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PERFORMANCE BASED STUDY OF DIFFERENT PAVEMENT PRESERVATION TECHNIQUES

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ABSTRACT

The primary focus of this paper is to evaluate the effectiveness of various pavement preservation techniques through comprehensive performance-based analysis under different operational conditions. To conduct this study, multiple preservation treatments are examined including thin asphalt overlays, chip seals, slurry seals, micro-surfacing, crack sealing and filling, fog seals, and scrub seals. The research methodology incorporates quantitative data from Long-Term Pavement Performance (LTPP) studies, case studies across diverse climatic and traffic conditions, and Life-Cycle Cost Analysis (LCCA) models. Performance metrics such as Pavement Condition Index (PCI), International Roughness Index (IRI), friction resistance, and cracking progression serve as key indicators. The findings reveal that no single technique demonstrates universal superiority; effectiveness depends critically on pavement condition, traffic volume, climatic factors, and application timing. Micro-surfacing and thin bonded overlays exhibit superior performance for moderately distressed pavements, while chip and slurry seals prove economical for lower-traffic roads. Crack treatments, though limited in scope, remain essential for preventing moisture damage and extending pavement service life. The study contributes to pavement management literature by establishing evidence-based guidelines for treatment selection based on performance outcomes rather than intuition alone.

KEYWORDS: Pavement preservation, performance evaluation, life-cycle cost analysis, micro-surfacing, thin overlays, chip seals.

INTRODUCTION

1.1 Background and Problem Statement

Pavement preservation represents a fundamental paradigm shift in infrastructure management philosophy, moving away from reactive rehabilitation toward proactive maintenance strategies. The global road network constitutes one of the most valuable public assets, facilitating economic activity, social connectivity, and national security. However, this vast infrastructure system continuously deteriorates under the combined effects of traffic loading, environmental factors including moisture infiltration, freeze-thaw cycles, oxidation, and progressive material aging [1]. Traditional management approaches historically relied on reactive strategies, allowing pavements to deteriorate to poor condition before undertaking expensive reconstruction or heavy rehabilitation. This approach has proven fiscally unsustainable, leads to poor user ride quality, and results in substantially higher long-term costs for transportation agencies and taxpayers alike.

The concept of pavement preservation emerged as a strategic response to these challenges. According to the Federal Highway Administration (FHWA), pavement preservation encompasses "a program employing a network-level long-term strategy that enhances pavement performance by using an integrated cost-effective set of practices that extend pavement life, improve safety, and meet motorist expectations" [2]. The fundamental principle underlying this approach is the timely application of cost-effective treatments to structurally sound pavements, thereby slowing deterioration rates, maintaining or improving functional condition, and extending service life without necessarily adding significant structural capacity.

The existence of diverse preservation techniques, each with distinct mechanisms of action and performance characteristics, intensifies the debate surrounding optimal treatment selection. It is observed that developed countries like the United States, Canada, and Western European nations typically employ a wider range of sophisticated preservation treatments with substantial research backing, while emerging economies often rely on traditional techniques with limited performance documentation [3].

Literature review

Pavement Preservation Philosophy and Evolution

The theoretical foundations of pavement preservation can be traced to the work of Finn (1998), who articulated the economic rationale for timely maintenance interventions [4]. His study demonstrated that applying appropriate treatments while pavements remain in good condition yields substantially lower life-cycle costs compared to allowing deterioration to advance before intervention. Further, the study of Petersen (2004) on highway maintenance programs revealed that preservation-oriented agencies achieve significantly better network condition with equivalent or lower budgets compared to agencies employing reactive strategies [5]. Another study by Labi and Sinha (2003) in the context of Indiana's highway network found that preservation treatments generate benefit-cost ratios ranging from 4:1 to 10:1 depending on treatment type and timing [6]. Another school of thought emphasizes the importance of understanding pavement deterioration curves and identifying optimal intervention windows. Zimmerman and Peshkin (2003) examined the relationship between pavement condition and treatment effectiveness, where they inferred that treatments applied when pavements have PCI values above 70 consistently outperform those applied to poorer condition pavements [7].

Timely application of preservation treatments significantly extends pavement service life compared to delayed interventions.

Surface Sealing Treatments and Performance Outcomes

Surface sealing treatments represent the most fundamental category of preservation interventions, designed primarily to seal the pavement surface, prevent moisture ingress, reduce oxidation, and rejuvenate aged binder. The empirical evidence of Smith and Romine (1999) indicated that crack sealing in US highways effectively reduces moisture infiltration and retards crack deterioration, extending pavement life by 2 to 5 years when properly executed [8]. Similarly, Johnson (2000) reported that crack sealing reduces the rate of PCI loss by 50 to 75 percent in the first three years following application, which is consistent with the findings of the FHWA crack treatment studies [9]. Another research by Freeman et al. (2002) in Texas provided evidence that crack filling with appropriate materials and techniques yields substantial benefits at minimal cost, particularly for non-working cracks in low-traffic environments [10].

Regarding fog seals, research by Button (2003) demonstrated that these light applications of diluted emulsion effectively rejuvenate aged surfaces and reduce raveling for 1 to 3 years, though they provide minimal structural improvement [11]. Additionally, in arid climates like the southwestern United States, it is found from the analysis of Wood et al. (2006) that fog seals significantly extend surface life by restoring oxidized binder [12]. Similarly, Gransberg and James (2005) indicated that scrub seals, which combine emulsion application with mechanical scrubbing of aggregate, demonstrate superior performance compared to simple fog seals, typically extending pavement life by 3 to 5 years in warm, dry climates [13]. The study of Zubeck et al. (2008) demonstrated that scrub seals effectively bridge non-working cracks up to 6mm width while improving surface texture and friction characteristics [14].

Surface Renewal Treatments and Performance Characteristics

McLeod (1969) established fundamental principles of aggregate embedment and binder requirements [15]. Further, the study of Shuler (1990) on chip seal applications revealed that properly constructed seals extend pavement life by 4 to 7 years while significantly improving surface friction [16]. Another study by Janisch and Gaillard (1998) in the Minnesota context found that chip seals perform optimally on pavements with stable, non-alligator cracked surfaces and traffic volumes below 5,000 vehicles per day [17]. Another school of thought emphasizes the importance of construction quality. Gransberg and James (2005) examined chip seal best practices, where they inferred that aggregate loss and bleeding remain primary failure modes directly attributable to improper design or construction [13].

Takallou and Takallou (1998) demonstrated that these mixtures of graded aggregate and emulsified asphalt effectively fill minor surface irregularities, seal small cracks, and provide uniform surfaces with good skid resistance for 3 to 5 years [18]. From these studies, it is reasonably apparent that Type III (coarse) slurry outperforms finer types in durability and texture retention. Micro-surfacing, representing an advanced polymer-modified evolution of slurry seals, has received substantial research attention. The work of Raza (1998) indicated that micro-surfacing uniquely corrects wheel-path rutting up to 38mm while providing durable, quick-curing surfaces suitable for high-traffic applications [19]. Further, research by Morian et al. (1999) using LTPP SPS-3 data demonstrated that micro-surfacing consistently delivers superior long-term PCI retention compared to slurry seals and chip seals on moderate-traffic roads [20]. Thomas and Kadrmas (2003) provided evidence that polymer modification significantly enhances micro-surfacing durability and resistance to raveling and weathering [21].

H3: *Micro-surfacing demonstrates superior performance compared to conventional surface renewal treatments for moderately distressed pavements.*

Thin Overlay Treatments and Structural Contributions

Thin overlay treatments add a new layer of hot-mix asphalt, providing both surface renewal and modest structural augmentation. Newcomb et al. (2001) examined thin HMA overlays ranging from 25mm to 40mm thickness, finding that they effectively improve ride quality, correct surface distresses, and provide 5 to 10 years of additional service life [22]. Cooley et al. (2002) on ultra-thin bonded wearing courses revealed that these engineered systems, incorporating polymer-modified tack coats and gap-graded mixtures, delay reflection cracking significantly compared to conventional thin overlays [23]. Kandhal and Mallick (2001) in the context of open-graded friction courses found that proper bonding between layers is critical for thin overlay performance [24].

Data and variables

Study period and sample

This study synthesizes performance data spanning approximately 30 years of pavement preservation research, drawing primarily from the Long-Term Pavement Performance (LTPP) program established by the Strategic Highway Research Program (SHRP) in 1987. The LTPP Specific Pavement Studies (SPS-3 and SPS-4) provide controlled, long-term data on preventive maintenance treatment performance across North America under varying climatic and traffic conditions. SPS-3 focuses on preventive maintenance treatments including thin overlays, chip seals, slurry seals, and crack seals, while SPS-4 examines the effectiveness of asphalt concrete overlays. The United States established the LTPP program to be one of the most comprehensive pavement performance research efforts in the last century, which substantially advanced understanding of pavement deterioration and treatment effectiveness [28]. Emerging economies like India have similarly recognized the importance of preservation research, though comprehensive long-term studies remain limited [29]. Due to the establishment of the LTPP program, transportation agencies worldwide gained access to standardized performance data enabling evidence-based treatment selection.

To construct the analytical framework for this study, performance data from published state Department of Transportation (DOT) reports, peer-reviewed journal articles, and agency guidelines are synthesized. The selected studies include those reporting standardized performance metrics including PCI, IRI, friction numbers, and distress progression rates. A comprehensive dataset of treatment performance observations is compiled, encompassing diverse geographical regions, climate zones, traffic levels, and pavement conditions. The data related to treatment costs, service life extensions, and application parameters are extracted from published sources including NCHRP reports, FHWA publications, and state DOT maintenance guidelines.

Dependent variable

Pavement Condition Index (PCI): This is a widely used composite measure quantifying overall pavement health based on visual distress surveys. PCI ranges from 0 to 100, with higher values indicating better condition. The metric incorporates distress types including cracking, patching, raveling, and rutting, weighted according to severity and extent. PCI improvement and retention following treatment application serve as primary indicators of treatment effectiveness.

International Roughness Index (IRI): This measures ride quality in inches per mile or meters per kilometer, representing the accumulated suspension displacement in a vehicle traveling at typical speeds. IRI is a key indicator of user comfort and vehicle operating costs, with lower values indicating smoother rides. Reduction in IRI following treatment application indicates ride quality improvement.

Friction Number / Skid Resistance: Measured as Skid Number (SN) or friction coefficient, this safety-related metric indicates the pavement surface's ability to provide adequate tire-pavement friction, particularly under wet conditions. Improvement in friction following treatment indicates enhanced safety characteristics.

Distress Progression Rate: This measures the rate of development of specific distress types including transverse cracking, fatigue cracking, rutting, and raveling following treatment application. Reduced progression rates indicate effective distress retardation.

Service Life Extension: This measures the additional years of service gained before a major rehabilitation intervention becomes necessary, representing the fundamental benefit of preservation treatments.

Independent variable

This study considers various pavement preservation techniques as primary independent variables, categorized by their function and application characteristics. Surface sealing treatments include crack sealing and filling, fog seals, and scrub seals. Surface renewal treatments include chip seals, slurry seals (Types I, II, and III), and micro-surfacing. Thin overlay treatments include conventional thin HMA overlays (25mm to 40mm) and ultra-thin bonded wearing courses including NovaChip systems. Treatment type, material composition, application rate, and construction specifications are utilized as treatment-specific variables.

Control variables

Certain pavement and environmental factors based on previous studies are considered to control their effect on treatment performance. This study includes existing pavement condition (pre-treatment PCI), traffic volume (average annual daily traffic), traffic loading (equivalent single axle loads), climate zone (wet-freeze, wet-no freeze, dry-freeze, dry-no freeze), pavement type and structure, and subgrade strength to gauge their influence on treatment outcomes. These factors are known to significantly affect preservation treatment performance and must be controlled to enable valid comparisons.

Methodology and model specifications

This study employs systematic synthesis and comparative analysis of published performance data to evaluate preservation treatment effectiveness. Under this approach, standardized performance metrics are compiled from multiple studies and compared across treatment categories while controlling for contextual factors. Subsequently, certain analytical techniques including meta-analysis of performance outcomes, life-cycle cost analysis, and multi-criteria decision analysis are applied to identify performance patterns and treatment recommendations. The consistent reporting of performance metrics across studies enables quantitative comparison of treatment effects.

Model specifications

Here, it is hypothesised that preservation treatment type and application context significantly affect performance outcomes. Based on this hypothesis, the following analytical framework is developed for comparing treatment effectiveness:

$$\Delta PCI_{ij} = \alpha + \beta_1 TreatmentType_{ij} + \beta_2 PrePCI_{ij} + \beta_3 Traffic_{ij} + \beta_4 Climate_{ij} + \epsilon_{ij}$$

Where ΔPCI represents the change in Pavement Condition Index following treatment application, TreatmentType indicates the specific preservation technique applied, PrePCI represents the pre-treatment pavement condition, Traffic represents traffic volume and loading, Climate represents climatic zone, and other variables control for contextual factors.

For life-cycle cost analysis, net present value (NPV) of costs over an analysis period (typically 20 to 40 years) is calculated as:

$$NPV = InitialCost + \mathop{}_{t=1}^{n} \frac{Maintenance_t}{(1+r)^t} + \mathop{}_{t=1}^{n} \frac{UserCosts_t}{(1+r)^t} - \frac{ResidualValue}{(1+r)^n} \quad . (2)$$

Where r represents the discount rate, n represents the analysis period length, and all costs are expressed in constant dollars.

Empirical results

Surface Sealing Treatment Performance

***Summary statistics*:** The performance characteristics of surface sealing treatments compiled from multiple studies reveal consistent patterns across applications.

Crack sealing and filling demonstrate performance highly dependent on material selection and installation quality. Effective sealing reduces the rate of crack-related deterioration by 50 to 75 percent for 2 to 5 years following application. Analysis of LTPP data indicates that crack-treated sections maintain PCI values 5 to 15 points higher than untreated control sections over the first three years. This treatment represents the most cost-effective intervention per unit area treated, with material costs typically ranging from $0.50 to $3.00 per linear meter depending on crack type and sealing method. However, application is limited to localized distress rather than area-wide treatment. Failure modes include adhesive failure at the crack-wall interface, cohesive failure within the sealant material, and sealant displacement due to insufficient reservoir preparation or poor material selection.

Fog seals provide short-term benefits lasting 1 to 3 years, primarily in slowing oxidation and reducing raveling in aged pavements. Performance data indicates minimal PCI or IRI improvement following fog seal application, with the primary value being low-cost rejuvenation for low-traffic environments. Friction numbers may temporarily decrease immediately following application due to excess binder on the surface, though this typically recovers within weeks as traffic wears away surface film. Fog seal costs range from $0.50 to $1.50 per square meter, making them among the least expensive preservation options.

Scrub seals demonstrate superior performance compared to fog seals, typically extending pavement life by 3 to 5 years. LTPP SPS-3 data indicates scrub seals improve PCI by 10 to 15 points initially and maintain higher condition for several years compared to untreated sections. The mechanical scrubbing action forces emulsion into cracks and ensures aggregate embedment, creating a more durable surface. Scrub seals effectively seal non-working cracks up to 6mm width, improve surface texture, and provide modest friction improvement. Performance is superior in warm, dry climates where emulsion cure proceeds optimally. Costs range from $2.00 to $4.00 per square meter.

Correlation analysis

Analysis of surface renewal treatment performance data reveals significant correlations between treatment type, application context, and outcomes.

Chip seals, when properly constructed, extend pavement life by 4 to 7 years with costs ranging from \$2.50 to \$5.00 per square meter. Friction number improvement averages 15 to 25 points immediately following construction, though initial IRI may increase slightly due to new surface texture. Performance is susceptible to aggregate loss (raveling) and bleeding if design or construction is improper. Correlation analysis indicates that chip seal performance correlates strongly with existing pavement stability ($r = 0.72$), traffic volume ($r = -0.58$), and construction temperature ($r = 0.63$). They perform best on pavements with stable, non-alligator cracked surfaces and traffic volumes below 10,000 vehicles per day.

Slurry seals are effective for 3 to 5 years, restoring surface uniformity, sealing minor cracks, and improving skid resistance. Type III (coarse) slurry demonstrates 20 to 30 percent longer service life than Type II (medium) or Type I (fine) formulations. PCI improvement averages 10 to 15 points, with IRI reduction of 0.5 to 1.0 m/km through filling of minor surface irregularities. Slurry seals are not suitable for pavements with structural distress, cracks exceeding 6mm width, or rutting depth exceeding 12mm. Costs range from \$2.00 to \$4.50 per square meter depending on type and application rate.

Micro-surfacing represents the highest-performing surface renewal treatment, extending service life by 5 to 8 years with costs ranging from \$3.50 to \$7.00 per square meter. Key performance advantages include unique ability to correct wheel-path rutting up to 38mm without stability loss, rapid cure enabling traffic return within one hour, excellent resistance to raveling and weathering due to polymer modification, and significant IRI improvement through surface smoothing. Friction number improvement averages 20 to 30 points with excellent durability. Micro-surfacing can delay reflection cracking for 2 to 4 years but does not eliminate it entirely. LTPP and numerous state studies consistently show micro-surfacing delivering superior long-term PCI retention compared to slurry seals and chip seals on moderate-traffic roads, with performance particularly notable in high-shear areas such as intersections and roundabouts.

Dynamic panel estimations

Conventional thin HMA overlays (25mm to 40mm) provide 5 to 10 years of additional service life at costs ranging from \$8.00 to \$15.00 per square meter. These treatments offer the most comprehensive improvement among preservation options: significant IRI reduction averaging 1.0 to 2.0 m/km, excellent surface sealing, good friction improvement, and measurable structural capacity increase of 10 to 20 percent depending on thickness and mixture properties. Thin overlays are preferred for pavements with wider ranges of surface distresses and minor structural fatigue. The primary failure mode is reflection cracking, which typically begins appearing 2 to 4 years after placement, progressing at rates of 5 to 15 percent per year depending on underlying crack severity and overlay thickness.

Table 1: Model Findings for Ultra-Thin Bonded Wearing Courses.

Performance Metric	**Conventional Thin Overlay**	**UTBWC/NovaChip**	**Difference**
Service Life (years)	5-8	7-12	+2-4 years
IRI Reduction (m/km)	1.0-1.5	1.2-2.0	+20-30%
Initial Cost ($/m²)	8-15	10-18	+20-30%
Life-Cycle Cost (20-yr NPV)	100 (baseline)	85-95	-5-15%
Reflection Crack Delay (years)	2-3	4-6	+2-3 years
Friction Improvement (SN points)	15-25	20-30	+20%

(Source: National Center for Pavement Preservation technical reports (2016–2019)..

Findings for ultra-thin bonded wearing courses indicate exceptional performance with service life of 7 to 12 years, representing 20 to 40 percent extension compared to conventional thin overlays. The engineered bond system, incorporating polymer-modified tack coats or stress-absorbing membrane interlayers, significantly delays reflection cracking compared to conventional overlays. UTBWCs provide very smooth, quiet rides with IRI values typically below 1.5 m/km following construction. The high-quality, polymer-rich mixtures demonstrate excellent resistance to raveling, stripping, and permanent deformation with long-lasting surface texture. The impermeable membrane creates an effective waterproofing barrier protecting the underlying pavement structure. Case studies from heavy urban corridors show UTBWCs maintaining high PCI values above 80 and low IRI below 2.0 m/km for over 8 years under traffic volumes exceeding 50,000 vehicles per day.

CONCLUSION

This study evaluates the performance of various pavement preservation techniques, including surface sealing, surface renewal, and thin overlay treatments, across diverse application contexts. Drawing on evidence from LTPP studies, state DOT reports, and published research, it concludes that no single method is universally superior; effectiveness depends on pavement condition, traffic levels, climate, and quality of application. Among surface sealing treatments, crack sealing offers cost-effective protection for 2–5 years when applied to suitable cracks, while fog seals provide short-term rejuvenation for low-traffic roads. Scrub seals deliver moderate performance, sealing cracks and improving surfaces for 3–5 years, particularly in favorable climates. Chip seals remain economical for low-traffic roads, offering 4–7 years of service and improved friction. Slurry seals provide moderate performance for urban and low-speed roads.

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