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Economic Analysis of Pavement Preservation Techniques

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ABSTRACT

This paper summarizes the research study conducted to develop and implement a methodological framework, using an economic analysis technique, to evaluate the cost-effectiveness of the three different preventive maintenance treatments applied in Texas: chip seals, microsurfacing, and thin overlays. The analysis is based on a stochastic evaluation of the effective life and cost of +14,000 maintenance and rehabilitation projects built from 1994 to 2015. The effect of the traffic loads, traffic volume, and roadway type was also evaluated. The life-cycle cost of the preventive maintenance techniques was obtained using a Monte Carlo Simulation. Among the principal results, it was found that chip seals are the most cost-effective treatments and present the lower life-cycle cost variability. The effective life of all three treatments was found to be quite similar. Additionally, it was found that the chip seals and microsurfacing tend to present comparable life-cycle cost when using it on heavy trafficked roadways.

Keywords: Economic Analysis, Pavement Preservation, Preventive Maintenance, Chip Seal, Microsurfacing, Thin Overlay.

INTRODUCTION

Highways and road network represent a critical infrastructure asset for governments and citizens. However, keeping the pavements in good conditions has always been a challenge for transportation agencies. The American Society of Civil Engineers (ASCE) has rated the current condition of roads in America with a D+ (at risk), placed in the lowest possible tier [1]. The Federal Highway Administration (FHWA) estimates $170 billion dollars would be needed on an annual basis to improve the conditions and performance of existing roads [1].

A significant share of the highway cost is assigned to the implementation of pavement preservation techniques. These techniques are applied to extend the life of a pavement and in some cases, to increase its structural capacity. Despite the improvements in data collection for estimating the service life of maintenance and rehabilitation (M&R) practices, these data have not been extensively used [2]. Further, there is a lack of a sound methodology to objectively quantify the benefits of applying minor rehabilitation work, preventative maintenance or routine maintenance. Empirical evidence has shown timely maintenance to be the best approach to delay the deterioration rate of a given pavement surface, thus extending its service life.

Economic analysis is regularly used in transportation research, mainly as an evaluation tool to compare the life-cycle cost (LCC) of alternative projects [3, 4, 5]. Many research efforts have produced knowledge directed to improve the life-cycle cost analysis (LCCA) of pavements. Some studies have contributed to the field by exploring how governmental agencies can benefit from it, studying management strategies and developing sensitivity analysis for factors affecting LCCAs [3, 4, 5, 6]. However, no significant research has been done to quantify the service life cost of M&R treatments due to the short service life and the lack of availability of the actual cost and lifespan information. The access to M&R treatments service life data is limited [6, 7] and it is subjected to intense data processing [2]. Some researchers based their analysis on field tests [8], previous research findings [9], or examples data sets from pavement condition surveys [10].

The main objective of this research study was to develop and implement a methodological framework, using economic analysis, to evaluate the cost-effectiveness of the three-primary preventive maintenance (PM) treatments applied in Texas: chip seals, microsurfacing and thin overlays. A stochastic LCCA framework was developed to accomplish the goal, using historical information of more than 14,000 M&R projects constructed between 1994 and 2015 obtained from the Texas Department of Transportation's (TxDOT) databases.

The main contributions of this study can be summarized as follows: (1) it entails the use of actual cost and life data of PM treatments, obtained after processing M&R projects databases; (2) it uses a stochastic approach that allows the inclusion of uncertainty into the analysis; (3) it provides insights of cost-effectiveness of chip seals, microsurfacing, and thin overlays; and (4) it evaluates the effect of traffic volume, traffic load, and facility type on the LCC of the treatments.

The subsequent sections of this paper are organized as follows. "Preventive Maintenance Treatments" provides a general description of the main M&R concepts and describes the treatments analyzed. "Life Cycle Cost Analysis" presents an overview of the principal characteristics of the LCCA. "Case Study" provides a detailed explanation of the data processing and considerations regarding the case study. "LCCA of PM Treatments" presents the methodology framework, results, and discussion. The final section, "Summary and Conclusions," summarizes the main findings.

PREVENTIVE MAINTENANCE TREATMENTS

FHWA defines pavement preservation as a program employing a network-level, long-term strategy, looking to enhance the condition of the pavement network by implementing an integrated and cost-effective set of practices that extend the life of a pavement, improve safety and meet motorist expectations [11]. Pavement preservation practices are conformed by three main components: minor or non-structural rehabilitation, preventative maintenance (PM) and routine maintenance [11]. The PM process is the systematic application of a series of maintenance actions over the service life of a pavement, targeted to maintain a good condition, extend its lifespan, and minimize the LCC [11].

The application of PM treatments is a critical part of the pavement preservation program. Using PM treatments decreases the rate of pavement deterioration to meet performance standards. PM treatments are applied while the roadway is still in a good condition and shows only minimal distresses, before the pavement falls into a condition where placing structural overlays, major milling or reclaiming, or replacement is necessary [12].

Specific PM treatments exist for bituminous-surfaced and concrete-surfaced pavements, and may also include the maintenance of drainage features. This study is centered on three bituminous-surfaced treatments commonly used in Texas: chip seals, microsurfacing and thin overlays.

Chip Seal

Chip seal (or seal coat) is a surface treatment in which asphaltic material (typically asphalt cement or emulsified asphalt) is sprayed over the pavement surface followed by a uniform graded aggregate cover [13]. It is employed to correct minor deficiencies in the surface such as cracking, raveling, bleeding, and lack of skid resistance [14]. Although a chip seal can be applied to high-traffic volume roadways, it is generally limited to low-traffic volume roadways. Facilities with average daily traffic in excess of 10,000 vehicles per day will be considered as high traffic [14]. In general, chip seals are more effective in preventing reappearance of cracking than microsurfacing, with the asphalt rubber chip seal performing best overall [13].

Microsurfacing

Microsurfacing comprises a mixture of cationic polymer-modified asphalt emulsion, mineral aggregate, mineral filler, water, and other additives [15]. It is applied to prevent raveling and oxidation [13]. In addition to a lane or road-width treatment, microsurfacing has been used to fill minor rutting and it proved to be more effective than chip seals in preventing the reappearance of bleeding [13].

Thin Overlay

Thin overlays consist of a less than one inch thick hot-mix asphalt (HMA) overlay. It is composed of a compacted mixture of aggregate and asphalt binder mixed hot in a mixing plant [15]. Thin overlays are placed to improve friction, correct surface irregularities and reduce surface permeability. This treatment is not recommended when the surface presents existing rutting [14].

LIFE CYCLE COST ANALYSIS

The LCCA is a decision-support tool frequently employed by transportation agencies to compare total user and agency costs for different project alternatives. LCCA is considered a type of benefit-cost analysis (BCA), which is an economic analytical tool that compares benefits and costs for the different alternatives, allowing decision makers to select the optimal option [16].

Types of LCCA

The FWHA defines two approaches to prepare a LCCA: deterministic and stochastic (probabilistic). The methods differ in the manner they address the variability and uncertainty associated with the LCCA input parameters including activity cost, activity timing, and discount rate [16].

Deterministic LCCA Approach

The deterministic LCCA involves the use of fixed input values that result in deterministic output values. The value for each input parameter is usually estimated based on either historical evidence or engineering judgment [16]. Sensitivity conducted to test input assumptions by varying one input and holding other inputs constant should be conducted as a minimum requirement in deterministic LCCAs. This helps to determine the effect of the variation of parameters in the outputs. Some flaws in the deterministic approach include its failure to address simultaneous variation in multiple-input cases as well as the inability to convey the degree of uncertainty associated with the LCC estimates [16].

Stochastic LCCA Approach

The stochastic, or probabilistic LCCA allows the value of individual input parameters to be defined by a frequency (probability) distribution [16]. The probabilistic LCCA is more robust than the deterministic one, and involves the modeling of uncertainty as it takes probabilities into account [9]. To characterize these uncertainties, a stochastic LCCA approach combines probability descriptions of random variables and computer simulation techniques, commonly known as Monte Carlo Simulation (MCS) [17].

LCCA Methodology

FHWA has developed a methodology to estimate LCCAs for different alternatives [16]. It can be synthesized in five steps: (1) establish design alternatives; (2) determine activity timing, (3) estimate costs; (4) compute life-cycle costs; and (5) analyze the results. This methodology was used for conducting the LCCAs in this study.

The LCCA process is initiated after an asset has been selected to be improved and a range of possible alternatives have been identified to help accomplishing that improvement [16]. Each design alternative will have an expected initial design life, periodic maintenance treatments, and often a series of rehabilitation activities [17]. At least two mutually exclusive options ought to be considered. The economic difference between alternatives is then assumed to be attributable to the total cost that each of them represents [16]. Often, the identification of maintenance and rehabilitation activities is based on historical practice, research, and agency policies [16].

The second step consists of the activity timing. The service life of the initial pavement design and subsequent rehabilitation and maintenance activities have an impact on the LCCA outcomes as they directly affect the frequency of agency intervention. These will, in turn, affect agency costs along with user costs during the periods when the pavement is subjected to construction and maintenance activities [17]. The timing of activities should be based on existing performance records, such as those available from pavement management systems [16].

The third step is to estimate costs. The LCCA considers costs accrued to highway agencies and to users of the highway system, as a result of the agency construction and maintenance activities [16]. LCCAs do not require all costs associated with each alternative to be calculated. Only costs demonstrating differences between alternatives need be considered [16]. Costs common to all alternatives cancel out and these cost factors are consequently excluded from the LCCA calculations [17].

After that, the next step is to compute the LCC. Projected activity costs for alternatives need to consider the value of money over time [16]. Methods from the field of economics are applied to transform anticipated future costs to present value, so that the lifetime costs of different alternatives can be compared in a direct manner [16].

Several economic indicators can be considered during a LCCA. The most common ones include Benefit/Cost (B/C) Ratios, Internal Rate of Return (IRR), Net Present Value (NPV), and Equivalent Uniform Annual Costs (EUAC). The B/C analysis represents the net discounted benefits divided by net discounted costs for a given alternative. This methodology is not recommended for pavement analysis because of the difficulty in sorting out reliable benefit and cost estimates [12]. The IRR represents the discount rate necessary to make discounted cost and benefits equal. This index provides valuable information when budgets are constrained, or if the accuracy of the adopted discount rate is doubtful [17]. NPV and EUAC are typically used to convert cost streams into a single economic value by using a discount rate that resembles reality in a reliable manner [5].

The Net Present Value (NPV) or Net Present Worth (NPW) is the discounted monetary value of the expected net benefits. The NPV for the lifespan of a pavement section can be estimated using Equation 1. Present-worth costs of the strategies provide a fair comparison basis [5]. There is a strong agreement in the literature that NPV should be the economic efficiency indicator of choice [5, 17]. Continuous compounding (Equation 2) should be implemented when the time interval is not defined in round years. The NPV considered those costs accruing to highway agencies and to users of the highway system as a result of agency construction and M&R activities [16]. The salvage value includes the remaining serving live values and it is subtracted to the NPV.

$$NPV = Initial\ Cost + \sum_{k=1}^{N} M\&R\ Cost_k \left[\frac{1}{(1+i)^{n_k}}\right] - Salvage\ Value\ \left[\frac{1}{(1+i)^{n_k}}\right] \quad (1)$$

Where, i = discount rate; n = years of expenditure

$$NPV = Initial\ Cost + \sum_{k=1}^{N} M\&R\ Cost_k \left[\frac{1}{\exp\,(i*n_k)}\right] - Salvage\ Value\ \left[\frac{1}{\exp\,(i*n_k)}\right] \quad (2)$$

The Equivalent Uniform Annual Cost (EUAC) combines every NPV obtained for all discounted costs for a studied option and the benefits of an alternative to that option into equal annual payments over the analysis period. The EUAC indicator is a particularly meaningful when budgets are established on an annual basis [9]. It can be calculated by estimating the NPV in the first place and implementing Equation 3 afterwards.

$$EUAC = NPV \left[\frac{i(1+i)^n}{(1+i)^n-1}\right] \quad (3)$$

Finally, once the deterministic or probabilistic LCCAs have been computed, the present values of the differential costs may be compared across competing alternatives.

CASE STUDY

In the present research study, the analysis used pavement duration data containing historical information about maintenance and rehabilitation (M&R) projects in Texas. The available data was compiled from different databases of the Texas Department of Transportation (TxDOT). The final database required processing and merging information from Design and Construction

Information System (DCIS), Pavement Management Information System (PMIS), Maintenance Management Information System (MMIS), Site Manager (SM) and Compass.

TxDOT databases containing M&R project-related information can be divided into two groups regarding data formatting and content [18]. The first group includes DCIS and SM and contains data from contracted projects. The second group includes MMIS and Compass and contains data from internal or in-house projects performed by TxDOT personnel. The first group is the primary source of the data used in this study because it provides more detailed and precise information. The objective of processing the information is to obtain information about the M&R projects such as the location, effective life, cost, among other traffic information.

The final compiled database contains historical information of M&R projects constructed between 1994 and 2015. The present analysis only involves data from PM projects, including a total of 14,372 projects. The PM work only includes section with non-structural pavement damage.

Effective Life

The effective life of a treatment is a fundamental input in the LCCA. Therefore, obtaining this information from the databases is critical. This section explains the process to obtain the effective life of the PM treatments analyzed.

Data Processing

Every contracted M&R work uses an identification number called Control Section Job (CSJ). The CSJ contains nine digits, where the first six numbers refer to the control section (location of the roadway segment in the Texas highway network), and the last three numbers identify the job. The first step of the data processing consisted of obtaining initial and final dates for each CSJ. The initial date of a PM treatment corresponds to the day the work was completed and opened to traffic, in a particular control section. The final date corresponds to the day another treatment was placed in the same section. This information is obtained from the SM. The final date was reviewed and carefully corrected using information from the MMIS database.

In the present research, the difference between the initial and final date is defined as "effective life." The elapsed time between applying the treatment and applying another surface over it is an indicator of the treatment's effectiveness. This duration time does not discriminate between reactive and scheduled work; however, it provides an estimate of the treatment's "effective life" based on realistic field pavement data.

Also, the databases were used to verify that the final dates correspond to actual improvements in the pavement condition. This process was possible using performance curves from the PMIS database, which contains performance information regarding the Condition Score (CS). This indicator combines the ride quality and surface distress severity into an index that ranges from 0 to 100, where 100 indicates best conditions. Every time a new PM treatment is applied, the performance curve shows an increase. All pavement performance curves were inspected visually to verify that the final dates correspond to an increment in the CS value.

The service life of a surface depends mainly on wear and tear caused by traffic. Traffic information was extracted primarily from the PMIS database. Three indicators describe the traffic information: Annual Average Daily Traffic (AADT), Equivalent Single Axle Load (ESAL) and highway designation or roadbed type. The processing of this information consisted of obtaining average values for the PMIS sections located within the analyzed section. The traffic volume is represented by the AADT, which measures how busy a road is. AASHTO defines the AADT as the total amount of traffic on a highway segment for one year, divided by 365 days [19]. The traffic loads are characterized by ESAL, which is a concept developed for the

AASHO Road Test to establish a damaged relationship that compares the effects of different axles carrying different loads. The reference axle load is an 80 kN (18,000-lb.) single axle with dual tires [19].

The type of highway corresponds to TxDOT designations. TxDOT assigns a specific designation to highways located in Texas depending on their construction standards, design requirements and purpose [20]. Four hierarchies or roadway categories were defined for the analysis. Primary routes include Interstate Highways (IH) and US Highways (US) which form part of a system of expressways that go through more than one State [20]. US were implemented before IH. State Highways (SH) corresponds to a network connecting internal, state maintained roads. They can belong to both primary and secondary routes [20]. Farm to Market Highways (FM) are roadways that connect rural or agricultural areas to market towns and are part of a system of secondary routes.

Survival Analysis

The effective life of the evaluated PM treatment is highly variable. Thus, the most realistic approach to the LCCA is the stochastic method, including a probabilistic effective life. Survival analysis was applied to the PM treatments. This type of analysis allows the incorporation of both observed and censored data. Censored data corresponds to the cases where the treatment is still in use and its service life is not consumed yet. Including censored information to the LCCA allows an unbiased and more robust estimation. The survival analysis applied used the approach as suggested by Serigos et al. [18].

The survival probabilities of the three PM treatments were jointly estimated to reduce the impact of potential confounding factors on the comparison of the different PM treatment's effectiveness. Additionally, the development of an Accelerated Lifetime Model (ALM) adopting a Weibull distribution allows accounting for influence factors. This survival model was specified using chip seal as the base treatment and three covariates: traffic volume (in 10^3 ESAL), traffic load (AADT), and roadway type. This ALM model was estimated using the R statistical programming language (R Core Team 2014) employing the SURVIVAL package. By using this model, it was possible to obtain the scale (α) and shape (γ) parameters of the Weibull distribution, shown in Equation 4.

$$f(x|\alpha,\gamma) = \frac{\gamma}{\alpha}\left(\frac{x}{\alpha}\right)^{\gamma-1} e^{-(x/\alpha)^{\gamma}} \tag{4}$$

Where, x is a random variable, $\alpha > 0$ is the scale parameter, and $\gamma > 0$ is the shape parameter

Also, the Weibull probability distribution was estimated for each treatment based on traffic volume, traffic load, and roadway type. This modeling was applied to analyze the effect of the traffic variables in the LCC. The traffic volume consisted of three AADT ranges, lower than 5,000, between 5,000 and 10,000, and more than 10,000. The traffic load has three categories; the first corresponds to loads lower than 10^6 ESALS; the second group includes loads between 10^6 and 10^7 ESALs, and the last category incorporates loads greater than 10^7 ESALs. The roadway type categories were based on the four TxDOT designation explained previously.

Cost

The cost for each PM treatment was obtained from the final cost of each project, estimated once the treatment was placed. The information was obtained from the PMIS and the SM databases. Also, information of the total length of the section and the number of lanes were extracted. These data allow the estimation of the cost per lane-mile. The cost of each pavement segment is transformed into its 2016 value using the Inflation Index suggested by the United States Bureau of Statistics [21]. The variation of this cost is a consequence of the variable duration of the applied PM treatments, changes in the value of the used materials, the location of the project, employed workforce, among other variables. The project cost was also modeled using a probabilistic approach to take these variabilities into consideration in the LCCA.

The cost was modeled using a Lognormal probabilistic distribution, using the cost obtained from the databases. The Lognormal probability distribution avoids simulating negative costs and better represents the extreme values found in the analyzed data. This distribution also presents a mathematical advantage as it allows to use transformations to estimate costs parameters linearly. The Lognormal distribution, shown in Equation 5, requires the location (μ) and scale (σ) parameters. These parameters were obtained from Equations 6 and 7, respectively, using the information from the final PM projects' database. Also, the Lognormal distribution was estimated for each treatment based on the traffic volume, traffic load, and roadway type using the categories defined previously.

$$f(x|\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(lnx-\mu)^b}{2\sigma^2}} \tag{5}$$

Where, x ≥ 0 is a random variable, μ is the location parameter, and σ is the scale parameter

$$\mu = log\left(m^2/\sqrt{v + m^2}\right) \tag{6}$$

Where, m is the mean and v is the variance of the log-normal distribution

$$\sigma = \sqrt{log(v/m^2 + 1)} \tag{7}$$

LCCA OF PM TREATMENTS

A stochastic approach was utilized in this study because it allows to account for the uncertainty of the input parameters and to measure the variability of the LCCA outputs, which can be used for reliability analyses.

Methodology Framework

The analysis period was 25 years. An important assumption is that once a PM treatment was implemented in each section, the same type of treatment would be applied throughout time, as in common practice [22]. Although, it is important to mention that in some cases, a pavement with 25 years of successive maintenance may need a major repair to maintain a good condition. Thus, this period is established mainly for analysis purpose.

Figure 1 describes the methodological framework used for the analysis. The time between each PM treatment application corresponds to the effective life, which presents a Weibull probability distribution obtained from the survival analysis. When the treatment reached this effective life, another treatment is placed. Note that the terminal condition criteria may vary as the replacement of the treatment is based only on the effective life, which is considered an indicator of the treatment's effectiveness.

The cost of the treatment follows a Lognormal probability distribution. The total cost of maintenance of a pavement segment was computed as the sum of the cost for all the PM treatments applied during the analysis period minus the salvage value, at the end of the analysis period. The salvage was the estimated monetary value a pavement section would have at the end of its lifespan, as illustrated in Figure 1. Therefore, this value was calculated as the cost of the last PM cycle in the section times the percentage of the remaining life of that treatment, as shown in Equation 8.

$$S_{val} = \frac{m_{res}}{m}(Cost) \tag{8}$$

Where, m is the effective life, and m_{res} is the residual life

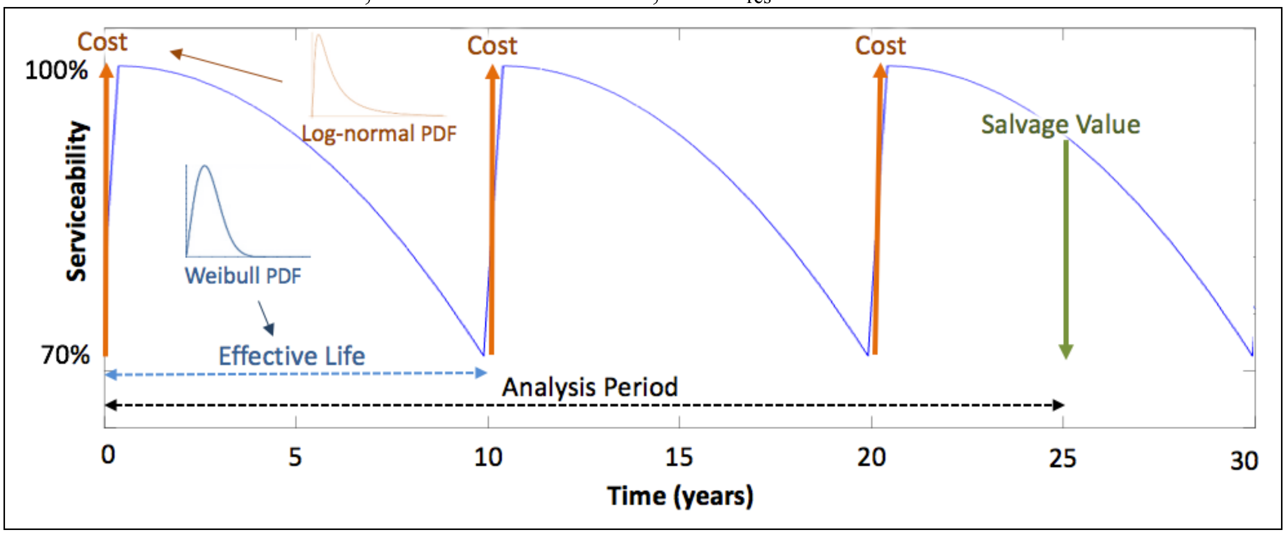


FIGURE 1 Life cycle cost analysis methodological framework.

The analysis consisted of Monte Carlo Simulation (MCS) using 100,000 repetitions. This type of evaluation allows the simulation of both the effective life and the cost using the respective probability distributions. It is possible to obtain a NPV for each of the simulations and thus, get a probability distribution for the NPV of each PM treatments. These results allowed analyzing the variability of the outputs. The interest rate used was4%, as suggested in the literature for estimating the NPV for highway projects in Texas [22].

The MCS was applied using MATLAB software. The first step was the simulation of the effective life using a random number generator in MATLAB. It was possible to obtain a total of 100,000 values that follow the Weibull distribution described by the scale (α) and shape (γ) parameters obtained from the survival analysis. Similarly, the simulation of the cost consisted of generating 100,000 random values that follow the Lognormal distribution described by the location (μ) and scale (σ) parameters. Finally, the LCC is estimating using the NPV for each of the 1000,000 outputs using the simulated life and cost. Thus, a total of 1000,000 NPVs are estimated which allows observing its variability. The NPV is obtained implementing Equation 9 in MATLAB. This process was applied for the three PM treatments using the complete database, but also for each of the three categories of AADT, three classes of ESAL, and four roadway types, segregated by the PM treatment. Thus, a total of 33 LCC distributions were estimated.

$$NPV_{jk} = C_{jk} + \sum_{x=1}^{z_1-1} \frac{C_{jk}}{exp\,[i\cdot(x\cdot m_{jk})]} - \frac{S_{val}}{exp\,(25\cdot i)} \tag{9}$$

Where,

j = PM treatment (chip seal, microsurfacing, thin overlay)

k = Monte Carlo iteration (1 to 100,000)

NPV_{jk} = Net Present Value of PM treatment j during iteration k

C_{jk} = cost of PM treatment j during iteration k

m_{jk} = effective life of PM treatment j during iteration k
$z = 25/m_{jk}$ (applications of the PM treatment j during the 25 years' analysis period)
z_1 = round down $\{z\}$
$S_{val} = [(z - z_1) \cdot C_{jk}]/m_{jk}$ (salvage value)
i = 0.04 (interest rate)

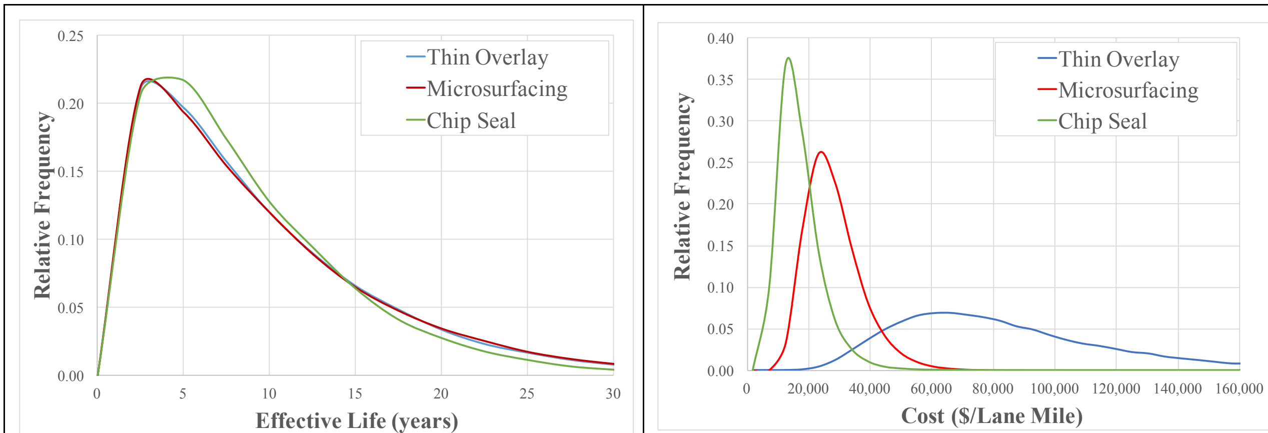
Results and Discussion

This section presents the results obtained from the analysis of the databases and the application of the LCCA framework. It also provides an examination and discussion of the main findings.

Effective Life and Cost

The effective life and cost obtained from the analysis of the databases are shown in Figure 2a and 2b, respectively. The three PM treatments presented similar effective life distribution, with a mean of 7.6 (chip seals), 8.6 (thin overlays), and 8.4 (microsurfacing) years. It is important to mention that thin overlays present a very similar probability distribution, with a higher variability compared to chip seals.

The cost of the PM treatments shows distinctive distributions. The chip seal showed a mean of approximately $14,500 per lane-mile with estimates located on a tight cost-interval and maximum amounts of around $50,000. Microsurfacing showed higher variability than chip seal, with an average of $25,600 per lane-mile. Thin overlays presented the greater cost and variability, with an average of $83,400 per lane-mile, approximately three times as expensive as microsurfacing and almost six times as chip seals.



a) Effective Life per treatment
b) Cost per treatment

FIGURE 2 Effective life and cost results.

LCCA Results

The results obtained from the LCCA (using MC) are shown in Figure 3. The probability distribution of the NPV, which represent the LCC, shows a marked difference between the cost of the treatments. The median was the preferred statistical indicator to describe the results because it is less sensitive to the extreme values, as compared to the mean value. Chips seals have the lower life-cycle cost with a median of $39,000. This treatment also present the lower variability. Microsurfacing present a LCC 70% higher, with a median of $66,000. Furthermore, thin overlay shows the higher LCC with a median of approximately $190,000 and a high variability. This cost is about five times greater than chip seals and about three times greater than microsurfacing.

Although the LCCA appears to indicate chip seals as the overall best PM treatment option, the selection of the treatment depends on different of factors, based on the characteristics of each treatment type. These factors include the environmental conditions of the pavement section because climate and soil has a lasting impact on pavements. Also, rural roads are generally cheaper to maintain than urban roads. The location within the road is also relevant as segments where acceleration/deceleration occurs ought to be more resistant, e.g. thin overlays are applied in intersections. Other factors include the availability of required materials as well as design traffic volumes and loads, and previous experience of the transportation agency.

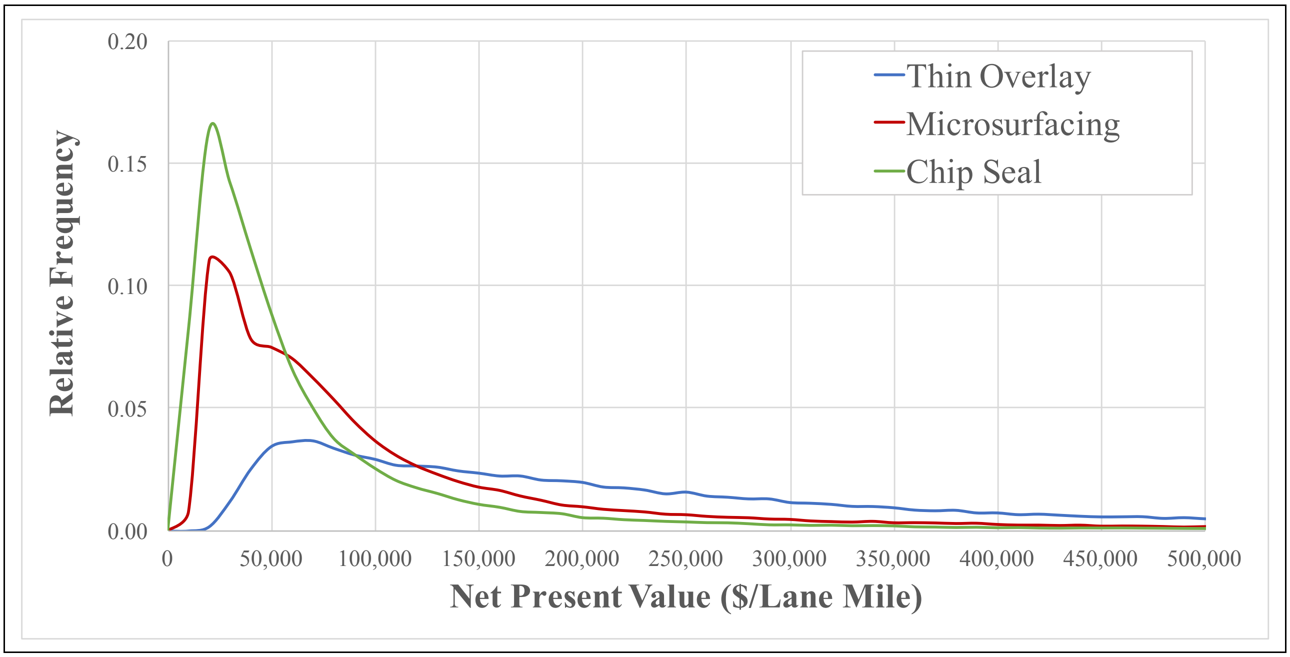


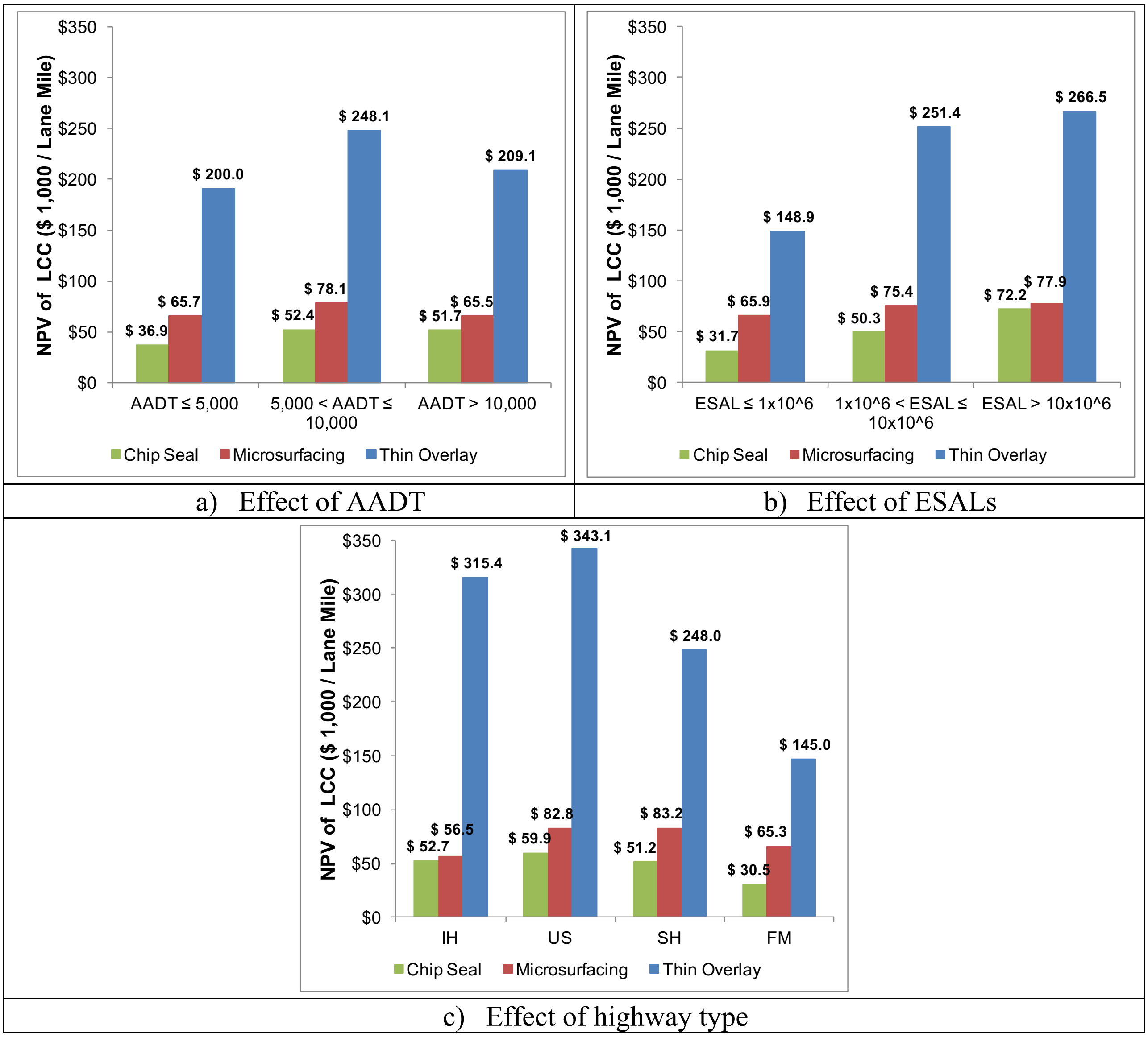
FIGURE 3 Life cycle cost analysis results.

Effect of Traffic Volume and Loads

Traffic volume and load information were also included to evaluate their influence on the effective life, cost, and LCC. The results of the median LCC values based on the AADT are shown in Figure 4a. The figure indicates that the second category presents the higher cost. However, the variation of the LCC is not significant among the three classes selected. This fact suggests that the PM treatment cost does not variate significantly for different ranges of AADT.

The effect of the traffic loads was analyzed using the ESALs. The results are shown in Figure 4b. In contrast to the AADT effect, the weight of the vehicles on a pavement section has a significant impact on the lifespan of the pavement, particularly when the loads are noticeably heavy. The cost per PM treatment increases as loads increases. The LCCA suggests that chip seals are the most efficient option, and thin overlays are the least efficient alternative, but microsurfacing performed better than seal coats under heavier traffic.

Additionally, the roadway type was also included in the analysis. The results of the median value of the LCC is shown in Figure 4c. In this case, the thin overlay presented the higher variability among the evaluated roadway types. FM presented the lower LCC, followed by SH. IH and US, corresponding to the principal roads of the country, presented the higher LCC.



a) Effect of AADT

b) Effect of ESALs

c) Effect of highway type

FIGURE 4 Effect of traffic volume and loads on the LCCA results (median values).

Cost Probability

The probabilities that a given PM treatment is more cost-effective (lower LCC) than another treatment option is an important indicator as it can be used for sensitivity analyses and to indicate which option to select in the case of uncertainty. Results of a sensitivity analysis indicating the likelihood of treatments being the most effective option were obtained using the 1,000,000 MCS iterations.

The probability of the LCC of chip seals being less than microsurfacing is 70%, and likely 85% compared to thin overlays. This suggests that overall seal coats are effective preventative maintenance options. The LCC of microsurfacing, in turn, is likely to be 75% less than thin overlays. These results provide an approximate comparison of the cost of PM treatments and can be used for practitioner as a first step in the process of decision making when the information is limited.

SUMMARY AND CONCLUSIONS

This study developed a LCCA framework aimed at evaluating and comparing the three primary PM treatments used in Texas: chip seals, microsurfacing, and thin overlays. The case study was developed based on 14,372 projects implemented between 1994 and 2015. The data collection included processing and merging information from different TxDOT databases. Information about effective life and cost of the project was gathered from the data available. A stochastic approach was used to take into account the data variability. Information on traffic volumes, loads and roadway type of the pavement sections was taken into consideration to gauge the impact of the variation on the effective life and costs affecting the LCCA. The LCC was estimating using MCS technique to simulate the effective life, cost, and NPV using different probability density functions.

The results of this study are based on real projects data. This study, thus, provides a more accurate estimation of the effective life, costs, and LCC of the PM treatments. The major findings and conclusions from this study are summarized as follows:

- The effective life of the PM treatments analyzed is similar.
- The LCC of the chip seals is significantly lower than the thin overlay and microsurfacing, and it presents the lower variability.
- Chip seals present the most cost-effective PM treatment, and thin overlays are the lest cost-effective. Microsurfacing are, in general, more expensive than chip seals but less costly than thin overlays.
- LLCs are not overly influenced by traffic volume expressed in terms of AADT.
- The LCCA based on ESAL suggests the cost of implementing chip seals notably increases as loads increase from low to medium and heavy. On the other hand, the LCCs for microsurfacing are not significantly changed as traffic loads increase.
- The LCC ratio between chip seals and microsurfacing decreases as loads increase. This suggests that for heavily trafficked pavement sections applying chip seals may be at least as effective as applying microsurfacing.

As the study only considered PM treatments in pavements that were structurally sound, it is recommended that the analysis be extended to investigate the relative benefits of chip seals when considering damaged pavement sections. Additionally, it is recommended to include into future studies the effect of other variables that were not considered and may affect LCC, such as the climate and type of material.

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