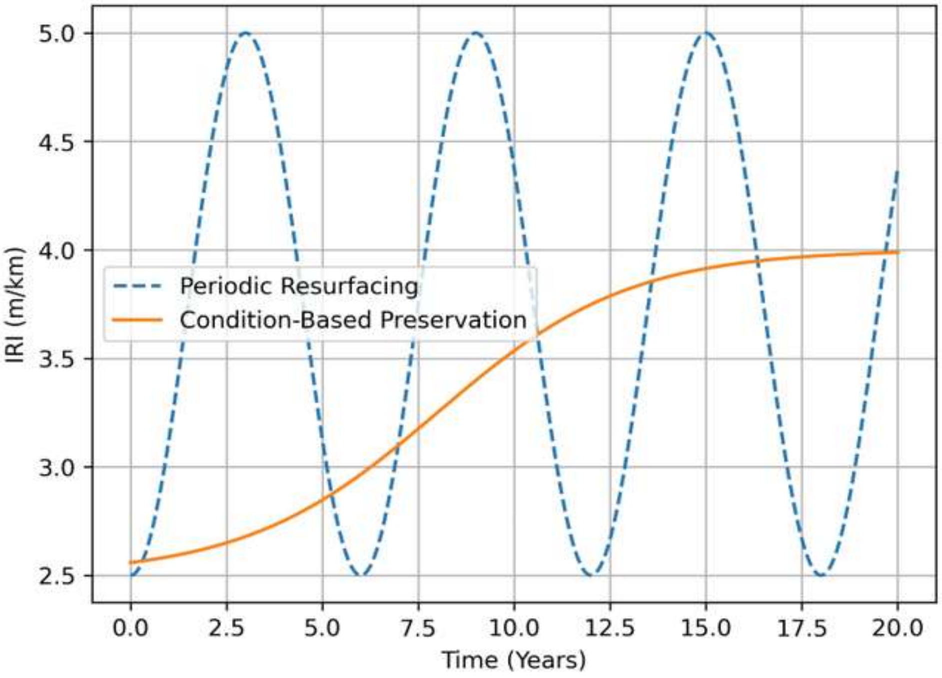

Figure 2. Comparative pavement performance trajectories under periodic resurfacing and condition-based preservation strategies illustrating non-linear deterioration behaviour and the stabilizing influence of timely preventive interventions.

8.4. Maintenance Intervention Schedule

The two maintenance strategies also differ in the timing and frequency of maintenance activities over the analysis horizon. Table 2 summarizes the indicative intervention schedule derived from the lifecycle simulation.

Table 2: Illustrative Maintenance Intervention Schedule

Year	Periodic Resurfacing Strategy	Condition-Based Preservation Strategy

3	-	Crack sealing
4	-	Thin overlay
6	Major overlay	-
8	-	Crack sealing
10	-	Thin overlay
12	Major overlay	-
15	-	Crack sealing
18	Major overlay	Thin overlay

The periodic resurfacing strategy is characterised by infrequent but high-cost overlay interventions, whereas the preservation strategy employs more frequent preventive treatments with lower individual costs. This difference in intervention philosophy significantly influences lifecycle cost distribution and pavement condition stability.

8.5. Lifecycle Maintenance Expenditure

Lifecycle economic implications of both strategies appear in Figure 3 through cumulative maintenance costs. Under periodic resurfacing, costs occur in large spikes from major overlay operations. Though interventions are few, each requires substantial rehabilitation cost. The preservation strategy distributes costs more uniformly through preventive treatments at earlier deterioration stages. While treatments occur more frequently, their cost is lower than major rehabilitation overlays. The cumulative trend in Figure 3 shows that preventive preservation can reduce long-term costs by avoiding severe deterioration requiring expensive rehabilitation.

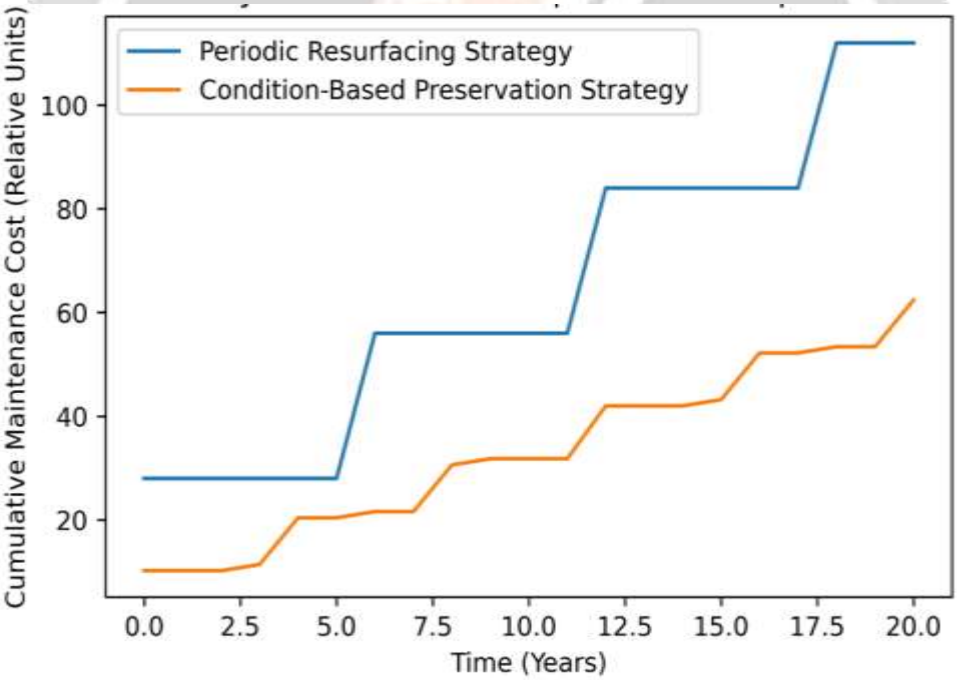

Figure 3. Lifecycle maintenance expenditure comparison illustrating cumulative agency cost trends under periodic resurfacing and condition-triggered preservation strategies over the analysis horizon.

8.6. Lifecycle Performance Indicators

The comparative lifecycle outcomes of the two maintenance strategies are summarized in Table 3.

Table 3: Lifecycle Performance Indicators

Indicator	Periodic Resurfacing	Condition-Based Preservation

Average IRI	4.5 m/km	3.3 m/km
Major overlays required	3	1
Total maintenance cost	100%	78%
Serviceability	Moderate	High

The results indicate that condition-based preservation improves pavement serviceability and reduces the need for structural rehabilitation interventions. The analysis demonstrates that lifecycle economic efficiency arises primarily from timely preventive maintenance rather than increased investment intensity.

8.7. Sensitivity Discussion

To assess robustness of the analytical findings, the model behaviour was conceptually examined under variations in traffic loading and intervention timing.

Higher traffic growth accelerates deterioration rates for both strategies; however, the relative advantage of preservation strategies increases because early interventions prevent rapid transition into high-distress conditions. Conversely, delayed preventive treatment significantly increases lifecycle costs as deterioration progresses beyond the range where low-cost preservation treatments remain effective. Across reasonable variations in deterioration behaviour and traffic conditions, the comparative results remain consistent: maintenance strategies based on condition-triggered interventions provide superior lifecycle stability compared with rigid periodic resurfacing regimes.

8.8. Engineering Interpretation

The lifecycle analysis highlights three key engineering insights. First, pavement performance is governed primarily by the timing of maintenance intervention rather than the magnitude of individual treatments. Second, preventive preservation strategies reduce lifecycle economic exposure by avoiding severe deterioration states that require high-cost structural rehabilitation. Third, condition-based maintenance enables highway agencies to maintain pavements within an optimal performance range, thereby improving long-term network serviceability and expenditure stability.

These analytical outcomes provide the evidentiary basis for the policy implications and institutional transition framework discussed in the subsequent section.

9. Policy Implications and Institutional Transition Framework

The lifecycle analysis indicates that improvements in pavement performance are primarily constrained by maintenance philosophy and institutional processes rather than technological limitations. Transitioning from time-based resurfacing to condition-based pavement preservation requires a shift toward integrated asset management frameworks, where maintenance decisions are guided by pavement condition, lifecycle performance, and economic optimisation. This transition necessitates alignment between condition assessment, prioritisation, budgeting, execution, and performance monitoring within a unified decision-making system.

9.1 Policy Implications for Indian Highway Agencies

9.1.1. Maintenance Policy Reform: Adopt preventive maintenance as the primary strategy, with condition-triggered interventions replacing fixed resurfacing cycles. Structural rehabilitation should be limited to cases justified by lifecycle evaluation.

***9.1.2. Budgeting and Financial Planning Reform*:** Transition from annual, project-based allocations toward multi-year lifecycle-based budgeting. Emphasise planned preservation expenditure (OPEX) over reactive rehabilitation (CAPEX) to stabilise long-term costs.

***9.1.3. Institutionalization of Pavement Management Systems*:** Establish PMS as a mandatory decision-support system incorporating condition data, performance prediction, treatment optimisation, and economic evaluation.

9.1.4. Data and Digital Infrastructure Development: Effective condition-based management necessitates systematic data acquisition (Sood, V. K., et al. 2023). Strengthen systematic data acquisition for key indicators such as roughness (IRI), distress, and traffic loading. Enable integration with digital asset management platforms for evidence-based planning.

***9.1.5. Capacity Building and Organizational Change*:** Develop institutional capacity in lifecycle analysis and asset management. Establish dedicated pavement management units and support decentralised decision-making using analytical tools.

Institutional resistance remains the largest barrier rather than engineering limitations. Figure 4 shows how closed-loop framework enables condition-based pavement management through feedback between assessment, prioritization, and maintenance. Performance monitoring outcomes integrate into planning cycles, enabling adaptive optimization of interventions. Such institutionalization shifts maintenance from reactive rehabilitation toward proactive preservation.

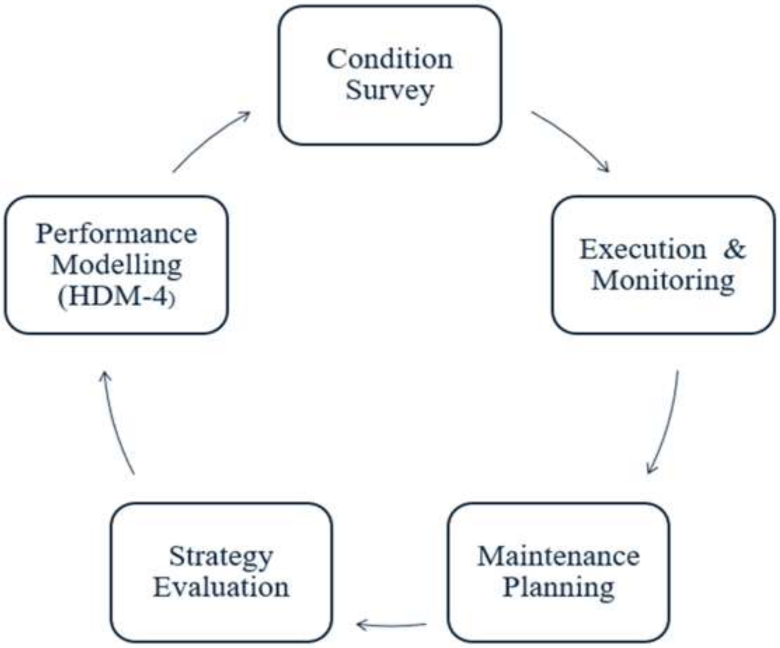

Figure 4. Closed-loop pavement asset management framework integrating condition surveys, HDM-4 performance modelling, lifecycle strategy evaluation, maintenance planning, execution, and performance monitoring.

Tables 4, 5, and 6 summarise the core transition elements, phased implementation pathway, and institutional responsibility structure required to operationalise condition-based pavement management. Together, these elements define a closed-loop governance framework in which condition monitoring, lifecycle evaluation, maintenance planning, and performance feedback are systematically integrated.

Table 4: Core Transition Elements

Traditional Practice	Transition Direction	Target System
Time-based resurfacing	Condition-based intervention	Pavement Management System (PMS)
Project-level decisions	Network-level optimisation	Asset management planning
Annual budgeting	Multi-year lifecycle planning	Performance budgeting
Reactive repairs	Preventive preservation	Risk-based maintenance

Table 5: Phased Institutional Transition Framework for Highway Asset Management

Phase	Time Horizon	Key Interventions / Actions	Intended Outcome

Phase I: Awareness and Pilot Implementation	0–2 Years	• Pilot Pavement Management System (PMS) on selected corridors • Introduce preventive maintenance trials • Develop performance indicators • Establish baseline condition database	Demonstration of economic benefits
Phase II: System Integration	3–5 Years	• Expand PMS to network level • Integrate budgeting with lifecycle-based outputs • Adopt standardized preservation decision trees • Initiate risk-based prioritization	Condition-driven maintenance programming
Phase III: Asset Management Maturity	5–10 Years	• Full-scale asset management adoption • Implement performance-linked funding allocation • Establish continuous monitoring and feedback mechanisms • Introduce predictive maintenance planning	Sustainable highway asset governance

Table 6: Proposed Institutional Responsibility Matrix for Pavement Management.

Level	Responsibility
Policy Authority	Maintenance policy adoption
Agency Headquarters	PMS development & standards
Regional Offices	Data collection & execution
Field Units	Treatment implementation
Audit/Review Units	Performance monitoring

9.2. Expected Strategic Outcomes

Adoption of the proposed framework is expected to (i) extend pavement service life, (ii) reduce frequency of major rehabilitation, (iii) improve serviceability and user experience, (iv) stabilise maintenance expenditure, and (v) enhance transparency and accountability in infrastructure management. Overall, the transition enables highway networks to evolve from reactive maintenance systems to performance-driven infrastructure assets.

10. Conclusions and Contributions

This study evaluated the lifecycle implications of pavement maintenance strategies, with particular emphasis on the role of intervention timing in influencing pavement performance, maintenance frequency, and long-term costs. The analysis demonstrates that periodic resurfacing results in significant fluctuations in pavement condition, with roughness increasing between intervention cycles, whereas condition-based preservation stabilises performance by applying timely preventive treatments. As a result, preservation strategies maintain pavement condition within narrower serviceability limits and significantly reduce the need for major rehabilitation interventions.

From an economic perspective, the findings indicate that preventive maintenance reduces cumulative lifecycle costs by approximately 20-25 percent by avoiding advanced deterioration states requiring high-cost structural overlays. In addition, preservation-based approaches distribute maintenance expenditure more evenly over time, improving budget predictability and financial efficiency. These outcomes confirm that lifecycle performance is governed more by the timing of interventions than by the scale of individual treatments.

The study contributes to pavement asset management by integrating HDM-4 based lifecycle modelling with an implementation-oriented institutional framework suited to Indian highway conditions. It demonstrates how performance-based maintenance planning, supported by condition indicators, can enhance infrastructure sustainability and optimise resource utilisation under constrained budgets. The proposed phased transition framework further provides a practical pathway for agencies to operationalise condition-based pavement management without requiring fully calibrated project-level models.

Overall, the research establishes that timely preventive maintenance, supported by systematic condition monitoring and lifecycle evaluation, offers a technically robust and economically efficient alternative to conventional time-based resurfacing. The transition to condition-responsive pavement preservation is therefore essential for improving long-term performance, reducing rehabilitation dependency, and strengthening the management of highway infrastructure as a strategic national asset.

11. Limitations and Future Research

This study presents a planning-level lifecycle evaluation of alternative pavement maintenance strategies using a simplified analytical framework. The results are intended to demonstrate comparative system behaviour rather than predict performance for specific road sections. Key assumptions related to deterioration behaviour, traffic loading, and treatment costs are representative and may vary across regions and operational conditions. In addition, the analysis focuses on agency costs and does not incorporate user costs, environmental impacts, or network-level optimisation.

Future research should extend this framework using field-calibrated performance models and project-level data to enhance predictive accuracy. Integration of user cost components, environmental considerations, and network optimisation techniques would enable more comprehensive lifecycle assessment. Further work on embedding such models within operational pavement management systems will strengthen the practical implementation of condition-based preservation strategies.

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