Prioritisation of Highway Maintenance Using Pavement Condition Road Safety Risk and Life Cycle Cost

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Abstract — Highway maintenance programmes must balance deteriorating pavement condition, preventable safety risk and limited financial resources. These objectives are related but are not interchangeable: the section with the worst surface condition may not offer the largest safety improvement, and the treatment with the lowest initial cost may require more expensive future interventions. This focused narrative review synthesises selected pavement-management research, an Indian urban-road application and official guidance on friction management and life-cycle cost analysis. It proposes a staged decision framework for Indian highway networks that first addresses urgent hazards and treatment feasibility, then compares treatment strategies over a common analysis period, and finally selects a budget-feasible portfolio. Condition and safety benefits are retained as distinct outcomes, while life-cycle cost informs alternative selection and affordability rather than being mechanically added to a deficiency score. Two explicitly hypothetical calculations demonstrate the distinction between initial and discounted cost, and between ranking individual projects and optimising a portfolio. The examples illustrate arithmetic and decision logic; they provide no evidence of field effectiveness. A prospective validation plan is proposed using independently measured pavement outcomes, safety observations and expenditure records. The framework offers an auditable research method whose performance depends on locally calibrated deterioration models, credible safety estimates and transparent treatment assumptions.

Keywords: Highway Maintenance; Pavement Management; Road Safety; Life-Cycle Cost; Prioritisation; Portfolio Optimisation; Asset Management

I. Introduction

Maintenance planning involves at least three decisions: which sections require intervention, which treatments are technically suitable, and which combination can be delivered within available funds. Combining these decisions in one ranking can conceal important differences. A poorly performing section may require rehabilitation, while an otherwise sound section may need a targeted friction treatment. Even when both are justified, their timing and funding implications can differ.

FHWA describes pavement management as a process linking condition data, performance forecasts, treatment recommendations and financial scenarios [1]. Its life-cycle cost guidance compares the expenditure streams of alternative strategies [2]. Safety-oriented friction management adds information that a general surface-condition indicator may not represent adequately [3, 4]. These perspectives suggest a staged decision process rather than a single “worst first” rule.

This paper asks how pavement condition, safety risk and life-cycle cost can be integrated without double counting or concealing mandatory action. The intended contribution is a transparent framework for research and subsequent adaptation to Indian highway programmes. It does not claim that integration itself is new: recent research already evaluates multiple objectives in pavement investment [5, 6]. The narrower contribution is an explicit separation of need, treatment effect, economic comparison and portfolio selection, together with reproducible examples and a validation design.

II. Review Approach and Evidence Boundaries

A focused narrative search was conducted on 1 November 2026 through web-indexed publisher, government and research-repository pages. Queries included “pavement life cycle cost analysis maintenance preservation safety friction management”, “pavement management prioritization multi objective safety asset management” and “highway pavement maintenance prioritization safety multi objective life cycle cost research Indian highways”. Eight sources were selected for direct relevance to the decision structure, measurement or implementation.

The evidence consists of official technical webpages [1]–[4], an official research summary [5], accessible portions of an Indian journal article [6], a research-preprint abstract [7] and an official explanation of life-cycle planning [8]. Source types are identified because guidance, modelled case-study results and independently observed treatment effects have different evidential strength. No systematic database coverage, pooled effect size or comprehensive novelty assessment is claimed.

The synthesis uses only claims supported by the material inspected. Numerical benefits reported elsewhere are not transferred to the proposed network. The worked examples are created solely to explain the mathematics. They contain no field measurements, calibrated crash modification factors, market rates or actual project estimates. No contract or Indian standard was supplied for this paper, so project-specific compliance requirements are outside its scope.

III. Literature Synthesis

A. Condition and Economic Assessment

The FHWA pavement-management overview [1] connects current inventory and condition with forecasts under alternative funding and treatment scenarios. Its emphasis on both timing and future condition supports evaluating the consequences of deferral rather than relying exclusively on today's distress. However, a forecast is only as credible as its input data and performance relationships; the guidance itself does not validate a model for a particular Indian road network.

FHWA's LCCA explanation [2] compares initial and subsequent agency and user costs through discounting. It also notes the assumption of comparable service when alternatives are assessed on cost alone. This matters because a low-cost

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strategy delivering materially inferior service cannot be called preferable solely on its discounted expenditure. The separate FHWA discussion of asset-management linkages [8] distinguishes network life-cycle planning from project-level LCCA. A portfolio decision therefore requires more than choosing the cheapest alternative for each section.

B. Safety as a Distinct Maintenance Objective

The pavement-friction primer [3] links friction measurement with both pavement asset management and road safety practice. Its coverage of texture, friction demand and measurement methods supports retaining safety-relevant surface characteristics separately from general distress. A condition rating should not be interpreted as a direct estimate of crash probability unless that relationship has been established for the relevant context.

FHWA's friction-management countermeasure guidance [4] describes combining friction, crash and roadway information to target treatment. It also cautions that an unstable underlying pavement can shorten the life of a high-friction treatment. The implication for this framework is that safety need and treatment feasibility must be evaluated together. The source does not justify applying one crash-reduction percentage to every resurfacing or friction intervention.

C. Multi-Objective and Spatial Applications

Robert, Bliss and Morrison [5] developed a prototype multi-objective approach for Michigan pavement rehabilitation and reconstruction, evaluated using 39 test projects. The official summary identifies asset condition, safety, accessibility and mobility, and environmental impacts among its objectives. This provides direct precedent for broader investment assessment. Its summary does not establish that Michigan preference weights or benefit relationships transfer to India.

Jain, Tiwari, Parida and Anbanandam [6] used HDM-4 to compare maintenance scenarios for a 116.16 km Pune urban-road network. Their analysis considers technical, economic and environmental outcomes, and reports a favourable condition-based scenario within that application. This is a relevant Indian example of model-based network assessment. Urban-network results should not be treated as measured savings for a rural national highway, nor as validation of the safety component proposed here.

Hanandeh, Elbagalati and Hajij [7] propose including spatial coordinates in maintenance prioritisation so that projects can be grouped for execution. The inspected preprint abstract describes applications to municipal project datasets. This introduces a practical consideration that independent segment rankings can miss: geographically related works may share mobilisation or traffic-management arrangements. Such savings require estimation, and grouping should not postpone urgent intervention merely to create a larger package.

Evidence	Contribution	Unresolved transfer issue
Pavement management [1]	Forecast condition and timing under budgets	Local deterioration calibration
LCCA and life-cycle planning [2, 8]	Separate strategy comparison from network planning	Comparable service and budget commitments
Friction guidance [3, 4]	Identify safety need and treatment suitability	Local friction demand and treatment effects
Michigan and Pune studies [5, 6]	Demonstrate multi-objective or network applications	Objectives and model outputs are context dependent
Spatial preprint [7]	Consider implementation geography	Actual bundling savings and scheduling effects

Table 1: summarises how the selected literature informs the proposed design.

IV. Proposed Decision Framework

A. Segment Definition and Minimum Evidence

The proposed analysis unit is a homogeneous section with consistent pavement structure, traffic environment and maintenance history. Section boundaries should change at meaningful changes in material, geometry, loading or drainage, rather than being selected solely for administrative convenience. Short safety-critical locations may need separate representation within longer pavement sections. Otherwise, an average condition value can conceal a localised problem.

Each record should retain survey date, direction, section length, lane configuration, distress measures, roughness where available, structural evidence where needed, drainage condition and previous treatments. Safety records should identify relevant crash types, severity, exposure and geometric context. Cost records should state quantities, price base, treatment timing, traffic-management needs and the source of expected service life. Unknown values should be flagged rather than silently replaced with favourable assumptions.

B. Urgent Action and Treatment Feasibility

The first stage separates conditions requiring immediate operational response from discretionary programme selection. Competent project personnel must determine those triggers under the applicable safety and maintenance arrangements. An economic score cannot excuse inaction on an identified imminent hazard. If available resources cannot meet mandatory needs, the output should show the shortfall and trigger escalation rather than imply that optimisation has resolved it.

The second stage identifies feasible treatment sequences for each section. Surface preservation, local repair, structural rehabilitation and targeted safety treatment have different applicability. A proposed sequence should address the diagnosed mechanism and specify its future maintenance requirements. Where uncertainty about structure or drainage could change the treatment class, additional investigation may be more valuable than immediately refining a numerical rank.

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C. Outcomes And Avoidance of Double Counting

Condition benefit is proposed as the difference between baseline and treatment performance over a common horizon. One option is the area between their condition curves, weighted by lane-kilometres, with the direction and scale of the condition measure stated. This represents preserved service over time rather than current deficiency alone. Structural adequacy and minimum service requirements remain constraints; a high average benefit cannot compensate for an infeasible treatment.

Safety benefit should represent an expected reduction in relevant harm, not simply the number of past crashes. Where suitable data and models exist, expected crash frequency by severity can be combined with defensible treatment effects. Where they do not, an explicitly qualitative risk screen should be used without presenting its score as predicted crashes prevented. An exposure-adjusted rate is useful diagnostically but is not automatically the correct measure of total preventable harm.

An accounting map should identify which outcome appears in which component. If crash costs are monetised in the economic objective, the same safety benefit must not be counted again through an independent safety term without an explicit preference rationale. Similarly, roughness-related user costs and a condition-benefit score may overlap. The proposed default keeps agency cost, non-crash user cost, physical condition benefit and safety benefit visible separately so the decision-maker can inspect that overlap.

V. Life-Cycle Cost and Portfolio Formulation

For an eligible treatment strategy, discounted cost is proposed as LCC = C0 + sum[(A_t + U_t)/(1+r)^t] − V_H/(1+r)^H. C0 is initial expenditure, A_t is subsequent agency expenditure, U_t is the defined user cost during year t, V_H is residual value at the horizon H, and r is the discount rate. Each cost category must be included once. A real discount rate requires constant-price costs; nominal costs require a compatible nominal rate. The formula is a proposed application of standard discounted-cost reasoning [2].

Alternatives should share a price base and analysis horizon. Different remaining lives require an explicit residual-value or continuation convention. User costs need a stated scope: construction delay, vehicle operation and other components should not be mixed inconsistently between alternatives. Agency-only and broader perspectives should be reported separately when both are useful. Future renewals must be included even when they fall outside the first annual budget.

For programme selection, let x_ik equal one when strategy k is selected for section i and zero otherwise. A candidate objective is to maximise the sum of [w_P × B_Pik/P_ref + w_S × B_Sik/S_ref] × x_ik, subject to one strategy per section, annual agency-budget limits and technical or safety constraints. B_P and B_S are incremental condition and safety benefits over a common baseline. P_ref and S_ref are fixed, published scaling constants, and the non-negative preference weights sum to one.

Fixed scales are preferable here to rescaling every candidate pool by its minimum and maximum, which can change rankings when unrelated candidates enter the list. Cost is represented by annual resource constraints and by comparison of efficient treatment alternatives. A further ceiling on discounted programme cost can be added when justified. This keeps the title's three dimensions integrated without treating “cheapness” as a compensating safety benefit.

For large networks, the formulation may need treatment dependencies, corridor interactions, scheduling and uncertain budgets. Where maintenance sequences are represented as complete alternatives, their annual cash flows and performance trajectories should be precomputed consistently. No universal solution algorithm is prescribed. Small candidate sets can be enumerated; larger sets may require optimisation software and a documented feasibility check.

VI. Hypothetical Worked Examples

A. Initial Cost Versus Discounted Cost

The following example is wholly hypothetical. Two technically feasible strategies, X and Y, are assumed to provide equivalent service over ten years. Amounts are illustrative INR lakh, not current rates. X costs 40 at year zero, requires 30 at year five and has a residual value of 5 at year ten. Y costs 55 initially, requires 10 at year seven and has a residual value of 10 at year ten. Other costs are assumed equal and cancel from this comparison; this is an agency-cost illustration, not a full project estimate.

At a hypothetical real discount rate of 5%, LCC_X = 40 + 30/(1.05)^5 − 5/(1.05)^10 = 60.44 lakh. LCC_Y = 55 + 10/(1.05)^7 − 10/(1.05)^10 = 55.97 lakh. Under the stated assumptions, Y has a higher initial expenditure but a lower discounted cost by 4.47 lakh. This is a mathematical consequence of the invented schedules, not evidence of the superiority of a particular field treatment.

Hypothetical discount rate	Strategy X LCC in INR lakh	Strategy Y LCC in INR lakh
3 percent	62.16	55.69
5 percent	60.44	55.97
8 percent	58.10	56.20

Discount-rate sensitivity does not exhaust uncertainty. The apparent preference may change if renewal occurs earlier, the assumed residual value is unsupported or work-zone costs differ. A practical assessment should vary those assumptions as well. The selected discount rates above are demonstration values and are not recommended Indian appraisal rates.

B. Individual Rank Versus Budget-Feasible Portfolio

The second example is independent of the first. Three hypothetical, optional projects are assumed technically feasible, with no outstanding urgent hazards. Each benefit is already divided by the same fixed reference scale, and all benefits are assumed additive. The annual budget is 80 lakh; no other-year budget binds in this simplified illustration. Condition and safety weights are 0.60 and 0.40. The score represents anticipated improvement, not baseline deficiency.

Project and initial cost	Scaled condition and safety benefits	Weighted benefit
A costing 60 lakh	Condition 0.90 and safety 0.20	0.60 × 0.90 + 0.40 × 0.20 = 0.62

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B costing 40 lakh	Condition 0.40 and safety 0.90	0.60 × 0.40 + 0.40 × 0.90 = 0.60
C costing 40 lakh	Condition 0.60 and safety 0.60	0.60 × 0.60 + 0.40 × 0.60 = 0.60

Ranking projects individually places A first. Selecting A leaves 20 lakh and prevents either remaining project from being funded. Its programme benefit is therefore 0.62. Selecting B and C uses the full 80 lakh and yields 1.20. Enumeration of the feasible choices—none, A, B, C, and B plus C—identifies B plus C as the optimum for this hypothetical objective. Neither pair containing A is affordable.

The portfolio preference also survives all non-negative condition–safety weight combinations in this particular example: B plus C supplies condition benefit 1.00 and safety benefit 1.50, compared with A's 0.90 and 0.20. Real portfolios need not show such dominance. The example demonstrates why an ordered list is not a substitute for constrained selection; it does not establish that the proposed framework will outperform existing practice in the field.

VII. Proposed Empirical Validation

A future study should assemble a multi-year section-level dataset linking consistent condition surveys, treatment dates, expenditure, traffic exposure and geocoded crash information. Deterioration models should be calibrated on one set of observations and tested on different roads or later periods. Measurements should distinguish forecast performance from actual post-treatment performance. Independent checks of a sample of records should test location accuracy, treatment coding and consistency of survey methods.

The framework should be compared against transparent baselines such as worst-condition-first, initial-cost ranking and the existing agency programme. All comparisons must use the same eligibility rules, budget, horizon and information available at the decision date. A retrospective comparison that uses later information to improve only the proposed method would be unfair. Differences should be reported in physical outcome units, discounted cost and unmet needs, not only in the framework's own weighted score.

Safety evaluation requires attention to regression to the mean, changing exposure, concurrent interventions and crash reporting. Where suitable safety-performance models and data exist, an empirical-Bayes or controlled before-and-after approach may be considered. Insufficient crash counts may require longer follow-up or intermediate measures; these must not be relabelled as demonstrated crash reductions. Treatment effects estimated for one geometry or traffic environment should be tested before transfer.

Sensitivity analysis should vary deterioration, treatment life, costs, budgets, discount rates and preference weights. Correlated uncertainties should be retained: for example, an adverse traffic or weather scenario may affect several sections together. Reporting how often projects enter an optimal programme across scenarios can reveal unstable choices, but these frequencies are probabilities only when the input distributions have a defensible interpretation. Model complexity should be justified by improvement over simpler methods.

VIII. Implementation and Discussion

For an IE or AE-supported highway programme, the proposed decision record should explain the observed need, eligible treatments, cost assumptions, expected outcomes and reason for selection or deferral. Responsibility for approval and implementation remains governed by the actual project arrangements. The research framework should supplement that process and should not be presented as authority to omit mandatory maintenance.

An annual programme should also identify unfunded mandatory needs, inspection priorities and committed future renewals. Geographic bundling may be evaluated where it changes mobilisation or traffic disruption, but the resulting savings should enter the model rather than remain an informal justification. Low-volume roads can have essential access functions; where minimum service or access requirements matter, they should be explicit constraints or separately justified objectives rather than hidden adjustments to scores.

The practical test is whether the framework helps an agency choose a feasible programme with better independently measured outcomes. Sophisticated weighting cannot compensate for poor treatment diagnosis or missing costs. A staged implementation using a small network, published assumptions and subsequent outcome checks would provide stronger evidence than immediate adoption of uncalibrated network-wide rankings.

IX. Limitations and Conclusion

This is a focused narrative review and methodological paper, not a systematic review or original field evaluation. Its eight-source evidence base is selective, and several sources are official summaries. The hypothetical examples establish arithmetic only. No locally fitted deterioration relationship, safety effect, validated preference weight or measured financial saving is supplied.

Highway maintenance prioritisation should distinguish current need from achievable treatment benefit, and project-level cost comparison from network-level allocation. The proposed framework integrates pavement condition, safety and life-cycle cost through feasibility screening, transparent economic comparison and constrained portfolio selection. Its research value lies in a testable decision structure and explicit accounting assumptions. Application to Indian highways requires local data, verification of contractual requirements and prospective evaluation before performance claims can be made.

X. Declarations

Data availability: No primary highway dataset was collected or analysed. All numerical examples are hypothetical and reproducible from the stated inputs. Research status: The proposed framework is unvalidated and the manuscript is a review draft. Author affiliations, funding, competing interests and any journal-required assistance disclosures should be completed by the submitting authors.

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