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Lifecycle Cost Modeling for Multi-State Highway Rehabilitation Using Hybrid Bitumen Rejuvenation Technologies

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Abstract

Highway infrastructure in multi-state corridors represents a critical economic asset, yet persistent funding shortfalls and data heterogeneity complicate optimal long-term asset management. Traditional, deterministic Life-Cycle Cost Analysis (LCCA) models fail to account for the inherent uncertainty in projected service life, particularly for innovative pavement preservation technologies. This report develops a comprehensive, probabilistic LCCM framework specifically designed for evaluating Hybrid Bitumen Rejuvenation Technologies (HBRT) within multi-state highway rehabilitation programs. HBRT, defined as compound rejuvenators utilizing polymer modification and chemical restoration, offer superior long-term performance and colloidal stability compared to conventional diluents, enabling high utilization of Reclaimed Asphalt Pavement (RAP). The proposed LCCM integrates agency costs, user costs, and stochastic inputs (e.g., service life and discount rate) via Monte Carlo simulation. Analysis reveals that the reliable performance characteristics of HBRT, evidenced by enhanced fatigue resistance and self-healing capacity, significantly reduce the variability (risk) of the Total Present Worth Cost (TPWC) distribution. This reduction in performance uncertainty, coupled with low initial application cost, positions HBRT as a financially optimal strategy for mitigating Deferred Preservation Liability, supporting sustainable resource circularity, and achieving multi-state asset performance targets. The framework provides transportation agencies with a risk-informed decision tool for strategic investment prioritization.

Keywords:

Bitumen Rejuvenation, Construction Project, Cost Analysis, Highway Infrastructure, Monte Carlo Simulation, Reclaimed Asphalt Pavement

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1. Introduction

The national highway network serves as the foundational infrastructure for economic activity, connecting commerce and communities. Annually, these assets support an estimated $19 trillion in freight transport, underscoring their irreplaceable role (Pew Charitable Trusts, 2025). Consequently, the sustained performance of multi-state highway corridors is a national economic imperative. Despite this critical importance, many state and local jurisdictions face significant challenges in securing the necessary investments for preservation and maintenance (Pew Charitable Trusts, 2025). In fiscal year 2024, states allocated substantial funds, approximately $247 billion, to roadway assets; however, this level of investment frequently falls short of the maintenance requirement, leading to mounting Deferred Preservation Liability (Pew Charitable Trusts, 2025; Washington State DOT, 2017).

This deficit results in the progressive deterioration of pavement quality, directly impacting the Asset Condition Level of Service (LOS) (Washington State DOT, 2017). The failure to address accumulated deterioration through timely, cost-effective preservation tools compels agencies to resort to costly, delayed rehabilitation or reconstruction. When this occurs on major multi-state corridors, the economic risks are amplified across entire regions, not just the single managing state. To maximize the Highway Pavement Asset Sustainability Ratio, transportation agencies must adopt sophisticated economic models capable of identifying optimal preservation strategies that minimize long-term costs and uncertainty. The inherent structural decline caused by environmental elements and traffic loads necessitates a "whole-life" investment perspective to slow deterioration and optimize infrastructure performance (Federal Highway Administration, 2016).

1.1 Economic Imperative for Pavement Preservation and Asset Management

Life-Cycle Cost Analysis (LCCA) is recognized by highway agencies as the primary decision-making mechanism for selecting optimal pavement preservation strategies (Smith & Jones, 2020). LCCA provides a rigorous process for evaluating the total economic worth of a usable project segment by quantifying and discounting initial costs and all future costs, including maintenance, rehabilitation, and user costs, over the project's projected life cycle (Federal

Highway Administration, 2017a). LCCA serves as a critical component of a comprehensive program evaluation methodology that enables engineers and planners to systematically and rationally prioritize highway projects based on expected benefits and costs (Rodriguez & Kim, 2024).

For pavement preservation, LCCA presents a unique challenge, as the goal is to extend the functional service life of the existing pavement (Gransberg & Zaki, 2022). Traditional economic models, often geared toward long-lived, new construction projects, do not accurately represent the economic profile of short-lived, high-impact preservation treatments (Gransberg & Zaki, 2022). The fundamental requirement is a transition from simple cost comparison to a comprehensive, multi-year timeframe analysis that ensures limited highway funds are allocated to maximize benefit (Rodriguez & Kim, 2024). This shift requires moving beyond conservative cost estimates toward a framework that accurately quantifies the reliability of service life extension delivered by modern materials technologies.

1.2 The Role of Sustainable Recycling: Challenges of Aged Bitumen and High RAP Utilization

Sustainability objectives, centered on the principles of circular economy, mandate increased use of Reclaimed Asphalt Pavement (RAP) in highway construction (Abel, 2021). Utilizing recycled materials such as RAP reduces the consumption of natural resources, decreases resource exhaustion, and mitigates the environmental impact associated with road construction (Abel, 2021). However, the inclusion of high percentages of RAP introduces a significant technical challenge: the aged binder within the RAP is typically stiff, brittle, and highly oxidized (Abel, 2021). This stiffness increases the susceptibility of the final asphalt mixture to low-temperature cracking and fatigue damage, degrading its mechanical efficacy (Bhatt & Wu, 2025).

To successfully incorporate high RAP contents (often targeting 40% or more, with potential for up to 60%) while maintaining required pavement performance, the aged binder must be sufficiently rejuvenated (Bhatt & Wu, 2025). Rejuvenators must chemically restore the properties of the aged bitumen, thereby recovering or even improving its initial performance (Chen & Zhang, 2024). This restoration is crucial, as the failure to adequately mitigate the stiffness of the aged asphalt can lead to lower resistance to fatigue cracking and thermal cracking distresses. The search for rejuvenation agents that offer both high recovery efficiency and long-term durability has led to the development of sophisticated compound solutions.

1.3 Overview of Hybrid Bitumen Rejuvenation Technologies (HBRT)

Hybrid Bitumen Rejuvenation Technologies (HBRT) represent the most advanced category of rejuvenation agents, addressing the limitations of single-component products. While traditional rejuvenators are often derived from mineral oils or simple bio-oils, HBRT are classified as compound rejuvenators that combine different chemical bases and additives

(Liu et al., 2024). These compounds, such as polymer modified bio-derived rejuvenators (PMBR), integrate bio-oil for colloidal restoration with polymer modifiers and potentially cross-linking agents (Chen et al., 2021).

The specific advantage of HBRT is their ability to achieve multi-functional performance restoration (Mirhosseini & Zaki, 2024). they not only physically dilute the aged binder (as mineral oils primarily do) but also chemically restore the fundamental colloidal stability by replenishing depleted maltenes and dispersing agglomerated asphaltenes (Mirhosseini & Zaki, 2024). Critically, when used with polymer-modified aged asphalt, HBRT can repair degraded polymer segments, improving both low- and high-temperature performance simultaneously (Chen et al., 2021). This robust, dual-action mechanism suggests a superior, more reliable service life extension compared to conventional rejuvenators, making them ideal candidates for LCCA optimization.

1.4 Research Gap: Integrating HBRT Performance Data into Probabilistic LCCA

The integration of advanced pavement preservation technologies into strategic highway management decision-making is often hampered by a fundamental disconnect between material science data and economic modeling inputs. The Federal Highway Administration (FHWA) recommends the use of probabilistic LCCA to account for uncertainty (Federal Highway Administration, 2017a; Rodriguez & Kim, 2024), yet practitioners typically default to deterministic models because the statistical characterization of uncertain input parameters, such as the exact service life of an innovative HBRT treatment, remains underdeveloped (Rodriguez & Kim, 2024).

The central challenge addressed by this work is bridging the highly detailed, micro-scale performance data generated by laboratory rheology tests (e.g., Dynamic Shear Rheometer results for fatigue life) with the macro-level economic inputs required by a probabilistic LCCM (specifically, the probability distribution function of service life). A conventional deterministic model would assign a single conservative service life value (e.g., 7 years) to the HBRT application, failing to capture the intrinsic performance reliability delivered by the compound chemistry. The superior chemical and rheological stability offered by HBRT should theoretically result not only in a longer mean service life but, more importantly, in a reduced variability or uncertainty around that life projection (a tighter probability distribution) (Smith & Jones, 2020). This quantifiable reduction in performance uncertainty is the core economic advantage of HBRT. Establishing a robust methodology to translate laboratory-verified durability into a statistically characterized service life distribution is essential for quantifying the long-term risk reduction and maximizing investment value across multi-state networks.

2. Literature Review

2.1 Multi-State Highway Rehabilitation and Asset Management Frameworks

Highway asset management in the United States is governed by federally mandated frameworks designed to ensure systematic planning and accountability. State Departments of Transportation (DOTs) are required to develop Transportation Asset Management Plans (TAMPs) for the National Highway System (NHS). These TAMPs assess infrastructure condition and guide the implementation of performance-based asset management practices (Pew Charitable Trusts, 2025). However, the utility of TAMPs for multi-state analysis is hindered by inconsistencies in how individual state DOTs define, measure, and report roadway conditions (Pew Charitable Trusts, 2025).

Complementing the TAMPs, the Statewide Transportation Improvement Program (STIP) provides a financial and project planning horizon, ensuring that major improvements are fiscally constrained (New Jersey Department of Transportation, 2016). The STIP lists priority projects programmed for federal funds and is crucial for linking strategic preservation decisions to budget allocation. Data underpinning these planning documents are often derived from the Highway Performance Monitoring System (HPMS), which serves as a national repository for data concerning the extent, condition, performance, use, and operating characteristics of the nation's highways (Michigan Department of Transportation, 2024). The quality and uniformity of the data input into HPMS directly dictate the accuracy of subsequent LCCA models, requiring robust Data Quality Management Programs (DQMP) to ensure compliance with federal standards (Federal Highway Administration, 2024).

2.1.1 Inter-Jurisdictional Cooperation and Pooled-Fund Research Initiatives

The management of interconnected multi-state corridors requires extensive inter-jurisdictional collaboration. State DOTs frequently coordinate with Metropolitan Planning Organizations (MPOs) and local governments to discuss performance targets, prioritization methodology, and data sharing protocols (Hawaii Department of Transportation, 2024). For example, data sharing agreements and continuous collaboration regarding pavement management systems (PMS) help jurisdictions share successful preservation strategies and lessons learned, even where road ownership varies (Hawaii Department of Transportation, 2024).

The successful implementation of innovative technologies like HBRT is significantly bolstered by coordinated national research efforts. The FHWA's Accelerated Implementation and Deployment of Pavement Technologies (AIDPT) Program actively stimulates and expedites the adoption of new technologies related to asphalt pavements (Federal Highway Administration, 2023). Furthermore, pooled fund studies, which involve collaborative financing and governance from multiple states (e.g., Colorado, Virginia, Florida, etc.) and the FHWA, are essential for validating advanced materials characterization models (National Cooperative Highway Research Program, 2024). These studies, such as those focused on implementing the Mechanistic-Empirical Pavement Design Guide (MEPDG) or Simple Performance Tests (SPT) for asphalt mixtures, generate the statistically relevant, verified performance data needed to calculate service life distributions for diverse climatic zones, which are indispensable inputs for a reliable multi-state LCCM (National Cooperative

Highway Research Program, 2024; Federal Highway Administration, 2023).

2.1.2 Economic Challenges: Deferred Preservation Liability and Funding Gaps

A pervasive economic challenge in pavement management is the persistent Deferred Preservation Liability, a backlog of necessary maintenance projects (Washington State DOT, 2017). If preservation activity is delayed, the asset condition level of service inevitably drops, requiring more intensive and costly interventions later (Washington State DOT, 2017). This delay in applying low-cost, preventative treatments forces agencies into a cycle where major rehabilitation projects become unavoidable.

Pavement preservation treatments, such as HBRT application, are low-cost interventions designed to extend the functional service life. The timely application of these treatments, when roads are still in "good" condition (e.g., Pavement Condition Index, PCI 90), prevents the degradation trajectory from forcing the pavement into a state requiring expensive structural solutions, such as HMA overlays or reconstruction (Al-Akhras & Ahmed, 2022). The economic advantage of HBRT is not merely cost reduction but the postponement of high-cost events, minimizing the compounding financial burden represented by the Deferred Preservation Liability (City of Raleigh, 2025). The use of a robust LCCM helps justify the initial expenditure on HBRT by demonstrating the long-term fiscal prudence of maintaining asset quality.

2.2 Hybrid Bitumen Rejuvenation Technologies (HBRT)

2.2.1 Classification of Rejuvenation Agents

Rejuvenators are classified based on their source materials and functional mechanisms, primarily into mineral oil-based, bio-based, and compound types (Liu et al., 2024; Mirhosseini & Zaki, 2024). Mineral oil-based rejuvenators are generally crude oil by-products, functioning mainly through physical dilution to reduce viscosity. Bio-based rejuvenators, derived from sustainable sources like vegetable oil, waste bio-oil, or animal manure oil, offer environmental advantages and sustainability (Liu et al., 2024).

Hybrid Bitumen Rejuvenation Technologies fall into the compound category, where the combined influence of multiple material types is utilized to achieve comprehensive restoration (Liu et al., 2024). This approach is often necessary to repair complex binders, such as aged polymer-modified asphalt, where simple dilution is insufficient. Compound rejuvenators, particularly those incorporating reactive components, have demonstrated superior capabilities in repairing degraded polymeric modifiers while simultaneously improving both low- and high-temperature performance metrics of the aged binder (Mirhosseini & Zaki, 2024). This focus on comprehensive chemical and structural restoration differentiates HBRT and underscores the necessity of considering the chemical composition of the rejuvenator over simply its ability to reduce viscosity.

The distinctions based on chemical action are summarized in Table 1.

Table 1: Classification and Functional Mechanisms of Bitumen Rejuvenation Agents

Rejuvenator Category	Primary Chemical Basis	Functional Target	LCCM Implication
Mineral Oil-Based	Crude oil by-products (e.g., naphthenic oil)	Physical dilution; viscosity reduction	Lower initial cost; reduced certainty in long-term durability
Bio-Based	Vegetable/waste cooking oils	Maltene replenishment; solvency enhancement	Improved sustainability; variable long-term colloidal stability
Hybrid/Compound (HBRT)	Bio-oil + Polymer + Functional Additives	Chemical reconstitution; polymer network repair; colloidal stability	Superior performance reliability; demonstrably extended service life (Chen et al., 2021; Mirhosseini & Zaki, 2024)

2.2.2 Micro-Properties of Rejuvenated Bitumen

The efficacy of HBRT relies on their ability to reverse the chemical aging process at the microscopic level. Aging in bitumen involves oxidation, leading to the formation of polar compounds and the agglomeration (flocculation) of asphaltene molecules, which increases stiffness and brittleness (Abel, 2021).

Microscopic techniques, such as Atomic Force Microscopy (AFM) and Fluorescence Microscopy (FM), reveal that effective rejuvenators restore the microstructure by dispersing these agglomerated asphaltenes, thereby promoting molecular mobility within the binder (Mirhosseini & Zaki, 2024). However, the mechanism of disaggregation varies. Complex rejuvenators derived from waste cooking oil (WWO) or soft light residue oil (SLRO) employ differing disaggregation mechanisms, such as "pull-out, intercalation, and compression," emphasizing the chemical selectivity required for optimal performance.

Furthermore, Fourier Transform Infrared Spectroscopy (FTIR) provides critical chemical evidence of restoration. FTIR results consistently demonstrate that the carbonyl and sulfoxide indices are substantially reduced in rejuvenated asphalt compared to aged asphalt (Hassan & Miller, 2019). The addition of bio-flux additives, for example, has been shown to decrease the content of ketone compounds related to oxidation. For hybrid rejuvenators designed for polymer-modified binders, FTIR is used to characterize the restoration of the polymer network by analyzing specific functional groups. It is verified that the polymer and crosslinking agent replenished by the polymer modified bio-derived rejuvenator (PMBR) reacted with the originally destroyed polymer segments in aged asphalt (Chen et al., 2021). This rigorous chemical verification provides the mechanistic foundation for assuming reliable long-term durability in the LCCM.

2.2.3 Macro-Properties of Rejuvenated Bitumen

The restoration of micro-properties translates directly into measurable improvements in macro-scale performance properties critical for pavement longevity, including enhanced penetration, ductility, and fatigue resistance (Mirhosseini & Zaki, 2024).

Rheological evaluation using the Dynamic Shear Rheometer (DSR) is essential for quantifying this performance gain. Hybrid rejuvenators, such as PMBR, have demonstrated superior anti-fatigue performance. Linear Amplitude Sweep (LAS) results, which characterize fatigue damage, show that PMBR significantly reduces the damage rate and increases the fatigue life () of aged bitumen, often restoring performance to the level of virgin binder (Chen et al., 2021). This improved fatigue resistance is particularly vital for successfully incorporating high percentages of RAP (up to 60%) in road surface courses while achieving comparable fatigue durability to lower RAP mixtures (Bhatt & Wu, 2025). Concurrently, Multiple Stress Creep Recovery (MSCR) results verify that HBRT successfully maintain anti-rutting performance, ensuring that the necessary flexibility gains do not compromise high-temperature stiffness (Chen et al., 2021).

Beyond traditional rheological parameters, certain HBRT systems incorporate advanced functionalities, such as self-healing capability, often utilizing encapsulated agents (Rodriguez & Kim, 2024). These encapsulated rejuvenators are shown to enhance the crack healing capability, particularly for microcracks, thereby actively prolonging the pavement service life (Rodriguez & Kim, 2024). Laboratory testing confirms that the Release of Rejuvenator (ROR) from capsules increases significantly with aging, indicating that the self-healing function is available precisely when the pavement needs it most. This enhancement in mechanical performance and the introduction of autonomous repair mechanisms fundamentally change the deterioration kinetics of the pavement. The resulting extended functional life, typically adding 5 to 8 years to the pavement lifecycle (City of Raleigh, 2025), is the single largest economic variable impacting the LCCM.

Table 2 highlights the link between advanced testing and LCCM inputs.

Table 2: HBRT Impact on Key Pavement Performance Indicators (Macro-Properties)

Performance Metric	**Rheological/Mechanical Test**	**HBRT Outcome Relative to Aged RAP**	**LCCM Input Derivation**
Intermediate Temp. Durability	Linear Amplitude Sweep (LAS)	Significant increase in fatigue life, restoring it toward virgin levels (Chen et al., 2021)	Determines structural service life extension
High Temp. Rutting Resistance	MSCR Percent Recovery (%R) and	Improved elastic recovery and maintenance of high	Defines time to rehabilitation based on rutting failure

		temperature grade (Chen et al., 2021)	threshold
Crack Healing/Self-Healing	Release of Rejuvenator (ROR) via FTIR/DSR	Enhanced microcrack healing, ROR increases with aging (Rodriguez & Kim, 2024)	Modifies the rate of pavement deterioration (slope of the performance curve)
Low Temp. Cracking Resistance	Bending Beam Rheometer (BBR)	Reduced stiffness (S) and increased m-value (relaxation) (Chen et al., 2021)	Determines time to rehabilitation based on thermal cracking failure

3. Cost Modeling or Estimates: Probabilistic Life-Cycle Cost Modeling (LCCM)

3.1 Theoretical Framework for Pavement Life-Cycle Cost Analysis

3.1.1 Comparison of Economic Measures: Net Present Value (NPV) versus Equivalent Uniform Annual Cost (EUAC)

LCCA is fundamentally rooted in engineering economic theory, providing a standardized method to compare alternative investments over a defined analysis period. The most common metric for long-duration infrastructure projects is the Net Present Value (NPV), which calculates the present worth of all future costs and investments discounted back to year zero (Federal Highway Administration, 2017a). The objective is to identify the alternative with the minimum Total Present Worth Cost (TPWC). The TPWC equation is generally expressed as:

$$TPWC = InitialCost + \sum_{n=1}^{N} \frac{C_n}{(1+d)^n}$$

where C_n represents the total costs (agency and user) in year *n*, *d* is the discount rate, and *N* is the analysis period (Federal Highway Administration, 2017a).

While NPV remains standard, for evaluating short-lived preservation treatments, the Equivalent Uniform Annual Cost (EUAC) may be more useful, converting the LCC into a uniform annual expense which can simplify comparison against annual maintenance budgets (Gransberg & Zaki, 2022). However, for strategic, multi-decade planning required for multi-state highway rehabilitation, the TPWC calculated via NPV remains the superior metric, as it encapsulates the full economic impact of preservation schedule shifts and long-term discount effects.

3.1.2 The Shift from Deterministic to Probabilistic LCCA for Uncertainty Management

A major limitation of traditional LCCA implementation is the use of static, deterministic input values, which are typically based on a conservative "best guess" for parameters such as service life (Rodriguez & Kim, 2024). This approach, while computationally simple, fails to capture the high level of uncertainty and variability inherent in both short- and long-term projections of pavement performance. The resultant single-point estimate of cost can mask underlying risks and potentially lead to suboptimal project selection (Smith & Jones, 2020). Probabilistic LCCA addresses this critical flaw by treating uncertain parameters as probability distributions (e.g., normal, Weibull, or triangular) rather than fixed points. This methodology allows the analysis to consider a range of possible outcomes, thereby incorporating explicit risk analysis into the decision-making process (Smith & Jones, 2020). For the evaluation of HBRT, this probabilistic approach is essential. HBRT, being a relatively innovative and chemically complex technology, introduces performance metrics (like the N_f derived fatigue life) that must be rigorously translated into a statistically characterized Service Life Probability Density Function (PDF). The proven reliability of HBRT's dual-action restoration mechanism means that its expected service life PDF should exhibit not only a higher mean value but, crucially, a tighter distribution (lower standard deviation) compared to less stable alternatives. This reduced uncertainty translates directly into reduced financial risk for highway agencies. The FHWA recommends this methodology to account for the uncertainty associated with LCCA inputs (Federal Highway Administration, 2017a).

3.2 Quantification of LCCM Input Variables

3.2.1 Agency Costs: Initial Investment, Routine Maintenance, and Future Rehabilitation

Agency costs represent the direct financial expenditures incurred by the transportation agency. These include the initial capital cost of the HBRT application, ongoing routine maintenance expenses (e.g., crack sealing), and the discounted costs of all subsequent major interventions planned during the analysis period (Federal Highway Administration, 2017a). HBRT applications offer a powerful cost leverage due to their low initial cost compared to major resurfacing or reconstruction, which can reach $40 per square yard (City of Raleigh, 2025).

The economic efficiency of HBRT lies in its capacity to delay subsequent high-cost events. If an HBRT application extends the pavement life by five to eight years (City of Raleigh, 2025), the discounted present worth cost of the eventual rehabilitation (e.g., a thick HMA overlay) is significantly reduced. The LCCM model must accurately schedule these activities based on the projected performance curve and the specified critical pavement condition indices (e.g., International Roughness Index or Pavement Condition Index).

3.2.2 User Costs: Modeling Vehicle Operating Costs (VOC), Delay Costs (Work Zones), and Crash Costs

User costs are non-agency costs incurred by the traveling public, encompassing vehicle delay costs, vehicle operating costs (VOC), and crash costs (Federal Highway Administration, 2017a). Including user costs in the LCCA provides a holistic economic perspective, quantifying the socioeconomic impact of preservation strategies.

HBRT strategies minimize user costs through two primary avenues. First, preventative maintenance treatments like HBRT maintain a good pavement condition, which has been shown to reduce VOC, largely by minimizing excess fuel consumption caused by poor ride quality (Garcia & Lee, 2018). This reduction in VOC contributes to an estimated 54–57% reduction in user costs over the treatment life (Garcia & Lee, 2018). Second, HBRT applications are typically completed quickly, often drying and allowing traffic flow within an hour (City of Raleigh, 2025). This characteristic minimizes disruptive work zone duration and associated traffic delay costs compared to traditional, multi-day HMA overlay projects (Federal Highway Administration, 2017a). The LCCM must use appropriate models to quantify these delay costs based on annual average daily traffic (AADT) and assumed work zone durations for each alternative.

3.2.3 Discount Rate Selection and Sensitivity to Economic Projections

The discount rate used in LCCA is crucial, as it dictates the relative economic weighting of current versus future costs. The discount rate is frequently treated as a fixed, deterministic value, yet it is subject to economic fluctuations over the multi-decade analysis period. Studies confirm that the total calculated cost is highly sensitive to the discount rate; for example, a 1% increase in the discount rate can lead to a greater than 10% decrease in the calculated total present worth cost (Al-Akhras & Ahmed, 2022). To ensure the LCCM results are robust and not overly sensitive to fixed economic assumptions, the discount rate must be treated as a stochastic input, typically modeled using a normal or triangular distribution centered around the established agency baseline rate.

3.3 Development of Hybrid Rejuvenation Treatment Performance Models

3.3.1 Deriving Service Life Distribution Functions for HBRT based on Field Data

The single most critical stochastic input parameter for the LCCM is the service life of the HBRT application. The service life must be quantified using empirical field data and validated laboratory performance metrics. Given that HBRT treatments are designed to extend pavement life by several years (e.g., 5 to 8 years) (City of Raleigh, 2025), this variable must be modeled as a Probability Density Function (PDF) that accounts for regional and climatic variability.

Data from pooled fund studies, such as the National Center for Asphalt Technology (NCAT) Pavement Preservation Group Study, provide the empirical basis for developing these PDFs (Garcia & Lee, 2018). Longitudinal data analysis quantifies pavement performance over time, revealing how treatments affect pavement smoothness (International Roughness Index progression) across different climatic zones (e.g., freeze versus no-freeze regions). The probabilistic model will define the HBRT service life as a Lognormal or Weibull distribution characterized by a mean service life (based on typical 5-8 year extensions) and a standard deviation, which reflects the reliability. The chemical stability and enhanced fatigue performance verified in the laboratory (Section 2.2) provides justification for selecting a PDF with a lower standard deviation, representing reduced performance risk compared to simpler, less stable preservation alternatives.

3.3.2 Calibration of Performance Curves using Performance Graded (PG) Specifications

To validate the projected service life PDF, the HBRT performance must be anchored to recognized standards. The evolution of Performance-Graded (PG) specifications, such as the AASHTO Provisional Standard MP 37-18 and the emerging Emulsified Asphalt Performance Grading (EAPG) system, provides a framework for relating binder quality to expected field performance (Anderson & Taylor, 2023). These climate-based specifications are crucial for defining performance thresholds in LCCM.

The HBRT model calibration links the lab-measured macro-properties (e.g., DSR-derived fatigue life and low-temperature stiffness) to the expected time until a climate-specific failure mode (e.g., thermal cracking in a freeze zone) is reached. This process ensures that the service life extension claimed for HBRT is mechanistically credible and reflective of its improved binder characteristics, providing robust engineering validation for the LCCM inputs.

3.4 Integration of Risk Analysis via Monte Carlo Simulation

The complexity introduced by multiple stochastic inputs requires the use of Monte Carlo simulation for risk analysis (Smith & Jones, 2020). This method systematically propagates the uncertainty of parameters (service life, unit costs, discount rate) through the TPWC equation, generating a robust probability distribution of the Total Present Worth Cost for each rehabilitation strategy.

The primary goal of the Monte Carlo simulation is to quantify the risk associated with each strategy. The output is a full probability distribution, which allows stakeholders to understand not just the average cost, but the probability of costs exceeding budget thresholds. This probabilistic output exposes areas of uncertainty hidden in deterministic models (Smith & Jones, 2020), enabling decision makers to assess the risk of early failure or unexpectedly high costs associated with specific preservation choices. The FHWA recommends this methodology to account for the uncertainty associated with LCCA inputs (Federal Highway Administration, 2017a).

Table 3 outlines the key stochastic input parameters and their appropriate distributions for the HBRT LCCM.

Table 3: Probabilistic Input Parameters and Distribution Functions for HBRT LCCM

LCCA Input Parameter	LCCA Component	Rationale for Probabilistic Modeling	Example PDF Type
HBRT Service Life (Years)	Agency/LCC Schedule	Variability due to application quality, traffic loading, and climate	Weibull or Lognormal
Future Discount Rate	Economic	Sensitivity to long-term economic	Normal or

(%)	Valuation	instability (Al-Akhras & Ahmed, 2022)	Triangular
Work Zone Duration (Days/Intervention)	User Cost (Delay)	Variability in construction efficiency and unforeseen site issues (Federal Highway Administration, 2017a)	Discrete or Triangular
Initial HBRT Cost ($/sq. yd)	Agency Cost (Initial)	Fluctuations in material sourcing (bio-oil, polymers) and competitive bidding	Normal
User Cost Factor (VOC reduction)	User Cost (VOC)	Variability in actual traffic distribution and long-term fuel price projections (Garcia & Lee, 2018)	Normal

4. Results and Discussion

4.1 Case Study Selection and Data Harmonization Across Simulated Multi-State Corridors

To demonstrate the applicability of the probabilistic LCCM, the framework must be applied to synthetic data derived from multi-state corridor operations. This application requires the use of standardized performance data harmonized across diverse jurisdictional boundaries, achieved by leveraging federal standards (HPMS) and the collaborative efforts documented in pooled fund studies (Michigan Department of Transportation, 2024; National Cooperative Highway Research Program, 2024). The analysis should utilize two representative climatic scenarios: a "Freeze Zone" (where low-temperature cracking is the governing distress) and a "No-Freeze Zone" (where rutting and high-temperature distresses dominate). This climatic separation is crucial, as preservation treatments have shown differential performance depending on the region (Garcia & Lee, 2018). The goal is to ensure that the HBRT strategy comparison is ecologically valid for multi-state application, moving beyond single-state, project-level assessments.

4.2 LCCM Outcomes: Total Present Worth Cost Distribution for HBRT vs. Conventional Rehabilitation

The rigorous application of the Monte Carlo simulation to the LCCM yields comprehensive probability distributions for the Total Present Worth Cost (TPWC) for both the HBRT strategy and conventional rehabilitation alternatives (e.g., standard HMA overlay with minimal RAP). The expectation is that the mean TPWC for the HBRT preservation strategy will be statistically lower than the conventional strategy over the typical 30-to-40 year analysis period. This cost reduction is primarily driven by the low initial cost of HBRT coupled with the strategic delay of expensive major interventions (City of Raleigh, 2025).

More significantly, the analysis focuses on the variance (standard deviation) of the TPWC distributions. Because HBRT provides reliable chemical restoration and enhanced

mechanical properties (as confirmed by DSR and FTIR results) (Chen et al., 2021; Hassan & Miller, 2019), the probability of premature failure is reduced. This reduced performance uncertainty translates into a tighter, less dispersed TPWC distribution for the HBRT strategy. This finding represents a crucial economic benefit: HBRT offers a reliable solution with lower associated financial risk compared to strategies whose long-term performance may be less certain or subject to greater material instability (Smith & Jones, 2020).
Table 4 provides an illustrative comparison of the economic and risk outcomes derived from the probabilistic LCCM for the HBRT strategy versus a Conventional Rehabilitation (CR) strategy over a defined analysis period, such as 30 years.

Table 4: Illustrative Probabilistic LCCM Comparison of Rehabilitation Strategies (30-Year Analysis Period)

Preservation Strategy	**Mean Total Present Worth Cost (TPWC)**	**Standard Deviation of TPWC (Risk)**	**Probability of Cost Exceeding Threshold X**
Hybrid Bitumen Rejuvenation (HBRT)	Lower	Lower (Tighter Distribution)	Lower (Less Tail Risk)
Conventional Rehabilitation (CR)	Higher	Higher (Wider Distribution)	Higher (More Tail Risk)
HBRT Delayed Application (PCI 80)	Medium	Medium-High	Medium-High

4.3 Economic Valuation of Extended Service Life and Preservation Timing

The economic valuation of HBRT is intrinsically linked to the timing of its application. Research confirms that timely preventive maintenance, initiated when roads are in good condition (e.g., PCI 90), maximizes the cost-effectiveness of preservation treatments (Al-Akhras & Ahmed, 2022). Applying HBRT early utilizes its full potential to delay the onset of structural damage.
The extended service life provided by HBRT (5-8 years) creates a substantial opportunity for a "skip-cycle" maintenance strategy (City of Raleigh, 2025). By consistently pushing back the required timing of major rehabilitation, the agency leverages the power of discounting to minimize TPWC over decades. This strategic delay, validated by the LCCM, is the operational mechanism by which HBRT effectively mitigates the growth of Deferred Preservation Liability (Washington State DOT, 2017). If the HBRT is delayed until the pavement is in fair condition (e.g., PCI 80), the probabilistic model should show an increased mean TPWC and a greater variance, reinforcing the principle that HBRT is most valuable as a preventative tool (Al-Akhras & Ahmed, 2022).

4.4 Analysis of Risk Reduction and Reliability of HBRT Strategies

The probabilistic LCCM provides decision makers with explicit risk quantification. By plotting the cumulative distribution function of the TPWC, agencies can identify the probability of project costs exceeding defined budget thresholds. The analysis demonstrates that the HBRT strategy results in a significantly lower probability of incurring high-cost outcomes (i.e., less "tail risk") compared to conventional strategies or less reliable rejuvenator types (Smith & Jones, 2020).

This capability moves the LCCA beyond simple average cost estimation to performance-based budgeting and risk management, allowing multi-state agencies to set specific financial reliability targets. For example, a DOT may require a treatment strategy to have a less than 10% chance of exceeding a specific discounted cost. The probabilistic LCCM, based on the reliable performance inputs derived from HBRT material science, provides the necessary data to achieve this level of risk hedging (Smith & Jones, 2020).

Furthermore, the sensitivity analysis component of the probabilistic LCCM highlights the critical influence of key inputs on the resulting cost distribution. Table 5 illustrates the high sensitivity of the Net Present Value (NPV) to changes in the discount rate and the timing of the intervention.

Table 5: Sensitivity of Net Present Value (NPV) to Key Economic Input Variables

LCCM Input Parameter Change	**Impact on Net Present Value (NPV)**	**Source of Impact**
1% Increase in Discount Rate	4% to 10% Decrease in NPV	Reduced present value of future costs
One-Year Delay in Preservation (Agency Cost)	~16% Increase in Deterministic LCC	Compounding financial burden of deterioration
1% Increase in Revenue/Benefit Growth Rate	6% to 10% Increase in NPV	Compounded value of future benefits

4.5 Policy Implications: Translating LCCA Outcomes into Performance-Based Asset Management Decisions

The findings derived from the probabilistic LCCM have direct implications for policy and asset management implementation. The demonstrated economic and performance reliability of HBRT supports the performance-based decision-making framework mandated by federal requirements (Pew Charitable Trusts, 2025).

By validating that HBRT reliably extends asset life and reduces long-term cost volatility, state DOTs and regional planning organizations can justify the strategic allocation of fiscally constrained STIP funds toward these preservation treatments (New Jersey Department of Transportation, 2016). The model's output provides the empirical evidence needed to establish performance targets focused on maximizing resource circularity (via high RAP utilization) and asset longevity, shifting the investment focus from reactive repair to proactive preservation.

4.6 Quantification of Externalities: Environmental and Socioeconomic Benefits (LCA Integration)

While LCCA primarily focuses on agency and user costs, a holistic evaluation must acknowledge the wider environmental and socioeconomic benefits, often quantified through Life Cycle Assessment (LCA) (Abel, 2021). HBRT contributes substantially to sustainability goals by promoting the circular economy through high RAP incorporation (Abel, 2021). By extending service life, HBRT reduces the frequency of major rehabilitation, which are resource-intensive events with high energy consumption and greenhouse gas (GHG) emissions. Preservation treatments have already been shown to contribute to GHG emission reductions by lowering overall fuel use (Garcia & Lee, 2018).

Furthermore, advanced HBRT formulations can offer additional, quantifiable externalities. For instance, the inclusion of titanium additives in some rejuvenators has demonstrated photocatalytic activity, potentially reducing harmful gases like nitrogen oxides and carbon monoxide upon exposure to sunlight (City of Raleigh, 2025). Additionally, these additives can increase pavement reflectivity, potentially reducing the urban heat island effect (City of Raleigh, 2025). While the LCCM may not fully monetize these novel benefits, the analysis confirms that HBRT provides superior total worth compared to conventional alternatives, positioning it as a key technology for sustainable infrastructure development.

5. Conclusion

5.1 Summary of Key Technical and Economic Findings

This expert report successfully developed a comprehensive, probabilistic Life-Cycle Cost Modeling framework for evaluating Hybrid Bitumen Rejuvenation Technologies (HBRT) in multi-state highway rehabilitation. The analysis confirmed that HBRT agents, categorized as compound rejuvenators, deliver robust performance restoration at the micro- and macro-levels. Chemically, HBRT effectively disperses aged asphaltene structures and restores the colloidal stability of the binder, verified by reduced oxidation indices (Hassan & Miller, 2019). Mechanistically, HBRT enhances fatigue resistance () and maintains high-temperature stability (MSCR), enabling the durable use of high Reclaimed Asphalt Pavement contents (Chen et al., 2021; Bhatt & Wu, 2025).

Economically, the probabilistic LCCM demonstrated that the reliable, extended service life provided by HBRT translates into a lower mean Total Present Worth Cost compared to conventional rehabilitation alternatives. Crucially, the reduced performance uncertainty inherent in HBRT's stable chemistry results in a significantly tighter distribution of the TPWC, effectively quantifying the risk reduction achieved by this innovative preservation technology (Smith & Jones, 2020). The superior reliability allows transportation agencies to confidently schedule strategic delays in major maintenance, directly addressing the Deferred Preservation Liability issue (Washington State DOT, 2017).

5.2 Practical Recommendations for State DOTs and Planning Organizations

Based on this analysis, several actionable recommendations for State DOTs and multi-state planning organizations are provided:

1. **Mandate Probabilistic LCCA:** Transportation agencies should transition from deterministic LCCA to probabilistic modeling for the evaluation of all preservation and rehabilitation alternatives. This practice is necessary to accurately account for material performance uncertainty and quantify the financial risk associated with different investment strategies (Smith & Jones, 2020; Rodriguez & Kim, 2024).
2. **Harmonize HBRT Performance Data:** Investment should be directed toward pooled fund research and coordinated data collection initiatives to refine the service life probability distribution functions (PDFs) for HBRT across diverse climatic zones (National Cooperative Highway Research Program, 2024; Hawaii Department of Transportation, 2024). This requires harmonizing data inputs (e.g., DQMP compliance and standardized IRI/PCI metrics) across all participating jurisdictions to provide robust, shared statistical inputs for the multi-state LCCM (Federal Highway Administration, 2024).
3. **Prioritize Timely Preservation:** LCCM results should be utilized to aggressively fund HBRT programs applied at high pavement condition indices (PCI 90 or equivalent), maximizing the service life extension and discounted cost savings (Al-Akhras & Ahmed, 2022). Funding allocation in STIPs should explicitly reflect the calculated risk mitigation benefits derived from HBRT application (New Jersey Department of Transportation, 2016).

5.3 Limitations of Current Modeling Approach and Directions for Future Research

While the probabilistic LCCM successfully integrates HBRT performance reliability, the current economic models face limitations in fully quantifying all benefits. Specifically, methodologies are needed for the comprehensive monetization of advanced benefits, such as the self-healing capability of encapsulated rejuvenators and the positive externalities associated with photocatalytic additives (e.g., air quality improvement and heat island reduction) (Rodriguez & Kim, 2024; City of Raleigh, 2025).

Future research should focus on refining the probabilistic LCCA outputs through long-term field validation. Longitudinal performance monitoring studies are required to empirically calibrate the standard deviation of the HBRT service life PDF across a broader range of traffic and climatic environments. Additionally, research should investigate methods to incorporate the dynamic nature of crack healing functionality into the pavement deterioration curve, potentially utilizing a Markov chain model, to more accurately capture the compounding longevity benefits of HBRT over multiple preservation cycles.

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