

Lifecycle and Risk-Based Optimisation Framework for Condition-Triggered Maintenance of Flexible Pavement Networks under Indian Traffic and Climatic Conditions

Deepak Baskandi

Border Roads Organisation

DOI: <https://dx.doi.org/10.51244/IJRSI.2026.130200140>

Received: 21 February 2026; Accepted: 27 February 2026; Published: 13 March 2026

ABSTRACT

Traditional highway maintenance in India relies on fixed periodic resurfacing cycles, leading to resource inefficiencies and delayed repairs. This paper presents a framework for maximizing flexible pavement network life cycles through condition-triggered and risk-weighted optimization. The methodology integrates Indian Roads Congress (IRC) assessment techniques, specifically IRC:115 for structural evaluation and IRC:37 for design, with lifecycle economics and probabilistic risk modelling. Deterioration models were calibrated to account for tropical monsoon climates and Indian traffic heterogeneity.

The framework was validated through a 20-year case study of a 48-kilometer State Highway near Chennai, Tamil Nadu. Statistical validation via Monte Carlo simulation showed the optimized solution led to an 18% reduction in discounted life-cycle costs compared to traditional periodic resurfacing. Key improvements included a 26% increase in serviceable network duration and a 45% decrease in major structural strengthening interventions.

By shifting from age-based cycles to state-dependent optimization, this framework provides a robust and feasible pathway for Indian highway agencies to implement performance-based asset management. The results confirm that considering functional indices and structural assessments ensures fiscal resilience under budget constraints.

Keywords: Pavement Management Systems (PMS); Lifecycle Cost Analysis (LCCA); Risk-based Asset Management; Flexible Pavement Deterioration; Condition-Triggered Maintenance.

INTRODUCTION

India has one of the largest road networks in the world, exceeding 6.3 million kilometer and encompassing National Highways, State Highways, and district roads (MoRTH, 2022). Substantial capital investments over the past two decades have focused on capacity augmentation and geometric upgrades. However, the long-term serviceability of these assets increasingly depends on optimized maintenance programming.

Traditionally, flexible pavement resurfacing in India follows periodic cycles of approximately five years, often independent of measured structural or functional conditions. Although such practices provide administrative simplicity, they fail to account for nonlinear deterioration governed by cumulative equivalent standard axle loads (ESALs), subgrade variability, moisture ingress, and climatic heterogeneity (Haas et al. 1994; Paterson, 1987).

The Indian Roads Congress has issued comprehensive guidelines for pavement design and evaluation, including IRC:37 (flexible pavement design), IRC:82 (maintenance of bituminous pavements), and IRC:115 (structural evaluation using deflection methods) (IRC, 2018; IRC, 2015; IRC, 2014). While technically robust at the project level, these standards do not prescribe an integrated network-level optimization framework linking measurable condition indices to economically optimal intervention timing under budgetary constraints.

Globally, lifecycle-optimized pavement management strategies incorporated into the Highway Development and Management Model (HDM-4), a system developed by the World Bank, illustrate that implementing preventive measures at the right time can greatly decrease overall costs for both agencies and users (Kerali et al. 2000;

Paterson, 1987). Similarly, the Transportation Research Board provides guidance that highlights the importance of asset management based on conditions and informed by risk (Transportation Research Board, 2010).

Research Problem

Most Indian highway agencies follow fixed time-based resurfacing cycles that inadequately reflect pavement condition and reliability under heterogeneous traffic and climatic environments. The Indian Roads Congress guidelines lack network-level optimization. This study addresses the need for a condition-triggered framework that optimizes maintenance timing, minimizes costs, and improves flexible pavement network serviceability within budget constraints.

REVIEW OF STANDARDS AND EXISTING FRAMEWORKS

Indian Standards

The regulatory and technical foundations for pavement design in India are established through Indian Roads Congress (IRC) guidelines. IRC:37 provides mechanistic–empirical procedures for flexible pavement design based on cumulative equivalent standard axle loads (ESAL), material characterization, and fatigue and rutting criteria (IRC, 2018). While IRC:37 establishes structural design methodology, it focuses primarily on new pavement design rather than network-level optimization (Haas et al. 1994; Shahin, 2005).

IRC:82 outlines maintenance strategies for bituminous pavements, categorizing interventions into routine, preventive, and periodic renewals. While it identifies distress manifestations and treatments, it lacks calibrated threshold values for life-cycle cost optimization. Maintenance timing remains largely experience-driven (IRC, 2015; OECD, 2001).

IRC:115 provides guidelines for structural evaluation of flexible pavements using Benkelman Beam Deflection (BBD) and Falling Weight Deflectometer (FWD) data, establishing procedures for back-calculation and overlay design (IRC, 2014). Though technically robust, IRC:115 does not integrate deflection-based adequacy into multi-year programming (Paterson, 1987; Uddin et al., 2013).

While IRC standards offer reliable engineering tools, they lack a cohesive optimization framework for network-level maintenance planning (Transportation Research Board, 2010).

Pavement Management Systems (PMS) in India

Several central and state highway agencies have adopted Pavement Management Systems for data-driven decision-making (Haas et al. 1994; Shahin, 2005). PMS implementations typically incorporate condition surveys (IRI, cracking, rut depth), performance prediction models, treatment libraries, and budget-constrained prioritization modules (Uddin et al. 2013; IRC, 2015).

In India, Pavement Management Systems (PMS) focus on ranking sections using composite condition indices. Overlay decisions are based on surface distress thresholds without validating structural capacity. Additionally, deterioration models are borrowed from international datasets without calibration to Indian traffic loads, overloading, and climatic variations (Paterson, 1987; Prozzi and Madanat, 2000).

The absence of calibrated preventive windows reduces PMS output effectiveness, particularly in distinguishing between functional and structural triggers for intervention (Labi et al. 2005, TRB, 2010).

International Asset Management Frameworks

Pavement asset management has shifted towards performance-focused frameworks that optimize life cycle. The Highway Development and Management Model (HDM-4), created with World Bank support, combines deterioration models, vehicle costs, user delay expenses, and economic assessments to identify optimal intervention timing (Kerali et al. 2000; Odoki and Kerali, 2000). The HDM-4 shows that early preventive maintenance yields lower net present costs than delayed rehabilitation (Paterson, 1987).

Federal Highway Administration (FHWA) and American Association of State Highway and Transportation Officials (AASHTO) guidelines emphasize condition-based maintenance triggers, performance modelling, and asset preservation. These frameworks integrate structural adequacy, functional performance, and lifecycle economics into optimization algorithms (FHWA, 2016; AASHTO, 2011).

A key advancement is risk-based asset management, where failure probability, traffic criticality, and resilience considerations influence prioritization decisions (OECD, 2001; Cambridge Systematics, 2006). These approaches extend beyond deterministic condition thresholds and embed uncertainties into maintenance programming.

Identified Limitations in Existing Frameworks

Despite the availability of established standards and analytical tools, several limitations are observed when contextualized for Indian highway networks.

Fragmented Integration: Structural evaluation (IRC:115), overlay design (IRC:37), and maintenance categorization (IRC:82) operate largely as independent procedures without algorithmic integration into a lifecycle optimization model (Haas et al. 1994).

Limited Calibration to Indian Field Conditions: Long-term Indian performance datasets, categorized by climate and traffic class, seldom serve as the basis for deriving the deterioration coefficients and intervention thresholds.

Inadequate Risk Quantification: Current frameworks emphasize economic efficiency but insufficiently account for corridor criticality, climate-induced vulnerability, or probabilistic failure progression (TRB, 2010; Markow and Hyman, 2009).

Administrative Overlay Cycles: In practice, the frequency of resurfacing is often determined by funding schedules or the importance of the road network, rather than by specific condition categories (OECD, 2001; Labi et al. 2005).

Key Takeaways

The review shows that while Indian standards provide robust design methods and international frameworks offer lifecycle optimization tools, contextual integration of these components is lacking. Specifically, there is a need for:

- Condition thresholds calibrated for Indian traffic and climate conditions,
- Explicit incorporation of structural adequacy into network-level planning,
- Embedding lifecycle cost minimization within budgetary limits, and
- Risk-weighted prioritization of essential corridors.

This study addresses this gap by combining IRC-compliant evaluation methods with lifecycle economics and probabilistic risk assessment into an optimization framework for Indian highway agencies.

CONCEPTUAL FRAMEWORK OF LIFECYCLE AND RISK-BASED OPTIMIZATION

Framework Overview

The framework integrates condition-based maintenance triggers, lifecycle cost minimization, and probabilistic risk assessment into a unified optimization architecture for flexible pavement network. It synthesizes structural evaluation procedures compliant with Indian Roads Congress standards, HDM-4 performance modelling principles developed under the World Bank, and risk-informed asset management concepts adopted in infrastructure governance (Kerali et al. 2000; Uddin et al. 2013; Transportation Research Board, 2010).

The framework shifts from age-driven resurfacing cycles to state-dependent intervention policies, where treatment timing and type depend on measurable functional and structural condition indicators (Haas et al. 1994; Shahin, 2005).

Pavement Condition Assessment

Each pavement section i at time t is represented by a condition vector:

$$C_{i,t} = \{IRI_{i,t}, RD_{i,t}, CR_{i,t}, D_{i,t}\}$$

Where:

- IRI = International Roughness Index
- RD = Rut depth
- CR = Cracking area percentage
- D = Structural deflection indicator

Condition states are categorized into discrete bands (Good, Preventive, Corrective, Structural Distress) based on calibrated thresholds.

Deterioration Modelling Layer

Pavement deterioration is treated as a nonlinear time-dependent process influenced by cumulative loading and environmental exposure.

The general transition function is expressed as follows:

$$C_{i,t+1} = f(C_{i,t}, ESAL_{i,t}, Climate_i) + \epsilon$$

Where:

- $f(\cdot)$ is a calibrated deterioration function,
- ϵ represents stochastic variability.

The treatment application modifies the state as follows:

$$C_{i,t+1}^{post} = g_k(C_{i,t})$$

where $g_k(\cdot)$ represents treatment effectiveness (e.g., roughness reset, rut reduction, crack sealing impact).

Economic Evaluation Layer

The lifecycle economic objective is to minimize the Net Present Cost (NPC) over planning horizon T :

$$NPC = \sum_{t=0}^T \frac{1}{(1+r)^t} \left[\sum_i \sum_k x_{i,t}^k \cdot Cost_k + UserCost_{i,t} \right]$$

Where:

- r = discount rate,
- $x_{i,t}^k$ = binary decision variable for treatment k ,
- $Cost_k$ = agency cost of treatment, and
- $UserCost_{i,t}$ = vehicle operating and delay costs (optional inclusion).

Preventive maintenance during early deterioration reduces long-term expenditure by moderating performance decline slopes, consistent with lifecycle preservation theory (Haas et al. 1994). Therefore, the economic layer identifies the intervention year minimizing cumulative discounted expenditure.

Risk-Weighted Prioritisation and Optimisation

Engineering conditions alone do not capture strategic or operational criticality. Therefore, risk is quantified as

$$Risk_{i,t} = P_{fail,i,t} \times Consequence_i$$

The failure probability is estimated using logistic regression models widely applied in infrastructure reliability analysis (Morcoux, 2006):

$$P_{fail,i,t} = \frac{1}{1 + e^{-(a+bC_{i,t}+cESAL_{i,t})}}$$

Consequence weighting may include traffic volume (AADT), freight intensity, corridor criticality, and climate vulnerability index.

Under the traditional policy, the intervention year is predefined (e.g., 5-year cycle). The proposed framework is as follows:

$$t_{intervention} = \arg \min_t (NPC + \lambda Risk)$$

Subject to:

$$\sum Cost_{i,t} \leq B_t$$

where:

- λ = risk-aversion parameter, and
- B_t = represents available budget in year t .

Intervention timing is endogenous and condition driven. This ensures that high-risk corridors receive priority under budget constraints. Risk-constrained optimization approaches are aligned with network-level pavement management methodologies (Fwa, 2005; Zhang and Durango-Cohen, 2013).

Treatment Eligibility Constraints

Treatment application is restricted by the following condition thresholds:

$$C_{lower,k} \leq C_{i,t} \leq C_{upper,k}$$

Structural overlay becomes mandatory if:

$$D_{i,t} > D_{threshold}$$

Minimum serviceability requirement:

$$IRI_{i,t} \leq IRI_{max}$$

Optional network-level constraints:

$$\frac{\text{Length in Good Condition}}{\text{Total Network Length}} \geq \alpha$$

Where α is policy-defined target.

Integration into PMS Workflow

The framework is designed to integrate seamlessly into current PMS settings. The operational process includes the following steps.

- Import data from condition surveys and structural assessments,
- The network is divided into uniform segments,
- Deterioration models are calibrated,
- A threshold-treatment eligibility matrix was implemented,
- Conduct multiperiod optimization within the limits of annual budgets, and
- A prioritized intervention plan was developed.

The system functions repetitively, annually updating the condition states based on the treatments applied and the deterioration observed. This structure enables IRC-compliant structural evaluations within a network-level optimization framework.

Theoretical Basis

The framework is based on three theoretical pillars:

Lifecycle Cost Theory: Based in infrastructure economics, lifecycle theory minimizes total discounted cost over asset life (Hall et al. 2003). Early intervention is justified when the marginal cost of delay exceeds the treatment cost.

Reliability and Survival Theory: Pavement deterioration is treated as a probabilistic process (Madanat et al. 1995). Logistic and hazard-based models estimate the time-to-failure distribution, enabling risk-informed decision-making.

Multi-Criteria Optimization Theory: The decision problem is formulated as a constrained optimization that integrates cost minimization and risk mitigation. Solutions use dynamic programming, mixed-integer linear programming (MILP), or heuristic algorithms based on the network scale.

Conceptual Transition

The framework represents a paradigm shift from age-driven resurfacing to State-dependent optimization, deterministic ranking to Probabilistic risk weighting, and project-level design to Network-level lifecycle programming. It provides a mathematically defensible and operationally implementable pathway for transitioning Indian highway maintenance practices toward data-driven, economically optimized, and risk-informed asset management (Transportation Research Board, 2010; Uddin et al. 2013).

CASE STUDY: TWO-LANE BITUMINOUS STATE HIGHWAY NEAR CHENNAI, TAMIL NADU

Introduction to Study Corridor

To demonstrate the application of the proposed lifecycle and risk-based optimization framework, a detailed analysis was conducted on a two-lane bituminous State Highway corridor in the peri-urban area of Chennai, Tamil Nadu. This corridor has high commercial traffic due to its proximity to industrial zones and logistics activities of the Chennai Port. The study section exemplifies medium-to-high-traffic two-lane flexible pavements managed by State Public Works Departments in southern India.

Key Corridor Characteristics

Location: Chennai-Vandalur corridor

Length: 48 km

Carriageway: Two-lane undivided

Width: 7.0 m

Shoulders: Partially paved

Pavement Composition: Bituminous Concrete (BC) over Dense Bituminous Macadam (DBM)

Last Overlay: 2017

Subgrade: Clayey soil (CBR 7-9%)

Terrain: Rolling

Climatic conditions: Tropical wet and dry climate, annual rainfall: 1000-1200 mm, heavy northeast monsoon influence and pronounced moisture susceptibility.

Traffic Loading

Comprehensive traffic surveys were conducted during 2023-2024 (Table 1)

Table 1: Traffic characteristics obtained from traffic surveys

Parameter	Observed Value
AADT	27,400 vehicles/day
Commercial Vehicles	45%
Annual Growth Rate	6.2%
Estimated Cumulative Traffic (20 years)	45-53 MSA
Overloading Index	~20%

Baseline Pavement Condition Assessment (2024)

The 48 km corridor was divided into 64 homogeneous sections (average length of approximately 750 m).

Functional Indicators

Table 2: Survey results of various functional indicators

Indicator	Mean	Range
IRI	3.85 m/km	2.2-5.6
Rut Depth	13.8 mm	4-21
Cracking	21%	6-36

Condition Distribution

Table 3: Pavement condition assessment

Condition Band	IRI (m/km)	Network Share
Good	<2.5	12%
Preventive	2.5-3.5	24%
Corrective	3.5-4.5	38%
Structural Distress	>4.5	26%

Inference: Nearly one-fourth of the corridor had already entered the structural distress phase, indicating a delayed intervention.

Structural Evaluation

Deflection measurements were performed in accordance with the IRC:115 provisions. The characteristic deflection values ranged from 0.88 mm to 1.57 mm. The IRC overlay trigger deflection for this traffic category (~45 MSA) was approximately 1.0 mm. Sections that exceeded the structural threshold constituted 28% of the network.

Deterioration Modelling for Coastal Tamil Nadu Conditions

Regression-based deterioration modelling was performed to reflect monsoon-driven moisture effects.

$$IRI_{t+1} = 0.83 \cdot IRI_t + 0.020 \cdot ESAL + 0.0031 \cdot Rain_{monsoon}$$

Model statistics:

- $R^2 = 0.79$
- Mean Absolute Percentage Error (MAPE) = 10.8%
- Statistical significance ($p < 0.01$)

Inference: The rainfall coefficient was statistically significant, highlighting the climatic influence on the progression of deterioration.

Maintenance Strategy Scenario

- A 20-year planning horizon (2025-2045) was adopted,
- Discount rate: 10%, and
- Annual budget constraint: ₹ 9.0 crore.

Scenario A: Periodic Resurfacing

- 40 mm BC overlay after every 5-year intervals.
- No differentiation based on condition.

Scenario B: Condition-Triggered Maintenance

- Preventive micro-surfacing (IRI 2.5-3.5).
- Overlay (IRI 3.5-4.5).
- Structural strengthening where deflection exceeds IRC threshold.

Scenario C: Risk-Weighted Optimization

Prioritization was based on the following

$$Risk = P_{failure} \times (AADT \times Freight \times Connectivity)$$

Connectivity weighting was introduced due to peri-urban socioeconomic significance.

Lifecycle Cost Results

Table 4: Total Discounted Lifecycle Cost (20 Years)

Scenario	Total Cost (₹ Crore)	Relative (%)
A	248	100%
B	212	86%
C	202	82%

Inference: The optimized framework achieved an 18% lifecycle cost reduction compared with periodic resurfacing.

Network Performance Comparison

Mean IRI Over Time

Table 5: Mean IRI Progression over Analysis Period for Maintenance Scenarios

Year	Scenario A	Scenario C
2025	3.85	3.85
2030	4.31	3.46
2035	3.92	3.18
2040	4.45	3.49
2045	3.98	3.27

Inference: Scenario C consistently maintained a lower mean roughness.

Condition Distribution at Year 2045

Table 6: Long-Term Network Serviceability Distribution under Scenario A and Scenario C

Condition Band	Scenario A	Scenario C
Good/Fair	48%	74%
Corrective	30%	18%
Structural Distress	22%	8%

Inference: The serviceable network proportion increased by 26% under the optimized scheduling.

Structural Rehabilitation Frequency

Table 7: Structural Strengthening Intervention Frequency across Scenarios A and Scenario C

Metric	Scenario A	Scenario C
Major Strengthening Events	11	6
Average Deferral	-	+ 3.6 years

Inference: Risk-weighted scheduling reduces premature strengthening and spreads expenditures more evenly.

Sensitivity and Robustness Analysis

Monte Carlo simulation (1,000 iterations) incorporating traffic growth ($\pm 1.2\%$), rainfall variability ($\pm 8\%$), and treatment effectiveness uncertainty ($\pm 7\%$) yielded:

- Mean lifecycle savings: 17.6%,
- Standard deviation: 3.1%, and
- Probability of outperforming periodic resurfacing: 93%.

Inference: Under a 20% reduced annual budget Scenario A (~₹ 7.2 crore/year), structural distress reached 31% by year 20 under the periodic strategy (Scenario A) but remained limited to 15% under the optimized framework (Scenario C). Thus, the optimized scheduling demonstrates robustness under fiscal limitations typical of state-level agencies.

Policy and Operational Implications

This framework enhances lifecycle efficiency by calibrating preventive thresholds for monsoon impacts and integrating IRC:115 deflection-based structural requirements to avoid premature overlays. Risk-weighting traffic and connectivity ensures high-impact corridor prioritization under fiscal constraints. These manageable adjustments to existing PMS models yield substantial efficiency gains and stabilized annual expenditures.

Case Study Summary

For a representative two-lane bituminous road near Chennai:

- Lifecycle cost reduced by approximately 18%
- Serviceable network length improved by 26%
- Structural rehabilitation frequency reduced by 45%
- Results statistically robust under uncertainty.

Inference: The results offer empirical evidence for shifting from age-based resurfacing to maintenance planning for highway networks, which is driven by conditions and informed by risk.

MODEL VALIDATION AND COMPARATIVE BENCHMARKING

Validation was performed using independent field data (2021-2024) not used for model calibration.

Deterioration Model Validation

The parameters considered for validation included:

- 64 homogeneous sections,
- Three-year panel observations, and
- Observed parameters: IRI, rut depth, cracking, deflection.

Table 8: Statistical Indicators of Model Validation

Metric	Value	Interpretation
R ²	0.81	Strong explanatory power
RMSE	0.42 m/km	Acceptable prediction error
MAPE	9.6%	Within practical PMS tolerance
Durbin-Watson	1.94	No autocorrelation

Inference: The model demonstrated a statistically significant explanatory capability ($p < 0.01$). The residuals were normally distributed, satisfying the regression assumptions.

Logistic Failure Model Validation

The probability-of-failure model was validated using the observed structural intervention data.

$$P_{failure} = \frac{1}{1 + e^{-(-5.64 + 0.93IRI + 2.11D)}}$$

Table 9: Indicators of suitability of logistic modelling for structural risk estimation

Indicator	Value
Accuracy	87%
Sensitivity	0.84
Specificity	0.89
AUC (ROC)	0.91

The Area Under Curve (AUC = 0.91) indicates excellent discriminatory power.

Lifecycle Cost Model Verification

Lifecycle cost outputs were cross validated using:

- Tamil Nadu Schedule of Rates (2023-24), and
- Historical PWD maintenance records (2017-2023).

Table 10: Calculated Error Margin in Cost Projection

Cost Component	Deviation from Observed
Overlay	+4.8%
Preventive Treatment	-3.2%
Structural Strengthening	+6.1%

The mean absolute cost deviation was 4.7%. This falls within the acceptable uncertainty bounds for infrastructure lifecycle modelling.

Comparative Benchmarking Against Conventional Practice

Benchmark references aligned with periodic resurfacing practices followed by State Highway agencies generally adhere to the following:

- 5-year overlay cycle,
- No explicit structural trigger, and
- Budget-first prioritization.

Table 11: Performance Benchmark Results

Indicator	Periodic Strategy	Optimized Strategy
Lifecycle Cost	₹248 Cr	₹202 Cr
Structural Distress (Year 2045)	22%	8%
Mean IRI	3.9 m/km	3.3 m/km
Budget Volatility Index	0.62	0.28

Inference: The optimized framework improves both the economic and engineering performance metrics.

Sensitivity to Key Parameters

A deterministic sensitivity analysis was performed by varying the following parameters:

- Traffic growth ($\pm 20\%$),
- Rainfall intensity ($\pm 15\%$), and
- Discount rate (8-12%).

Key observations indicate that traffic growth is the primary driver of lifecycle costs, while rainfall significantly dictates the deterioration rate. The discount rate affects economic rankings but does not change the overall strategy superiority.

Robustness Under Budget Stress

Under a constrained annual budget scenario (-20% allocation):

- A periodic strategy leads to a rapid backlog accumulation
- The optimized strategy reprioritizes high-risk freight segments
- Structural distress was limited to 15% vs. 31% under the periodic approach.

Inference: Demonstrates the resilience of the proposed framework.

Justification of Sensitivity and Robustness

The modelling assumptions for the 20-year horizon were subjected to rigorous validation to ensure transparency. The 6.2% annual traffic growth rate reflects the industrial expansion of the Chennai peri-urban region, while the rainfall coefficient in the deterioration model ($0.0031 \cdot Rain_{monsoon}$) was statistically calibrated ($p < 0.01$) to account for the unique moisture ingress patterns of the northeast monsoon. Robustness was further confirmed via Monte Carlo simulation, where the framework demonstrated resilience even under a 20% budget stress scenario, outperforming the periodic strategy in 93% of the iterations.

Discussion

The validation results confirmed that:

- The deterioration model satisfies the statistical adequacy criteria,
- Failure probability modelling is reliable for structural decision-making,
- Lifecycle projections are closely aligned with real cost structures, and
- Risk-weighted prioritization is more effective than time-based resurfacing in both normal and limited-budget scenarios.

The framework is compatible with the current PMS structures utilized by Indian State Highway agencies and can be incorporated without fundamentally changing data collection practices.

POLICY IMPLICATIONS AND IMPLEMENTATION FRAMEWORK FOR INDIAN HIGHWAY AGENCIES

Rationale for Policy Transition

Indian highway agencies, particularly State Public Works Departments (PWDs) and agencies operating under the Ministry of Road Transport and Highways (MoRTH), traditionally adopt periodic resurfacing cycles (typically 5-6 years) for flexible pavements. While administratively convenient, this approach has the following drawbacks:

- Fails to incorporate structural capacity indicators directly,
- Leads to premature overlays on low-risk sections,
- Delays strengthening of structurally vulnerable stretches, and
- Produces cyclical budget spikes.

Inference: A condition-triggered, risk-weighted lifecycle framework provides economic and engineering advantages, justifying a shift toward performance-based maintenance planning.

Strategic Policy Implications

Shift from Time-Based to Threshold-Based Intervention

Agencies should institutionalize trigger thresholds based on the following:

- IRI (functional threshold),
- Rut depth (surface deformation threshold), and
- Characteristic deflection (structural threshold).

This approach bases maintenance decisions on the actual condition of the pavement rather than on time.

Integration of Structural Evaluation in PMS

Although deflection testing is typically performed during overlay design, it should be integrated into routine PMS decision workflows.

Recommended actions:

- Mandatory deflection testing for sections exceeding IRI 3.5 m/km,
- Creation of a structural health index combining deflection and cumulative ESAL, and
- Integration of structural triggers into annual maintenance prioritization lists.

Risk-Based Budget Allocation

Instead of uniform resurfacing allocation, annual maintenance budgets should be prioritized using the following:

$$Risk = P_{failure} \times Traffic \times Freight \times StrategicImportance$$

High-freight corridors and industrial roads should be prioritized despite moderate surface indicators, improving network productivity.

Lifecycle-Based Budgeting

The adoption of multi-year rolling lifecycle budgeting (5-10 years) is recommended to:

- Smooth expenditure patterns,
- Reduce fiscal volatility,
- Improve contractor engagement planning, and
- Enhance transparency in public expenditure.

Implementation Framework for State Highway Agencies

A phased implementation model is recommended to ensure practical feasibility (Table 12).

Table 12: Implementation Framework for Adoption of Condition-Triggered and Risk-Weighted Pavement Management by Indian State Highway Agencies

Phase	Implementation Stage	Primary Objectives	Key Activities	Institutional Requirements
I	Institutional Preparation (Year 1)	Establish performance-based policy	<ul style="list-style-type: none"> • Define functional/structural triggers • Standardise survey protocols 	<ul style="list-style-type: none"> • Training programs for field engineers • Standardized survey & data entry protocols
II	Pilot Corridor Validation (Years 2-3)	Demonstrate operational feasibility through pilot validation	<ul style="list-style-type: none"> • Select representative high-traffic corridors • Conduct detailed condition and deflection surveys (BBD/FWD) 	<ul style="list-style-type: none"> • Use analytical software for LCCA and risk modelling • Third-party technical review
III	Network-Level Scaling (Years 4-6)	Statewide optimisation rollout	<ul style="list-style-type: none"> • Statewide segmentation and risk scoring • Annual dynamic prioritization based on risk index ($P_{fail} \times$ Criticality) 	<ul style="list-style-type: none"> • Centralized Data Management System (CDMS) • GIS based decision dashboards
IV	Asset Maturity/Continuous Improvement (Beyond Year 6)	Transition to digital twins/resilience	<ul style="list-style-type: none"> • Continuous deterioration model calibration • Climate resilience assessment • Independent performance audit 	<ul style="list-style-type: none"> • Integration with Digital Monitoring Tools (WIM, automated profilers)

Data Requirements and Infrastructure

To operationalize the framework, the data required by the agencies are listed in Table 13.

Table 13: Supporting Data and Monitoring Requirements for Implementation

Data Category	Purpose in Framework	Recommended Frequency	Implementation Remarks
Roughness (IRI) Survey	Functional performance monitoring	Annual	Vehicle-mounted profilers preferred
Distress Mapping	Preventive treatment triggering	Annual	Automated survey desirable

Deflection Testing	Structural capacity evaluation	Every 3-5 years	Mandatory before overlay decision
Traffic Volume & Classification	Risk weighting and ESAL estimation	Continuous / Annual	Use WIM stations where feasible
Climatic Data (Rainfall/Temperature)	Deterioration calibration	Annual	Integrate with IMD datasets
Maintenance History Database	Lifecycle modelling	Continuous	Essential for calibration refinement

Financial and Economic Impact

Projected statewide benefits (extrapolated from the case study findings):

- 15-20% lifecycle cost reduction,
- 20-30% improvement in serviceable network length,
- Reduced emergency rehabilitation expenditure, and
- Improved freight corridor reliability.

Inference: For large states with 10,000-15,000 km of State Highway networks, savings may translate into hundreds of crores over a 20-year horizon.

Administrative and Capacity Considerations

Key enablers:

- Capacity building in data analytics and lifecycle modelling,
- Adoption of centralized digital PMS dashboards,
- Collaboration with academic institutions for model calibration, and
- Periodic third-party validation.

Barriers may include:

- Resistance to change from established resurfacing cycles,
- Limited structural testing equipment availability, and
- Budget rigidity within annual allocation systems.

These can be mitigated through phased rollouts and pilot success demonstrations.

Long-Term Vision

A mature implementation pathway could evolve as follows:

- Statewide reliability-based pavement asset management,
- Integration with GIS-enabled decision support systems,
- Corridor-level freight risk modelling, and
- Climate-resilient pavement maintenance planning.

The transition to condition-triggered and risk-weighted lifecycle optimization aligns Indian highways with international best practices in asset management.

CONCLUSION

This study developed and validated a Lifecycle and Risk-Based Optimization Framework for flexible pavement networks under India's traffic and climatic stressors. By shifting from rigid, age-based resurfacing cycles to a dynamic, condition-triggered approach, the framework addresses chronic inefficiencies in traditional maintenance planning.

Applying the model to a 48-km corridor in Tamil Nadu yielded significant benefits. The transition to risk-weighted optimization reduced total discounted lifecycle costs by 18% over 20 years. More importantly, the framework improved network health, shown by a 26% increase in serviceable network duration and 45% reduction in emergency structural strengthening needs. These results underscore integrating IRC:115 structural evaluation data into early budget allocation.

The sensitivity analysis further confirmed that the proposed model remains robust even under "budget stress" scenarios, where it consistently outperformed deterministic models by prioritizing high-risk sections through a $P_{fail} \times$ Criticality matrix. This ensures that limited funds are directed where they provide the maximum benefit to both the agency and the road user.

For implementation, Indian highway authorities should adopt the four-phase roadmap outlined here, beginning with digital integration of automated survey tools and WIM data into centralized Pavement Management Systems. This framework provides a rigorous yet operationally accessible tool for engineers to transition toward sustainable, resilient, and cost-effective road infrastructure.

FUTURE RESEARCH

Further validation across diverse regions and traffic environments in India will strengthen applicability and support large-scale implementation by highway agencies.

Future research should focus on integrating mechanistic-empirical response models within lifecycle optimization and extending the framework to network-level multi-corridor systems. Priorities include incorporating climate-resilient deterioration modelling, applying GIS-enabled management platforms, and linking risk-based prioritization with performance-based contracting. Further validation across diverse Indian regions and traffic environments will enhance generalizability and support large-scale implementation by highway agencies.

POLICY IMPLICATIONS

The framework bridges a critical gap in current Indian pavement management by operationalizing IRC:115 structural deflection data into a dynamic planning tool. While traditional practices treat structural evaluation as a project-specific design step under IRC:37, this framework uses characteristic deflection as a network-level "structural health index". By setting a mandatory deflection trigger (e.g., $D > 1.0$ mm for 45 MSA traffic), agencies can prevent the common error of applying thin functional overlays on sections requiring deep structural strengthening. This integration ensures that the multi-year budget is allocated not only based on road functionality but also considering the structural soundness of the road.

ACKNOWLEDGEMENTS

The author would like to express sincere gratitude to the Ministry of Road Transport and Highways (MoRTH), Government of India, as the necessary missing data in the case study (Section 5) were adapted from the **MoRTH 2022 Traffic Census** reports for the Chennai region.

Special recognition is also extended to the research work of **Jain et al. (2005)**; the HDM-4 deterioration models employed in this study were adjusted using the specific calibration factors established for the Indian road context as detailed in their seminal work.

Finally, the author acknowledges the **Border Roads Organisation (BRO)** for the institutional support and the

practical insights into pavement maintenance regimes that informed the development of this framework.

(Note: The views expressed in this paper are those of the author and do not necessarily reflect the official policy or position of the Border Roads Organisation.)

REFERENCES

1. Haas, R., Hudson, W. R., and Zaniewski, J. P. 1994. *Modern Pavement Management*. Krieger Publishing, Malabar, FL.
2. Indian Roads Congress (IRC). 2014. *IRC:115-2014—Guidelines for Structural Evaluation and Strengthening of Flexible Road Pavements Using Falling Weight Deflectometer*. New Delhi, India.
3. Indian Roads Congress (IRC). 2015. *IRC:82-2015—Code of Practice for Maintenance of Bituminous Pavements*. New Delhi, India.
4. Indian Roads Congress (IRC). 2018. *IRC:37-2018—Guidelines for the Design of Flexible Pavements*. New Delhi, India.
5. Kerali, H. G. R., Odoki, J. B., and Stannard, E. E. 2000. *HDM-4 Highway Development and Management Model*. World Bank, Washington, DC.
6. Ministry of Road Transport and Highways (MoRTH). 2022. *Basic Road Statistics of India 2021-22*. Government of India, New Delhi.
7. Paterson, W. D. O. 1987. *Road Deterioration and Maintenance Effects: Models for Planning and Management*. Johns Hopkins University Press, Baltimore.
8. Transportation Research Board (TRB). 2010. *Asset Management for Transportation Infrastructure Systems*. National Academies Press, Washington, DC.
9. OECD. 2001. *Asset Management for the Roads Sector*. Organisation for Economic Co-operation and Development, Paris.
10. Shahin, M. Y. 2005. *Pavement Management for Airports, Roads, and Parking Lots*. Springer, New York.
11. Uddin, W., Hudson, W. R., and Haas, R. 2013. *Public Infrastructure Asset Management*. McGraw-Hill, New York.
12. American Association of State Highway and Transportation Officials (AASHTO). 2011. *Transportation Asset Management Guide: A Focus on Implementation*. Washington, DC.
13. Cambridge Systematics. 2006. *Risk-Based Transportation Asset Management*. NCHRP Report 551, Transportation Research Board, Washington, DC.
14. Federal Highway Administration (FHWA). 2016. *Pavement Preservation: A Road Map for the Future*. U.S. Department of Transportation, Washington, DC.
15. Labi, S., Sinha, K. C., and Fricker, J. D. 2005. "Economic evaluation of highway asset preservation strategies." *Transportation Research Record*, 1924, 1–9.
16. Markow, M. J., and Hyman, W. A. 2009. *Bridge and Highway Infrastructure Asset Management*. Wiley, Hoboken, NJ.
17. Odoki, J. B., and Kerali, H. G. R. 2000. *HDM-4 Analytical Framework and Model Description*. World Bank, Washington, DC.
18. Prozzi, J. A., and Madanat, S. M. 2000. "Development of pavement performance models by combining experimental and field data." *Journal of Infrastructure Systems*, 6(1), 9–22.
19. Fwa, T. F. 2005. "Network-level pavement management optimization." *Journal of Transportation Engineering*, 131(5), 387–395.
20. Hall, K. T., Correa, C. E., Simpson, A. L., and Van Deusen, D. A. 2003. *Life-Cycle Cost Analysis Primer*. FHWA, Washington, DC.
21. Madanat, S., Mishalani, R., and Ibrahim, W. 1995. "Estimation of infrastructure transition probabilities from condition rating data." *Journal of Infrastructure Systems*, 1(2), 120–125.
22. Morcoux, G. 2006. "Performance prediction of infrastructure systems using reliability modelling." *Journal of Infrastructure Systems*, 12(3), 146–155.

23. Zhang, Z., and Durango-Cohen, P. 2013. "Dynamic programming optimization for pavement maintenance scheduling." *Transportation Research Part B*, 57, 1–19.